Designing Wearables

a Practice-led Framework for Enhancement Technologies

PhD Thesis

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Designing Wearables: a Practice-led Framework for Enhancement Technologies

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Abstract

My research asks the question *How can design re-think the approach to enhancement technologies*? I approach this question through reflective practice-led inquiry, designing wearable systems aimed at questioning, extending and reframing the very notion of enhancement. Through three projects and the thesis, I offer a new approach to enhancement focused on expanding an agent's senses within its environment to access hidden affordances. My research aims at establishing a pragmatic and practice-led approach to enhancement systems that translates philosophical debates into actionable artefacts.

The research's intended audience includes researchers and practitioners seeking a pragmatic approach to design enhancement technologies that extend the sensory information available to an agent. It also contributes to theories of enhancement by developing a design-led methodology for sensory enhancement that uses ideas from theories of embodiment, affordance, and design cybernetics.

The thesis builds on the debate concerning human augmentation, which has often followed subjective and ambiguous assumptions. Modern approaches to the subject – bio-conservatism and bio-liberalism – contend that enhancement technologies affect humanity's essence despite different defining perspectives. I argue for separating the notion of "enhancement" from "human", focusing instead on any agent's body and senses, or lack thereof. I redefine enhancement as the practice of enabling agents to perceive environmental information they traditionally would not have access to. This information is presented to the agent through feedback loops that use the agent's pre-existing senses. I define this practice as *sensory layering*.

I first establish a body-centric framework that addresses enhancement technology agnostically as the enhancement of both humans and human-made agents such as robots. This acknowledges but deliberately sets aside much of the debate about what is essentially human. Within this framework, I redefine enhancements as devices expanding an agent's senses in its environment to access hidden affordances. Next, I elaborate on five guidelines that facilitate cutting through the cross-domain knowledge needed to develop pragmatic enhancements. Finally, I explore these five guidelines through three case studies to enhance the navigation abilities of human and human-made agents.

The five design guidelines for practitioners approaching wearable enhancement form parts of an overall design strategy and are concerned with: (1) selecting the hidden affordance to target, (2) selecting a pre-existing sense to design on, (3) deciding on how the feedback loop integrates with the agent's pre-existing senses, (4) locating the wearable on the agent's body, and (5) making the final design accessible to and reproducible by a larger community.

The three case studies of wearable enhancements are used to gauge the guidelines' value, utility and transferability. Further, they present several advancements in the state-of-the-art in robotics, Human-Computer Interaction and wearables.

The first case is a robot's resilience to motor faults. The project aims to develop a motor assembly that predicts a fault and switches to a backup system. The system allows a robot to keep moving by anticipating and preventing hardware failures. I employed on-device deep learning algorithms and a custom 3D-printed motor assembly. This project illustrates how the design guidelines apply to human-made agents. It highlights the importance of Guideline 3 when designing robotic enhancements.

The second case study investigates how a human's sense of direction can be enhanced by layering the perception of magnetic North. This project aimed to exemplify a design pipeline for body-moulded wearable enhancements, resulting in a wearable device moulded on the wearer's body. To this end, I employed photogrammetry and 3D printing. This prototype highlights Guidelines 2 and 4.

The final case study looks into layering digital audio information on humans moving through a physical space. This project introduces a hybrid bone and soft tissue conduction headset and a mixed reality experience that provides contextual audio feedback. The hybrid headset was designed to address the limited ability of off-the-shelf bone conducting headphones to reproduce a wide range of sound frequencies without occluding the ear canal. Further, the system employs centimetre-level accurate ultra-wideband sensors to track wearers indoors, streaming their position data to a simulation in real-time. Based on their position, the wearers receive layered sound cues about the environment they are navigating. This final prototype highlights the role of Guidelines 3 and 4.

My contribution to knowledge is threefold. First, each of the three case studies presents a distinct design innovation: a novel redundant actuator in robotics, a body-centric design pipeline for wearable systems, and a hybrid bone and soft-tissue conduction headset for immersive audio experiences. Second, the research introduces and rigorously explores five design guidelines, forming a new, pragmatic framework for developing enhancement technologies. These guidelines provide practitioners with a method for navigating complex domains like design and robotics through sensory layering. Finally, this framework also advances enhancement theory by challenging traditional, human-centric views of enhancement, proposing an agent-centric – whether human or human-made – epistemology.

My research materialises theoretical concepts, via experiential prototypes, to explore and reflect on the theory of enhancement itself.

Keywords: Enhancement, Posthumanism, Cybernetics, Wearables, Robotics.

Publications

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1 Introduction

Throughout history, humans have had an insatiable desire to better themselves by pushing beyond their limits. We plan our diets, track our sleep, meditate and even enrol in top universities to sharpen our cognitive abilities. We design machines that can transport us to distant planets and – in some dreams – colonise them. We have tried many methods to enhance our physical and cognitive capacities, from chemical agents to mechanical gizmos and learning strategies.

My research explores why and how design practice, in conversation with theory, can offer a pragmatic approach to translating philosophical discourse into experiential artefacts. In line with established design movements, such as Speculative and Fiction Design, I argue that complex issues like enhancement technologies cannot be examined in a vacuum. Instead, the issue should be embodied in physical artefacts that allow users to experience what it *would look and feel like* if the technology was here. I also extend this approach by developing fully functional prototypes and documenting my practice to allow others to repeat, remix or extend my work.

In this chapter, I introduce my research, explain why design is viable for exploring enhancement technologies, and describe my research approach, which led to my choice of designing a framework for enhancement technologies. I do not include references in this chapter, as it is intended to introduce the broad issues of principle and how they inform – and are informed by – my practice. The next chapter expands on this introduction, contextualising it in the relevant literature.

In popular culture, the notion of enhancement is often associated with fiction-inspired ideas of superheroes, galaxies far away and distant futures. This point introduces the first tension within the field: 'enhancement' and 'human' are often used in tandem. In this thesis, I argue that the two terms should be separated, as the definition of enhancement would depend on defining what a human is first – a matter not yet resolved and beyond the current scope of my research.

Instead, I argue for not pursuing a universal definition of either concept: my focus centres on the notion of an agent and their body. In my research, an *agent* refers to an individual – either human or human-made[1] – possessing the capacity for action and decision-making. The term encompasses the subjective, intentional nature of those actively engaging with their environment. Simultaneously, the *body* encompasses an agent's physical aspects, including sensory capabilities and cognitive functions. By emphasising the agent and their body, I aim to highlight enhancement's personalised and context-dependent nature.

In this PhD, I argue for using cybernetics, particularly the approach called design cybernetics, as the scaffolding to explore agent enhancement. In my research, design cybernetics is both the philosophical ambition to increase the amount of knowledge available to an agent and the practical epistemological framework to navigate the many disciplines involved in prototyping enhancement systems. I make the following arguments that culminate in a framework for designing enhancement technologies that I explore through my case studies:

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[1] My inquiry intentionally excludes animals and natural inanimate objects from the discussion due to its scope. While acknowledging the agency and importance of non-human entities in diverse contexts, my emphasis on human and human-made agents allows for a more focused examination of the interplay between action, body and environment.

1. Enhancement is defined as more opportunities for interaction – specifically, enhancing the senses to perceive sensory cues previously unreachable to the agent. I call this practice *sensory layering*.
2. Treating enhancement as a disembodied, theoretical construct does not allow for a focused and productive conversation. I cannot study enhancement independently as it is ultimately applied to a body. In my research, I focus on the agent's body as the sole starting point for enhancement.
3. Since enhancement starts from the body, the specific body is the baseline. I do not seek generalised definitions of "harder/better/faster/stronger". Instead, I reframe enhancement as contextual, body-specific sensory devices that enable human or human-made agents to access environmental affordances otherwise inaccessible.

I argue for embedding enhancement technology in everyday interactions. In this way, my practice and prototypes aim to be experiential: they externalise enhancement technology's ethical, social, and political implications through tangible and wearable artefacts. There are several benefits to my reflective and practice-led approach. I make the following high-level arguments, which I will then unpack and support throughout the subsequent chapters and case studies. The following points lead to new knowledge in the form of a novel epistemological position and a framework for designing enhancement technologies.

1. As new technologies with the potential for enhancement enter the mainstream, debating enhancements is increasingly a pressing issue. Hence, there is an urgent need to have these debates in meaningful ways beyond academia's (often) closed doors. My research exemplifies how 'philosophical' enhancement can be translated into 'experiential' enhancement, nudging the discourse towards a wider audience.
2. By shifting enhancement's focus from humans to agents (and, therefore, including human-made agents in the discussion), my approach does not have to resolve the conundrum of having to define what is 'normal' to define enhancement, eliminating this chicken-and-egg philosophical impasse.
3. I propose a new design framework for addressing the subject by integrating concepts from embodiment, design cybernetics and affordances with enhancement technology. This framework, operationalised through three case studies, presents the five guidelines for framing and designing wearable enhancement technology to expand the agent's sensory capabilities.

1.1 Who is this research for?

This research is written for those critically interested in enhancement but who challenge or do not assent to the equation *enhancement = better*. To be clear, I am not against reductionism as a scientific method, which is demonstrably effective in other domains. Instead, this research is for those unwilling to apply it to complex social phenomena such as enhancement, as it could lead to neglecting its ramifications and undervaluing the not merely material consequences of enhancement.

My goal has been to create accessible and specific transferable knowledge that can be applied by individuals who find the technical and conceptual aspects of enhancement technologies daunting. This research is intended to serve as a starting point, allowing others to explore, expand, and design enhancement technologies from their embodied understanding of the world.

My research will likely be of greater utility to some groups than others. Specifically, those engaged in Human-Computer Interaction (HCI), practitioners of Critical Design, and scholars of the Posthumanities may find my research's pragmatic and practice-oriented methodology particularly beneficial. By explicitly framing their work as an exploration of enhancement technologies, these researchers can leverage insights from my study to enrich the depth and relevance of their investigations. Moreover, my research holds significance for policymakers and ethicists tasked with navigating the complex landscape of technological advancements. It provides a valuable resource for these stakeholders to gain a nuanced understanding of the implications, challenges, and ethical considerations associated with enhancement technologies.

1.2 Motivation

My interest in enhancement started during my Master's Degree at the Royal College of Art. I was in the Service Design department, focusing on designing technologies for enhancement as a service – asking how to develop systems and technologies to make humans better equipped in their everyday lives. As I will argue in the next chapter, my initial position was naïve. Nevertheless, one of my projects, *Artificial Agency*, was foundational for spurring my interest in researching this field further with a PhD. I designed an arm-worn wearable device that monitored muscle contractions in the forearm – signalling the wearer's intention to strike. The signal would trigger a hacked transcutaneous electrical stimulation machine (TENS), spasming the wearer's arm (Figure 1.1). Initially, I intended to stop harmful behaviour (i.e., punching), but I quickly realised the larger issue: what about the wearer's agency? What if the wearer was in a dangerous situation and needed to use force to escape?

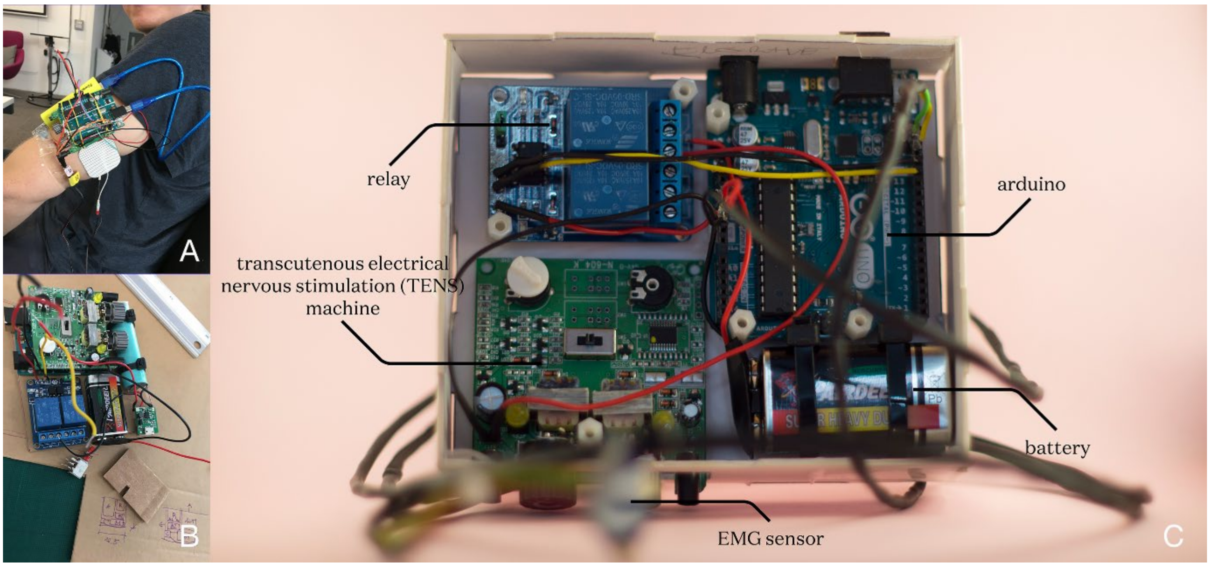

Figure 1.1 My first foray into wearable enhancement technology circa 2017. A and B show the 'muscle zapper' wearable prototyping, while C shows the final assembly intended to be worn around the waist.

This unresolved tension between individual agency and enhancement eventually led me to apply for my PhD at the Robotics Laboratory at the RCA, with a proposal titled *Wearable Soft Robots for Human Enhancement*. My goal was to explore advancements in medical technologies, such as soft robotics, and apply them to healthy individuals to enhance them. In this context, why not use Design and its human-centred sensibility to create even better enhancements?

My starting point was Transhumanism – the philosophical and intellectual movement that advocates using advanced technologies, such as robotics, to enhance human cognitive and physical abilities. While studying the literature, I quickly realised there was another way to think about human relations with technology: Posthumanism. This philosophical and cultural movement critically examines and challenges traditional notions of 'the human'. It explores the implications of emerging technologies and the changing relationships between humans and non-human entities, such as machines and the environment. Unlike Transhumanism, which often seeks to enhance or transcend human capabilities, Posthumanism questions the very idea of a fixed and unchanging human essence.

The tensions between Post- and Transhumanism made it clear that the subject of enhancement is less clear-cut than I initially thought. Can we define what a human is? Is enhancement really a synonym for 'better'? Can we create one-size-fits-all enhancements? What about individual agency? These tensions informed my PhD research approach, culminating in developing a framework for enhancement technology rooted in Embodiment, Design Cybernetics and Affordance Theory.

I want to stress at this point that I was quite free in choosing and pursuing my research topic and approach, as my PhD was self-funded. I was not bound by the directives of funding bodies or the need to align with a supervisor's focus area. Instead, I was free to experiment and reflect, to let the dialogue between theory and practice grow at its own pace.

This approach strongly influenced my choice of reflective practice, which I will discuss in detail later. Reflective practice allowed me to engage with my work as an ongoing dialogue between my experiences and enhancement theories. It let me rethink, refine and re-define as the research unfolded rather than forcing the process into a linear structure: in many ways, it was the natural extension of the freedom that shaped this entire project.

1.3 Research Approach: Conversations Between Theory and Practice

At this point, the reader may wonder why Design is the appropriate vector for approaching and exploring enhancement. First of all, the solutions proposed by Design are rarely final and indisputable. If we were to ask ten practitioners to answer a brief, we would receive ten different solutions and approaches (at least!). I do not find this performative connotation of Design problematic, especially in the case of enhancement. At the risk of sounding trite, we are all different. What the word enhancement means to me probably has a different meaning to the reader. This tension is not harmful – on the contrary, it allows for an explosion of different perspectives, each of value.

Further, design is not bound by predetermined outcomes; it thrives in uncertainty and complexity. When approaching enhancement, this adaptability becomes crucial. Enhancement is not a static or universally defined concept – it evolves with i.e., technological advancements, cultural shifts, and individual preferences. Design's iterative process allows for continuous reassessment and refinement of ideas, ensuring that the interventions proposed remain relevant and responsive to the changing landscape. This fluidity ensures that ongoing developments and practices dynamically shape enhancement.

Design – and above all, Design Practice – thrives on the cyclical and conversational process between theory and practice, between proposing solutions and asking questions, between demonstrating how the world is and how it could be. The enhancement problem should also be a design problem in which practical and ethical issues are explored and presented tangibly. In other words, the designer can be a political actor who creates, contextualises and reflects on the problem of enhancement, explaining how they arrived at the conclusion presented.

My research, like most of design, is the more or less conscious result of my understanding of the current state of the world. Personal views inevitably influence and reinforce the worldview in which it was created; hence, design outcomes often reinforce dominant cultural perspectives without scrutinising them. On the other hand, when we investigate the first principles of a situation, it is frequently argued that the design is too theoretical or not sufficiently focused on practical action.

This is a false dichotomy. Classifying designs as ‘theoretical’ or ‘practical’ overlooks the necessary reflection that an individual’s worldview is fundamentally and intrinsically informed by their position in the world. While undoubtedly useful, allowing us to avoid getting entangled in complex issues without clear answers, separating theory from practice implies refraining from taking a critical position on the principles of the problem itself, nullifying the possibility of exploring radically different positions and perspectives. This problem is evident for enhancement, as argued in the next chapter, where the true nature of the term is often left unclear, leading to conversations based on personal assumptions about the meaning of the word.

I myself have been guilty of this mindset. In my initial PhD proposal, I narrowly focused on a solution (soft robotics) for the presumed problem of enhancement. My initial proposal assumed that the field of enhancement was correctly and fully defined – in other words, that the theory was already in place, and I could ‘simply’ colour within the lines using the new and exciting technology, contributing new knowledge.

However, my initial position did not leverage the strength of design. Design arguably sits between theory and practice, drawing from various branches of knowledge, synthesising them, and expressing them in a unified form. To be concrete, I provide an example from my background as a service designer. Methods imported from ethnography, social sciences, systems thinking, human factors, interaction design, and various digital technologies are often used when designing a service. The inclusion (or omission) of any of these elements inevitably results in a different service. These branches of knowledge are more or less ‘standard’ in service design practice because other researchers and practitioners have reflected on their experience and communicated which aspects have been helpful in their practice. In other words, reflection (or, more precisely, Reflective Practice) has led to the semi-standardisation of practice by creating guidelines and best practices.

I believe this approach is very promising for enhancement. Contrary to what I thought at the beginning of my doctoral studies, and as I will discuss more thoroughly in the next chapter, there is no unified theory on the subject. In fact, it is not necessary to have one. I would even further state that there should not be a fixed and immovable structure for designing enhancements, as it would inevitably be based on personal assumptions and probably not transparently communicated.

This problem was the most challenging aspect to address in my research. How can I simultaneously create wearable enhancements using a transparent methodology without declaring that my approach is the only one? How do I create experiential enhancement examples, simultaneously stating that they are partial and decidedly not a one-size-fits-all solution?

My solution was to externalise the dialogue between theory and practice that I conducted. In this sense, my design is intended as a verb and not a noun: my practice, even though it results in physical objects, functioning prototypes encapsulating an instance of enhancement, is to be understood as the process that led to informed decisions culminating in the instance. My prototypes, even though they bring important technical design innovations, are also vehicles for communicating a new epistemic position regarding enhancement. I selected these projects to inform and challenge the new theoretical position I was forming and they are not, strictly speaking, sequential.

This process culminates in formulating a framework, a collection of design guidelines to shape (and criticise!) a clear position before and during practice. Before explaining why I decided to crystallise my work into only five guidelines, I elaborate on what I mean by a framework, why I chose to create a framework instead of, for example, a manifesto, and finally, how one can put a framework into practice.

1.3.1 Frameworks: what and why?

A framework is a conceptual construct that provides a structured approach to understanding and analysing a complex phenomenon crafted to enable decision-making. It is an integrated set of concepts, each of which plays a vital role. Unlike causal or analytical approaches, a framework allows an interpretative approach to social reality: it does not offer a quantitative explanation but provides guidelines for interpreting and connecting situations. A framework prioritises understanding intentions and cannot predict outcomes. In other words, a framework is indeterministic.

Further, in contrast to a methodology – usually closely linked to the desired outcome of a field of study – a framework offers a more flexible structure. It serves as a structured approach to addressing the complexities of enhancement technology, allowing for the systematic inclusion of various components, processes, and tools. The framework's loose yet coherent structure provides ample space for adaptability, accommodating the evolving landscape of enhancement technologies.

The framework I bring forward in this thesis links the concepts of cybernetics, embodiment and affordances to redefine enhancement as sensory layering. Within this thesis, sensory layering is my preferred term for adding layers of sensory information deriving from environmental affordances in addition to the agent's pre-existing sensing capabilities.

1.3.2 Operationalising a Framework

The nature of a design framework, as described above, is mainly bottom-up. Its development occurs through a continuous iteration that generalises from concrete examples. In the context of this thesis, the framework took shape through a reflective analysis of three case studies. It is crucial to clarify that, despite the linear narrative of a thesis, the genesis of the design framework presented here was anything but linear. Instead, my three case studies can be thought of as probes, inserted into different elements of enhancement, each illuminating a unique aspect of this landscape. By exploring these distinct territories, I aimed to generate a nuanced and generative understanding of the possibilities and challenges inherent in enhancement technologies.

To operationalise the framework – that is, to translate the abstract concepts of cybernetics, embodiment and affordances into actionable guidance (Figure 1.2) – I decided to define five clear and specific design guidelines. Although they will be discussed in depth in the following chapters, here is an overview:

1. Establish hidden affordances,
2. Determine which sense to layer,
3. Establish sensory feedback loops,
4. Determine the wearable enhancement system's placement on the body,
5. Design for accessibility and distribution.

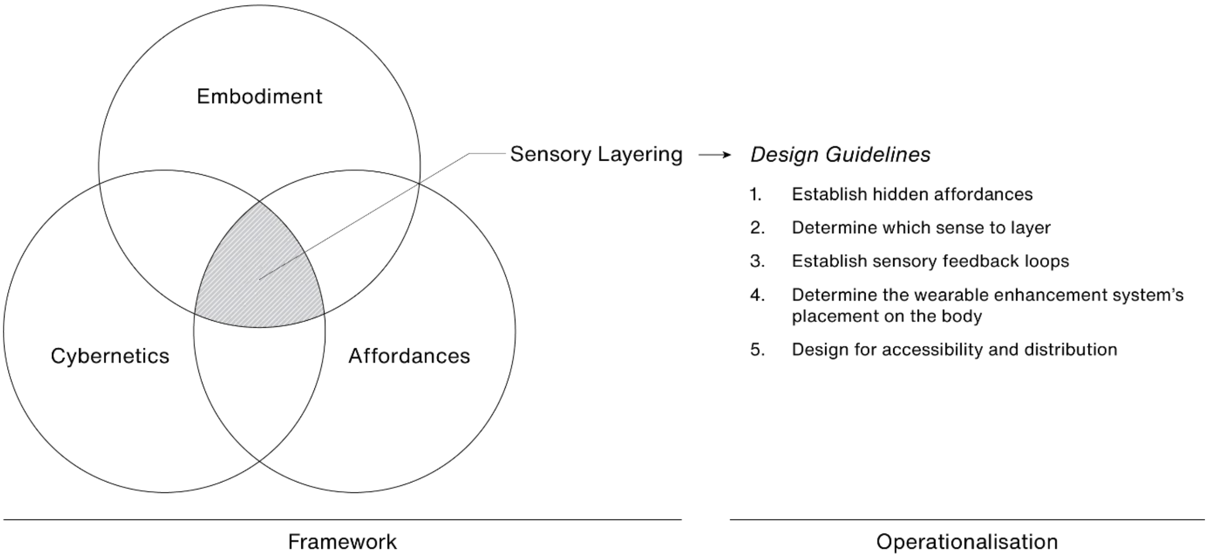

Figure 1.2 The framework proposed in this thesis and its operationalisation through five design guidelines.

1.3.3 Why Guidelines?

Despite frequent conflation, principles, guidelines, and heuristics possess distinct characteristics and nuance in the enhancement space. Principles provide fundamental truths, while heuristics offer rule-of-thumb solutions without theoretical grounding. In contrast, guidelines occupy a middle ground, offering recommendations for context-specific design issues that combine specificity and flexibility.

In my research, I choose to use guidelines as a framework because they provide actionable advice that can be tailored to unique situations. Guidelines allow designers to navigate complex problems with adaptability and critical thinking. Using guidelines, I aim to capture and reapply design expertise, facilitating effective decision-making and problem-solving in the early design stages.

I argue for design guidelines in my research because they provide pragmatic direction, informing others' practice by being the intermediary interface between instances, such as the prototypes discussed in chapters 4 to 6, and the expert knowledge necessary for designing enhancement technologies. Guidelines offer a transferable and adaptive approach, allowing for partiality and revision, making them beneficial for problem-framing and problem-solving throughout the practice.

1.4 Research Aims and Questions

My research outlines a pragmatic and practice-led approach to translate philosophical debates on enhancement technology into actionable artefacts and vice versa. I provide a transferable framework for approaching enhancement technologies from a practice-led perspective.

My research explores the question: *How can design re-think the approach to enhancement technologies?* Two intertwined but distinct motivations drive my inquiry. First, I seek to challenge and expand the existing paradigms of enhancement technologies by exploring new ways of thinking about and engaging with these systems. Second, I aim to uncover the specific qualities and methods within design that make it particularly suited to this task, offering insights that might not emerge from other disciplines.

Several sub-questions arise from my dual focus:

- *How can a pragmatic design framework for enhancement technologies be developed from an embodied approach?* This sub-question highlights design's practical and theoretical foundations, shifting focus from abstract concepts to grounded experiences.
- *What are the critical points that practitioners should consider when designing enhancement technologies?* Here, the emphasis is on identifying what design can uniquely offer regarding priorities, considerations, and methods that diverge from conventional or engineering-driven approaches.
- *How can a design framework for wearable enhancements be transferred to other practitioners*? This sub-question asks how a design framework can be shared while remaining flexible and adaptive to diverse applications.
- *How can a framework be developed that guides practitioners without prescribing a checklist?* This final sub-question addresses the tension between structure and creativity, exploring how design frameworks can provide direction without stifling innovation or exploration.

1.5 Thesis Structure

Chapter 2 surveys the history and literature of enhancement, highlighting key tensions within the field. It introduces the central theoretical positions that inform my research: Embodiment, Cybernetics, and Affordance Theory. These theories help to reframe enhancement as contextual, body-specific sensory devices that enable human or human-made agents to access environmental affordances otherwise inaccessible. I term this practice *sensory layering*. Additionally, this chapter explains why my research led to developing a framework and a set of guidelines.

Chapter 3 presents the primary methods employed in my research: critical design, reflective practice, experience prototyping, and externalisation. By articulating the rationale for these methods, the chapter distils my reflections into five guidelines for other practitioners to leverage when designing enhancement technologies. I designed these guidelines to be flexible and generative rather than a fixed set of rules. These guidelines are formulated as clearly and explicitly as possible, both to help the reader conduct their own research and to take responsibility for my practice. My ambition is to offer a compass for navigating through the tensions of enhancement. Similar to the performative properties of Design, this chapter offers a starting point, one of many possibilities. I aim to demonstrate how others can develop their own enhancement practice, by guiding the reader through case studies in the next three chapters.

The first case study explores how human-made agents can be enhanced using the sensory layering guidelines. Utilising standard robotics methodologies of mechanical, hardware, and software design, I developed a system capable of predicting motor faults and automatically switching to redundancies. This practice-led prototype, grounded in design practice, investigates how wearable sensory extensions can enhance agents' awareness of their surroundings. The objectives of this case study include establishing sensory layering guidelines in a real-world robotics context, enhancing the robot's control system awareness via AI, and designing a preventative, redundant hardware system with increased degrees of freedom. The developed prototype addresses unequal access to enhancement technologies and demonstrates how sensory layering guidelines help navigate technological challenges, leading to a fully functional actuating assembly. This chapter is central to one of the thesis's core claims, in illustrating how my approach to enhancement technologies can be applied to human-made agents as much as to humans.

The second case study explores the guidelines to enhance human agents by designing a body-moulded wearable navigation system. It emphasises the importance of designing for the agent's body using body scanning techniques and haptic feedback. My objective was to create a wearable system that provides a way to sense magnetic North and develop a transferrable pipeline for generating body-moulded wearables. This chapter contributes to the thesis by demonstrating the practical foundation for prototyping sensory layering wearables and highlighting the lack of a viable, fully open design pipeline for enhancement technologies. It also surfaces the tension between tailoring wearables to one agent versus designing for a wider range of bodies, which I explore in the next chapter.

The third case study explores layering digital affordances onto human agents via sound, probing whether my guidelines can be applied to hybrid reality and hidden digital affordances. This chapter combines methods from the previous two studies, employing body moulding, sensors for indoor localisation, and a 3D video game engine to provide access to digital spatialised sounds while navigating the physical environment. This chapter demonstrates how the design guidelines help in generating novel technical solutions. Further, my reflective practice throughout this case study surfaced Guideline 5.

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2 Literature Review: Redefining Enhancement as Sensory Layering

2.1 Introduction

> *The whole becomes not only more than but very different from the sum of its parts. […]*
>
> *More is different.* (Anderson, 1972)

This chapter surveys the literature and others' practice surrounding the three epistemological pillars of my work: Embodiment, Cybernetics and Affordance Theory. Before that, I must clarify what enhancement means and how it shapes my approach. I argue that enhancement can be redefined as layering new information onto an agent's body. The opening quote captures the essence of my argument: enhancement does not necessarily equate to 'more' or 'better'. It can simply mean having access to sensory information that an agent would not previously have the senses to interact with.

To clarify the subject matter, I will first briefly discuss the current interpretations of what it means to be human, followed by a discussion about the term 'enhancement' in opposition to other terms such as augmentation, prosthesis and tools. After this preamble, I review how the interplay between an embodied approach to cognition, Design Cybernetics and Affordance Theory led me to reframe enhancement as the practice of sensory layering – i.e., integrating new senses with an agent's existing body. I then review how practitioners in Robotics and Design have approached the same subject matter.

My research comes at an opportune time, as evidenced by recent news headlines that have sparked controversy, such as genome-edited twins (Jiankui et al., 2018), the exponential growth of stimulant users in college (Frood, 2018), and brain-computer interfaces (Neuralink, 2022), to name a few. However, beyond the sensational public debate over enhancement technologies, I propose a more pragmatic approach to the subject, allowing more focused discussion. This point is especially relevant when considering Kaspersky's 16-nation study on the future of human augmentation (Opinium Research, 2020). The study focused on enhancing cognitive or physical abilities without specifying precisely which ones or how. It included 14,500 adults from sixteen countries in Europe and North America and found that, on average, 63% of the population would consider adopting some form of technological enhancement system. However, 69% of those polled were concerned about the unequal social distribution of these technologies, which they believe will widen the wealth gap between social classes.

The following two sections introduce and expand the central term in my research: *human*. What exactly is meant by this collective term? How do other scholars and practitioners define humans and humanity? From there, I analyse human enhancement and position my research within current interpretations of the subject matter. Besides providing an overview of *what* enhancement is, I discuss *whom* I enhance within my research.

2.1.1 What is a Human?

Being human is an open notion which can be viewed and approached from several standpoints, including the evolutionary, the technological, and the ecological (Ferrando, 2019, pp.153-154; Vita-More, 2004). In this landscape, several schools of thought have advanced the notion of the 'posthuman', becoming a de-facto umbrella term for all future visions of the human. This generalisation, though, adds to the confusion about the various currents that are included under the umbrella: Posthumanism (e.g., Ferrando, 2014), Transhumanism (e.g., Hughes, 2004, p.52), New Materialism (e.g., Tuin and Dolphijn, 2012, pp.13-16), Anti-Humanism (e.g., Valone, 1991), and Meta-Humanism (metabody, 2022). Despite the apparent similarity of the terms, each tradition presents distinct – albeit sometimes overlapping – conceptions of what a human is, what it will be and what it means to be human. Most misunderstandings lie in the somewhat liberal use of the words Transhumanism and Posthumanism. I will explore the range of positions that lie under the two broad headings of Transhumanisms and Posthumanisms.

Transhumanisms can be considered in line with both neohumanist (Sarkar, 1987) and ultrahuman (Ferrando, 2014, p.27) schools of thought: the human is firmly at the centre of the universe, does not forego its control over the natural world and is self-designated as the sole agent able to care for and influence the world. Transhumanisms are rooted in the Enlightenment ideas of rationality, progress, and anthropocentrism. Since its first use in Julian Huxley's (1927) controversial book "Religion Without Revelation" – referring to a new belief in the human race's ability to transcend its condition as a whole and realise the many beneficial possibilities – the term 'transhuman' has been shaped by its first adopters in the specific context of cutting-edge science, whether genetics, prostheses and implants or in-vitro fertilisation (Bernal and Wark, 1929; Haldane, 1923; Muller, 1935).

Transhumanisms in their current form can be understood as movements operating between the blurred boundaries of emerging fields such as synthetic biology, cognitive science, and information technology, aiming to ameliorate the human condition. Furthermore, Transhumanisms make a moral claim that humans ought to be radically enhanced to achieve vastly greater capabilities than they currently have to become posthuman (Boström, 2005a). Hence, at its core, transhumanism advocates for morphological freedom – the right to modify and enhance the human body (Sandberg, 2013).

Modern Tranhumanisms, regardless of their inclination – whether technoprogressist (Boström, 2005a; Hughes, 2004), extropian (Hughes, 2004; More, 2013, 2003), singularitarian (Kurzweil, 2023, 2006; Vinge, 2013) or hedonistic (Pearce, 1995) – view the human biological body as a non-essential component, which can be altered and, ultimately, replaced. Human identity is a pattern of information; the body is merely the "original prosthesis" (Hayles, 1999). This sharp – yet implicit – distinction between identity and body present in modern Transhumanisms is rooted in Cartesian dualism[2] and libertarianism: the body (or individual body parts) constitute private property (Andrews, 1986), and the mind is a disembodied, rational element, bound to a constrained "meat-machine" as Marvin Minsky put it (Weizenbaum, 2008).

On the other hand, Posthumanisms sustain that humanity has already become posthuman. This philosophical movement has its roots in the first wave of Postmodernism with Derrida's

[2] In his Discourse on Method (Descartes, 1637) Descartes postulates the existence of the *res cogitans* and the *res extensa*. According to Descartes, human self-awareness is a product of the *res cogitans*, the 'mental substance' which exists independently from any other substance. The *res extensa*, conversely, is the 'corporal substance', it denotes all that is material extension and mechanical movement.

deconstruction of the human (Derrida, 1997) and Foucault's "death of men" (Han-Pile, 2010) but flourished in the Nineties through the critical writings of feminist authors. Braidotti (2013) defines Posthumanisms as post-humanism, post-anthropocentrism and post-dualism. In this framework, the human is a nomadic, plural, and fluid notion, characterised by multiplicities of assemblages of 'not yet' in 'states of becoming' (Braidotti, 2019). Subjectivity becomes an open frame that includes humans, nonhumans, and the planet as a whole.

In this context, Posthumanisms explicitly challenge the Western patriarchal and colonial assumptions of the human identity as unchanging, self-evident and derived from nature, or, in other words, the ideal notion of the Vitruvian man: white, European, beautiful, educated and moral. Hence, the self sheds its previous connotations of autonomy and precise boundaries, separated from the environment (Hayles, 1999).

Haraway (1991) expands on the "breached boundaries" of the posthuman in her Cyborg Manifesto. Her political and moral image of the cyborg is critical of the biological essentialism of second-wave feminists: by removing the unspoken dualisms between human and machine, nature and culture, male and female, real and fictional, she celebrated the transgression of perceived boundaries between organism and machine. The cyborg embodies the tensions and possibilities arising from the debate on human enhancement – the cyborg ushers in the idea of the human as a hybrid.

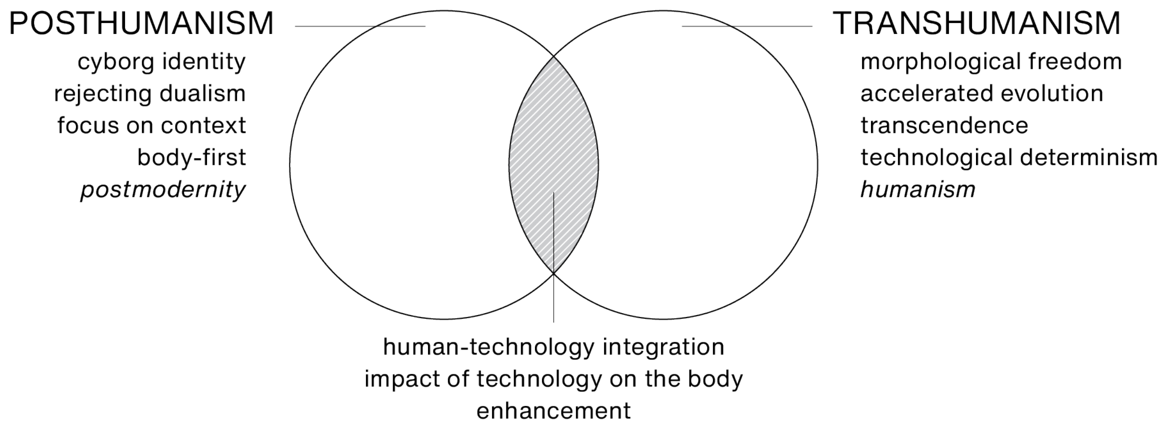

Figure 2.1 The intersection of Post- and Transhumanism focuses on integrating humans with technology, considering its impact and debating enhancement.

2.1.2 From Human to Posthuman: Cybernetic Organisms and Emergent Properties

The term cyborg, a portmanteau of *cybernetic* and *organism*, indicates a being derived from the fusion of parts of an organism with mechanical and electronic parts. Clynes and Kline (1960) coined the term to define a human/machine system that can survive in an extra-terrestrial environment. Their seminal work is the first to subvert the previous assumptions in research on space exploration. Instead of creating a 'safety bubble' that mimics the terrestrial environment for safeguarding humans in space, they propose an almost Darwinian approach, in which the human body adapts to the space environment through new drugs and cybernetic systems.

Despite creating a concrete proposal about what their cyborg would look like – by implanting osmotic pumps in mice which could deliver small and timed dosages of drugs to regulate, for example, their blood pressure levels – for the authors, the term 'cyborg' does not indicate a fixed organism. Rather, cyborgs are a class of heterogeneous organisms adapted to a specific goal. Therefore, the body of a cyborg cannot be a discrete and bounded whole but a zone of influence and organised forces (Appleby, 2002).

The cyborg concept challenges the Vitruvian ideal of humanity discussed in the previous section: its transgressional nature eclipses the mind/body duality and fully embodies postmodernity and the posthuman (Balsamo, 1995). Nevertheless, how does this transgression happen? This transgression becomes apparent by returning to the idea that the body is not seen as private property in Posthumanism. On the contrary, it is interconnected, inhabited and porous, composed of living and non-living tissues and ripe with relationships with other organisms. In other words, the body is an *assemblage*.

Assemblage theory emerges from the work of Deleuze and Guattari (1983) to connote an irreducible and decomposable whole (DeLanda, 2006, pp.10-14). Understanding how the word 'assemblage' came to be is helpful. In A System of Logic (Mill, 1843), Mill laid the foundation for the Emergentist movement by comparing the fields of Physics and Chemistry. Mill noted that in some physical systems, complex and dynamic forces result from a linear combination of simple motions. On the other hand, he also noted that the same linear addition does not occur in chemical reactions. By combining individual atoms into a molecule, the latter would gain unexpected properties. An example is a reaction between oxygen and hydrogen to form water. The distinct atoms are, per se, highly reactive and combustible, while their combination is quite the opposite and is indeed used to quench fires (DeLanda, 2012; Mill, 1843).

The new property, 'wetness', is emergent: it emerges from the constant interactions between its parts. If these parts stop interacting with each other, the emergent property will cease to exist. In other words, the properties of an assemblage cannot be reduced to the sum of the properties of the parts (DeLanda, 2006).

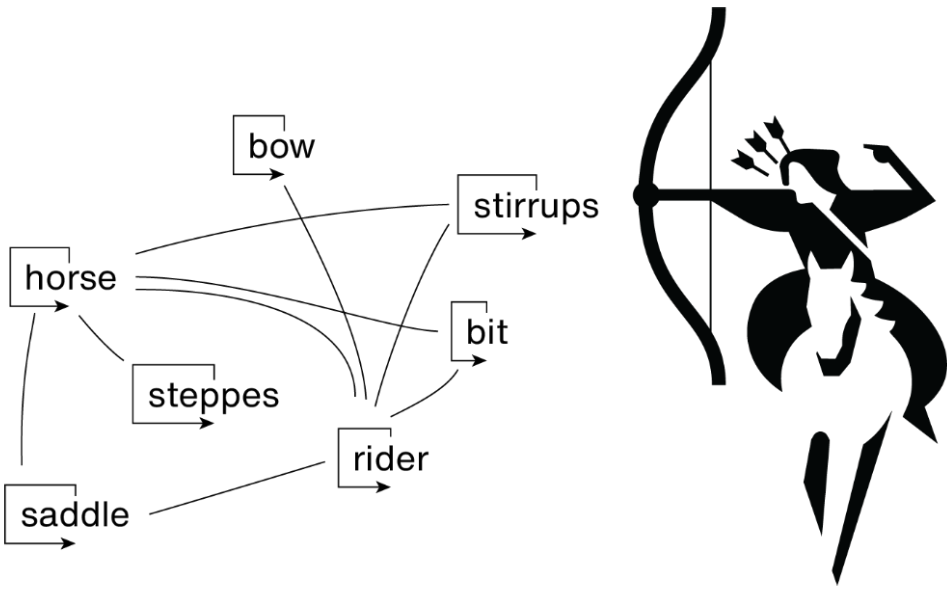

Figure 2.2 One of Deleuze's favourite examples for illustrating an assemblage: the horseback archer. The combination of the horse, the stirrups, the rider, its riding gear, and the environment exhibit emergent properties. Image adapted from the Emergent Futures Lab (2020).

Once a whole presents emergent properties, it is tempting to affirm that the parts have fused and disappeared into the whole, as discussed by Hegel (1812 [2015]). Similarly to Mill's line of reasoning, Hegel argues that in the case of chemistry, the individual elements fuse in what he calls a "totality". Deleuze created the concept of assemblage precisely to counter Hegel's idea of totality (Deleuze and Parnet, 1987).

Deleuze explains that the difference between an assemblage and a totality lies in the relationships between the parts: if the parts of a whole do not have an independent existence, if their properties and their identity are defined by their relationship, then they manifest a relationship of interiority (or, to use Hegel's words, they constitute a seamless totality). By contrast, Deleuze describes relationships of exteriority, where the parts still interact with one another but retain their identity throughout that interaction. Hence, 'decomposable' is framed as 'having relationships of exteriority'. A necessary consequence of the distinction between interiority and exteriority is that parts of an assemblage can be detached from it and moved to another assemblage because they are not fused in the whole (DeLanda, 2012). This point constitutes the foundation of my reasoning for researching enhancement technologies through wearable technology, as discussed later in section 2.7.

I have shown how humanity is an open notion, while the Posthuman interpretation highlights its fluidity. The Posthuman conception has no space for mind and body dualism. Instead, as embodied in Haraway's interpretation of the cyborg, a human can be conceived as a hybrid – an assemblage of parts that, although maintaining their identity, interact with each other. The implications of this approach to enhancement are twofold. Firstly, discussing mind enhancement separately from body enhancement is redundant, as explored further in section 0. Secondly, designing enhancement technologies from a posthuman perspective requires the notion of embodiment – an approach to interactive technologies based on the epistemological premise that human and non-human agents comprehend the environment by interacting with it through their bodies (Loke and Robertson, 2013; Merleau-Ponty, 1962) – is needed, as discussed in section 2.3. First, however, further clarity is necessary to define my research's boundaries: what is enhancement? Can enhancement be measured? How does it relate to the concepts of augmentation, tool or prosthesis?

2.2 What exactly is Human Enhancement?

The term *human enhancement* refers to the possibility of a technological intervention on the human body to improve or implement new capabilities (Buchanan, 2011). However, this definition is vague and complex due to its indissoluble link with the concept of human nature – a concept difficult to pin down once and for all, as discussed in the previous section. Bioethicists (Earp et al., 2014) have pointed out the difficulty in debating human enhancement, and its use has been questioned because it carries implicit assumptions (Parens, 1998; Sanzeni et al., 2022).

Tracing the origins of the field, the word 'enhancement' started to appear in the literature around the 1920s. The following decades were particularly fecund for the subject matter, with several new concepts introduced: expanding the human's ability to store and retrieve information via external systems (Bush, 1945), permanently amplifying intelligence to enhance decision-making (Ashby, 1957) or operational framework to enhance "Man's intellect" (Engelbert, 1962). However, the modern definition of enhancement as the convergence of nano- and biotechnologies, information technologies, and cognitive science did not emerge until the 2000s (Roco and Bainbridge, 2003). This convergence would enable humanity to perform unprecedented interventions on their bodies, resulting in improved performance in various aspects. In Roco and Bainbridge's seminal work, there is a paradigm shift:

technology and medicine become vehicles for treating the sick but also enhancement tools for extending individuals' physical characteristics and mental capacities. They highlight multiple aspects of what could be meant by 'human enhancement', ranging from brain-machine interfaces to "ensure military superiority" (p.5), bioengineering to "endow people with entirely new senses" (p.99), such as the ability to sense radioactivity (p.167), to "new and imaginary technologies [to] improve the ability to learn and/or perform more intelligently" (p.104).

Roco and Bainbridge's report – and, arguably, most of the subsequent work in human enhancement – fails to account for any criticality regarding the concepts of 'better' and anthropocentrism. However, these core ideas have been challenged in other fields: Ginsberg (2017) looks at the meaning of 'better' in the field of Design, Braidotti (2013, 2011) pioneered research in the post-humanities around the concept of the anti-human and others, such as Haraway (1991), Barad (2003) Deleuze and Guattari (1983) deconstructed the issues revolving around a Renaissance-derived anthropocentric view of the world. While arguing from very different perspectives, these authors agree to condemn an essential image of 'Man' and human exceptionalism, which parallels my thesis' collective and equal focus on human and human-made agents.

2.2.1 The Modern Debate

The discourse on human enhancement frequently revolves around whether there is a typical level of naturalness that all humanity shares (also known as 'species-typicality'). The enhancement dilemma asks whether enhancing one trait beyond the species-typical level would constitute a moral violation (Eberl, 2014). The field of human enhancement stands in an "epistemological middle zone" (Bess, 2010), where, on one side, there is binary clarity (natural versus unnatural, more versus better, moral versus immoral, etc.). On the other side, there is relativism, which problematises each concept. Bess (2010) suggests that these two positions are not mutually exclusive. Instead, they represent the ends of a spectrum with which the design space is conversing.

There are two leading epistemological positions in the modern debate about human enhancement: bio-liberalism and bio-conservatism (Agar, 2013; Al-Rodhan, 2011; Fukuyama, 2002; Kass, 2003; McKibben, 2004, p. 230; Ramsey, 1970, p. 121; Sandel, 2004). The bio-liberal approach is founded on a dualistic view of humans. Oppositely, the bio-conservative approach employs essentialist techniques to illustrate the effects of potential and profound transformations on humanity. Bio-liberalism views human enhancement as progress, advocating for using technology to improve the human condition. In contrast, bio-conservatism views human enhancement as a distortion of humanity itself. Bio-liberals believe that technology can be used to modify, if not transcend, the limitations of the human body. In contrast, bio-conservatives are concerned that enhancement technologies will undermine what it means to be human.

Scholars have yet to explore the pragmatic aspects of human enhancement besides the epistemological differences between bio-liberals and bio-conservatives (Sanzeni et al., 2022). In their study, Savulescu et al. (2011) proposed four potential methodologies for the development of enhancement technologies:

1. The sociological-pragmatic approach views enhancement as a socially constructed concept (Wolpe, 2002) that depends on the cultural and historical context in which it exists (Canton, 2003, p. 74).

2. The ideological approach avoids defining the term "enhancement" itself, instead relying on projecting ethical values onto specific technologies to evaluate them (Savulescu et al., 2011, p. 4).
3. The "not-medicine" approach considers any biomedical intervention beyond restoring or maintaining health as an enhancement (Juengst, 2000; Parens, 2000; Ven et al., 2019, p. 3).
4. The functional approach defines enhancement in a particular context and improves the output quality of a specific function, such as cognition (Earp et al., 2014).

2.2.2 "Normal" as the Benchmark for Enhancement

Although helpful in charting the current debate, the problematic concept of "norm" or "baseline" appears in all existing frameworks proposed by Savulescu et al. Indeed, the word "normal" can have many meanings depending on the context (Sanzeni et al., 2022). For example, it could mean *typical* in the context of standard practice, *average* in describing a group of people, *innocuous* in a clinical context, or *best suited for evolution* in genetics (Murphy, 1972). Furthermore, within the medical sciences, "normal" can be used to outline a description of the ideal, broadening its meaning beyond the classically defined standard, *naturally occurring state free of disease* (Davis and Bradley, 1996). These descriptions, moreover, ignore that different modalities can functionally perform the same action: reading, for example, can be accomplished through the eyes, touch (e.g., Braille), or hearing (e.g., text-to-speech software). Research (Legge et al., 1999) shows that reading speed does not change when using visual and tactile systems. Furthermore, an action can be performed with varying degrees of precision. If restoring the function of a limb is impossible, a prosthesis that provides a comparable level of operability can be used instead (Silvers, 2000).

It is important to mention that 'enhancement' does not always imply 'more': in some cases, diminishing a specific trait can be a form of enhancement, such as reducing traumatic memories of war or ill-directed lust (Earp et al., 2014). Another situation where enhancement can be achieved via diminishment is Deep Brain Stimulation (DBS). During this surgical procedure, electrodes are implanted in a patient's ventral intermediate nucleus of the thalamus to combat Parkinson's disease tremors (Perlmutter and Mink, 2006). Interestingly, DBS treatments can enhance patient well-being and happiness, especially for psychiatric disorders such as addiction, depression and obsessive-compulsive disorder (Schermer, 2013). Schermer's work sparked substantial debate around the role of medicine in enhancement (Rueda et al., 2021), especially about the role of brain-machine interfaces (Rabadán, 2021).

Other definitions of human enhancement distinguish between supposedly natural and unnatural improvements (Ida, 2010), the elimination of suffering for humans and non-human animals (Pearce, 1995, p.14), boundless expansion and self-transformation (More, 2003), and transcendence (Huxley, 1927). In contrast, the 'humane' framework (Cabrera, 2017) emphasises the social context of enhancement, asserting that research on enhancement technology should prioritise the overall benefit of society. For a more comprehensive review of the history of human enhancement, see (Boström, 2005b).

2.3 Embodiment and Enhancement

My approach to enhancement is rooted in the assumption that human and human-made agents understand the world through their bodily interaction with it. This epistemological position aligns with theories of embodied cognition (Foglia and Wilson, 2013; Garbarini and Adenzato, 2004; Seth and Bayne, 2022). In my research, the body is the starting point for enquiry and does not constitute a disturbance or is considered prone to failure, as is often postulated by transhumanists (Hauskeller, 2012). The centrality of the body and its interaction with the world to generate understanding aligns with design practice, where it has been argued that knowledge is implied, inferred, or visible only through action (Polanyi, 1966, pp.3-25; Schön, 1983, p.49). The embodied position is especially suited for enhancement technologies: these technical solutions are ultimately applied to the body and cannot be studied in isolation from it.

The embodied approach radically differs from the cognitivist approach of the 20th Century, in which the study of cognitive processes through mathematical models was favoured. Further, embodiment is in sharp opposition to the philosophies of mind based on a language of thought hypothesis (Fodor, 1975). The embodied cognition theory postulates that cognitive processes are not limited to an agent's cognitive system but include wider processes of interaction with the environment (Chemero, 2011; Lakoff and Johnson, 1999; Nöe, 2007).

The origin of the argument for embodied cognition can be traced to the work of Clarke and Chalmers about the extended mind (1998), or the "mind that spills out in the world" (Levy, 2007, pp.29–37); and Varela et al.'s theory of the embodied mind (1992), which highlights the fundamental importance of the physical characteristics of an agent in its cognitive abilities. Varela and colleagues claim that any experience depends on having a body with various senses (ibid, p.173), inevitably embedded in a biological, physiological and cultural context. This means that cognition is closely based on a perception-action loop: as an agent moves through an environment, its motion generates interaction opportunities, which produce new perception opportunities, which in turn will make apparent new possible activities (Shapiro, 2011). In other words, both the body and its situatedness in the world directly inform cognition (Lakoff and Johnson, 2003, 1999).

Empirical evidence supports the validity of designing enhancement technologies based on the embodiment assumption. The map of the body – or body schema (Head, 1920) – can be extended in the near-body region: through training, both humans and non-human primates can incorporate tools in their neural pathways, effectively considering them extensions of their bodies (di Pellegrino and Làdavas, 2015; Iriki et al., 1996; Làdavas, 2002; Maravita and Iriki, 2004) as shown in Figure 2.3. Human robotic enhancement studies recently confirmed this crucial point (Kieliba et al., 2021). The extension of the body in its near-body space, mediated by tools, is particularly relevant to this research since it allows perceiving previously unreachable affordances in the environment (Gibson, 1966, pp.287-303; Jin et al., 2018; Stoffregen, 2000).

The role of training and time is significant, as reported in the studies just cited. Human and non-human primates incorporated tools within their body schema after several minutes of using them. This point hints at two potential interpretations of temporality within tool use: duration of each use and duration of multiple uses or permanency of use. Spectacles provide an example of this distinction: they can be worn for short periods, e.g., when reading, or used over a prolonged period, eventually transitioning from being a foreign item resting on the nose to part of one's sense of self. In this thesis, I refer to the second case: enhancements are technologies that can be worn for extended periods, eventually becoming part of one's sense of self. In other words, tools can become new senses if they persist on an agent's body. The design implications of this position will be explored further in chapters 5 and 6.

Figure 2.3 Changes in brain activity as recorded in macaque brains following tool use (Maravita and Iriki, 2004), where a rake was given to the primates to reach for food. This experiment demonstrates how bimodal neurons – neurons responding to visual and sensory stimuli – expand during tool use to include the whole tool in the body schema (3b & 3c). The passive holding of the rake did not activate the neurons to include the tool in the body schema (3d). However, after tool use, the proximal neurons expanded the body schema to code the space accessible through the tool (3f & 3g).

Approaching enhancement through the lens of embodied cognition constitutes a subtle yet important shift from Transhumanisms' approaches to the subject matter. Transhumanisms have recently come to the fore as a bold approach to enhancement technologies and humanity's future. In transhumanist views, the body is acknowledged as fundamental yet is seen as an inherent limitation to humanity's potential (Boström, 2005b, p.4). It should be left behind so humans can transcend their limitations and realise their full potential (Kurzweil, 2006, p.283). By disregarding the body's importance in the knowledge-making process, transhumanism sidesteps the conversation on what constitutes 'better'.

My research follows the embodied framework: instead of relying on the normative framework for enhancement outlined in the previous section, where whether certain technologies are classified as enhancement is determined if they improve average functionality beyond what a 'normal' body can do, I argue that each individual's body and senses constitute normality and the baseline for sensory enhancement. Enhancement technologies are thus reframed as body-specific systems that enhance the wearer's knowledge of the environment they operate in, as I will argue in the next section. To use the words of Kirsh, "the future is prosthetic: a world of nuanced feedback and control through enhanced interaction" (2013). In this perspective, the body and its extension in the world become elements that can be mediated through Design. The following discussion approaches two other tensions in defining the role of embodiment in my work: the distinctions between tools and prostheses, and the differences between augmentation and enhancement.

2.3.1 Tools, Prostheses, Augmentation and Enhancement

Kirsh's quote on the future being prosthetic and the previous discussion on the cyborg might make me seem aligned with the current popular understanding of enhancement deriving from works of fiction, such as the Terminator or Robocop franchises. I distance my work from the often utopian or dystopian renditions of the cyborg, where flesh and machine bond effortlessly, creating more-than-human beings that compromise humanity's safety. These technological dreams – or nightmares – feed on the misconception around critical terms, such as *prosthesis*, *tool*, *enhancement* and *augmentation*. For clarity, I ground these terms in the current literature, explaining why this thesis focuses on enhancements.

Firstly, as Preester (2011) pointed out, *tools* and *prostheses* are often confused. In her work on how technology and the body interact, she points out that 'prosthesis' is usually employed as a general premise (ibid, p.120), becoming a de facto umbrella term for everyday objects, such as glasses, clothes or computers. However, a more apt term for these objects is *tool*: they are one of the media through which humans interact with the environment (Black, 2014), be it physical (glasses) or digital (computer). On the other hand, prosthesis refers to an "addition" to the body, both from a linguistic and humanities understanding and a clinical standpoint (Smith and Morra, 2005, p.91).

Similarly, *enhancement* and *augmentation* are terms often used interchangeably in the literature. However, one of the few formal definitions of the difference between the two states that augmentation refers to methods and technologies to enhance human cognition, action or senses (Papagiannis, 2017; Raisamo et al., 2019), whereas enhancement refers to the broader interdisciplinary field. Similarly, for others, enhancement is a broader term referring to overcoming the human body's limitations via technological means (Moore, 2008), biomedical engineering (Pio-Lopez, 2021), surgery (e.g., Devereaux, 2009) or other means. Although Raisamo et al. (2019) opt only to use augmentation in the context of human-technology interaction, I decided to use the word enhancement instead, as its broader connotations are suitable for my thesis' subject matter, which blurs the boundaries between human and human-made agents, as argued later. Further, three potential avenues for enhancement can be found in the literature: (i) enhancement of the senses, (ii) of action or (iii) of cognition, as discussed in the following sections.

Enhancing Senses

Sensory enhancement pertains to improving a pre-existing sense or its extension to perceive information beyond the human range (Jebari, 2015, p.827). Wright and Ward (2018) provide a useful taxonomy of sensory enhancements, individuating four categories:

1. Compensatory prostheses: tools that restore functionality in pre-existing sensory systems. Examples of sensory enhancements in these categories include reading glasses, contact lenses and hearing aids.
2. Within-sense referral: tools that modulate sensory information while preserving the perceiving modality. Examples include magnifying lenses, microscopes, telescopes and stethoscopes.
3. Between-sense referral: tools that translate an organ's traditionally sensed information onto another sense. These tools fit within the category of sensory substitution devices, which will be discussed later in section 2.7.1. An example of these tools is the BrainPort (Richardson et al., 2020), a wearable vision aid that translates visual information into vibration patterns.
4. Novel-sense referral: tools that convey information not usually available to the agent's sensory system. Thermal imaging cameras are an example of this category. Virtual, Augmented, and Extended Reality also fall within this category. Section 0 details how these design paradigms relate to enhancement.

Enhancing Actions

Action enhancement aims to remap the body's activities within local, remote, or virtual environments (Raisamo et al., 2019). Examples of local action enhancement are exoskeleton suits for enhanced strength and support (Murugan, 2021). An example of remote action enhancement is teleoperation, or transmitting control commands from a human to a robot over a communication channel (Moniruzzaman et al., 2022). Finally, virtual action enhancements are the most common examples, as many video games allow for actions normally unavailable to humans.

Enhancing Cognition

Cognition enhancements aim to improve mental capacities "beyond what is necessary to sustain or restore good health" (Juengst, 2000). Notably, Dresler et al. (2018) outline three strategies for cognitive enhancements:

1. Biochemical strategies, including improving nutrition, using natural compounds such as caffeine or sugar, drug use (pharmaceutical enhancements, such as amphetamines and recreational drugs) and genetic modification. This last strategy has not yet been applied to humans – besides the controversial genome-edited babies born in China (Greely, 2019), but was demonstrated with mice (e.g., Diana et al., 2007; Dubal et al., 2014).
2. Physical strategies, including various means of brain stimulation (such as electrical, magnetic, optical, and acoustic) and wearable or implantable brain-computer interfaces.
3. Behavioural strategies, including physical exercise, sleep and meditation, mnemonics and learning.

Enhancing Whom?

Another fundamental point to discuss is who the beneficiary of enhancement is. Perhaps surprisingly, the literature explicitly addressing this question is sparse. Sparrow's (2016) seminal work discusses five potential groups for which enhancement technology might be beneficial:

1. The individual: if we regard individuals as having the autonomy to decide for their bodies, they can alter them to their liking. If the premise is accepted, the debate on enhancement for this group becomes about the moral limits and whether such activity would conflict with other individuals or even collective interests (ibid, pp.128-133).
2. The 'World': if we believe that a larger community should be interested in enhancement technologies, enhancement should focus on impersonal welfare. In this context, enhancement technologies are approached from an altruist perspective, where the 'benefit for the world' is foremost (ibid, pp.133-134).
3. The species: if we focus on the survival of humans as a species, enhancement efforts should be directed towards increasing diversity – genetic or otherwise – in the species (ibid, pp.134-135).
4. The Nation: if we regard the complexity of allowing each individual the liberty of body self-determination, it is sensible to cede some power to an institution – such as the Nation – for establishing policy on the matter. Sparrow posits that, inevitably, these policies will be confined to the benefit of the Nation where they are written (ibid, pp.136-136).
5. The race: if we regard the interests of a certain race as more important than others, enhancement will focus only on that race (ibid, pp.136-137).

The last group mentioned is exceptionally problematic. The shadow of eugenics cannot be overlooked. Nevertheless, all the collectivist approaches in the above list carry some problems. Who gives the moral right to a practitioner to design for others? How can enhancement technologies developed for anyone other than an individual not fall into the normative framework? Although essential context for my work, these questions fall beyond my research scope and are still debated (for an overview, see Pugh et al., 2016)[3]. In this thesis, I focus on enhancing individuals: their bodies and senses are the baselines for designing wearable enhancement technology. Further, a corollary of this approach is that each individual is, by definition, unique. This point has a practical consequence: wearable enhancements are not one-size-fits-all systems. Rather, they are systems customised to an individual's body and previously existing senses.

This point was an early indicator for my fifth guideline, which I will discuss in depth in the next chapter. This guideline emphasises the importance of designing for accessibility and distribution. In this context, accessibility refers to physical access and enhancement technology's broader social and cultural implications. I need to recognise that each agent has distinct experiences, needs, and abilities to design enhancements in my research. Moreover, guideline 5 encourages me to consider the distribution of my design, particularly in terms of its openness and adaptability. Making my designs open-source allows others to build upon and modify them, cultivating a community-driven approach to enhancement technology.

Following the embodiment assumption, nevertheless, implies that the variables to consider grow exponentially: the designer must consider holistically the body, its environment and the interactions occurring between the two and consequently design wearable systems for engaging the wearer with additional sensory information in the environment. Going back to the discussion on normative frameworks for enhancement, my frame of reference shifts from defining what is 'better' to the human or human-made agent's body, the information available in the environment that is not currently sensed and how to convey them to the agent itself. As mentioned before, I use concepts deriving from the tradition of design cybernetics to analyse this complexity so that designing potential sensory expansion wearables would be feasible. Design cybernetics is an approach to complexity that enables exploring, embodying and testing a range of wearable enhancement solutions. This reference frame is suited for my area of inquiry, as it was recently appraised in terms of a practice-led approach (Glanville, 2006, p.66), mainly at the Royal College of Art.

2.4 Cybernetics, Design and Enhancement

Cybernetics originated and developed in the United States during the Second World War and the following period, with its first appearance in the first edition of the Macy Conferences in May 1942. These meetings led to the publication of essays that paved the way for the hypothesis of a unitary logic of the human brain and digital computer. In 1946, a new series of conferences funded by the Macy Foundation began, becoming a meeting point for developing the basis of a general science of self-regulation. The history of the cybernetic movement is characterised by a problematic institutionalisation and fragmentation of research orientations, with a polarisation between cybernetic engineering and sociological cybernetics. However, fundamental concepts such as feedback and self-regulation are still widely used today. The impact of cybernetics lies not so much in formal

[3] My framework does not ignore these ethical concerns, although its focus is not on them. My guidelines, introduced in the next chapter, are relevant to the issues highlighted here.

institutionalisation but in the cultural influence on technological development: at a theoretical level, the general explanatory model of self-regulation implicit in feedback persists.

Its founder, Norbert Wiener (1961), described cybernetics as the study of communication and control of machines and living beings. In its broadest interpretation, cybernetics is the science of action and knowledge, where mechanical and biological systems are analysed through how they act in the world, that is, the relationships they form with their context and environment. This approach makes it possible to identify correlations between systems of different types. These similarities may lead to interesting interpretations of the type of behaviour they display. A prominent example is homeostasis (Cannon, 1932; Rosenblueth et al., 1943; Turner, 2019), which indicates the range of biological control mechanisms that maintain a specific characteristic parameter of a living being within narrow predetermined constraints.

Together with Bigelow and Rosenblueth, Wiener (1943) proposed a classification of behaviour applicable to both machines and living organisms. They defined behaviour as any externally detectable modification of the object and introduced distinctions between active and passive behaviours, focusing on behaviours with a purpose. Purpose was defined as an end condition in which the object achieves a definite correlation in space or time regarding another object or event. When we perform a voluntary action, the choice concerns a specific purpose, not a particular movement. The novelty of the classification lies in the distinction between teleological (feedback) and non-teleological (non-feedback) behaviours. Feedback refers to the fraction of output that returns to the agent as input, distinguishing between negative (corrective) and reinforcing (positive) feedback. This feedback changes the relationship between subject-object or system-environment, inverting unilinear causality and adopting a circular, anti-determinist model of causality.

In the 1980s, Heinz von Foerster (2003a) introduced second-order cybernetics, highlighting the observer's fundamental role in the knowledge process. From this perspective, observer and observed are inseparable, and the observer is part of the field of observation. Including the observer in the field of observation, though, makes the observer partially unknown to themself, generating the need for continuous recursive observations. This model renders complete knowledge of things and situations unattainable. Second-order cybernetics has led, then, to a constructivist perspective, in which description is self-referential and contributes to the construction of reality but can never be wholly objective and exhaustive.

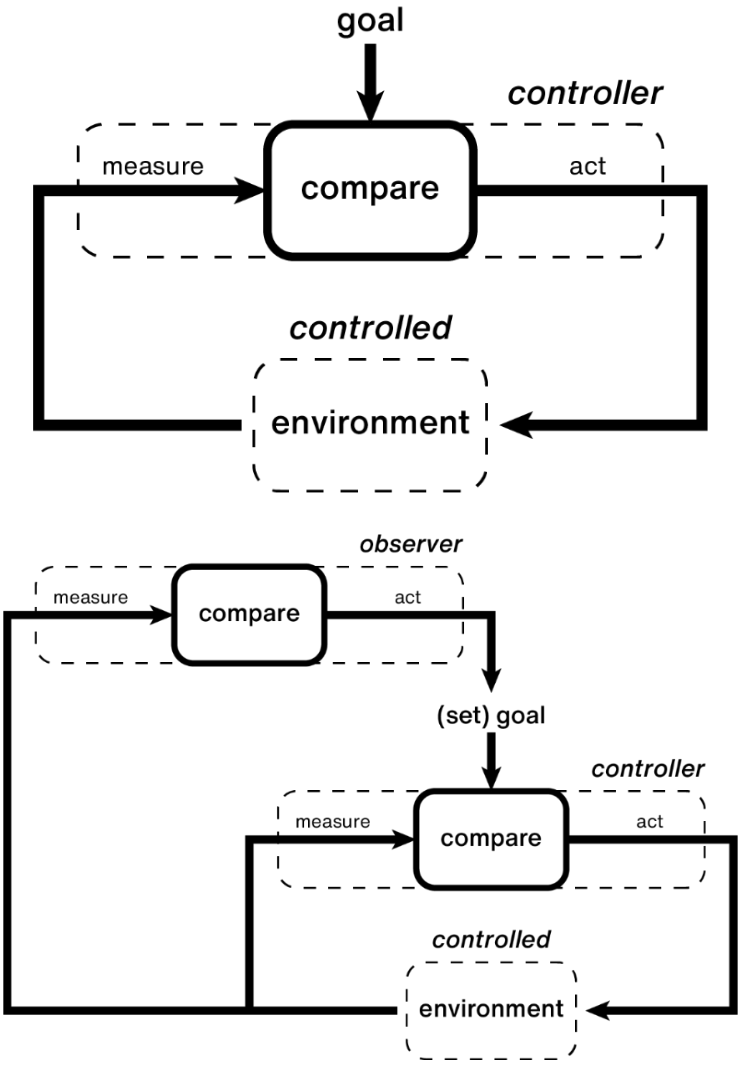

Figure 2.4 First-order cybernetic feedback loop (top) highlighting the circular interaction between the controller (agent) and controlled (environment). Second-order Cybernetics (bottom), where the observer is integral to the feedback loop. Images adapted from Dubberly and Pangaro (2007).

Academics have debated whether introducing third- and fourth-order cybernetic systems would be beneficial. According to Mancilla (2013, 2012, 2011), third-order cybernetics is a sociocybernetic system that focuses on the mutual observation of individuals interacting in society, while fourth-order cybernetic systems are self-observation systems. Lepskiy (2018) advocates third-order cybernetics as "dealing with the self-developing reflexive-active environment (distributed observer)". Yolles (2021) calls for developing Metacybernetics, a generalised theory for higher-order cybernetic explorations. Von Foerster, supported by Glanville (2002), believes that adding higher orders would not bring anything new since, in his opinion, "one has stepped into the domain of concepts that apply to themselves" (von Foerster, 2003b). As such, this suggests a reluctance to accept higher orders than second-order cybernetics.

2.4.1 The Emergence of Design Cybernetics

Cybernetics and design, although not always acknowledged, share a close association, with design initially being viewed as an art or craft before attempts to incorporate scientific principles during the first decades of the Twentieth century. Specifically, Design Research only started coalescing as a distinct field in the 1960s, with the first Conference on Design Methods of 1962, the establishment of the Design Research Society in 1966, and the appointment of Archer as the first Professor of Design Research at the Royal College of Art. Here, we have the first thread connecting design and cybernetics, as Archer's work drew on second-order cybernetics (Boyd Davis and Gristwood, 2016).

Until the 60s, the dominant design paradigm leaned toward a 'rational' approach with little interdisciplinary collaboration. However, exceptions like Brand's Whole Earth Catalogue (1968 – 1972) explored connections between systems, design, and science with a DIY twist. In 1968, Simon proposed a distinction between design and most forms of science, characterising design as "The Science of the Artificial", emphasising its concern with how things ought to be rather than how they are. This distinction became a defining factor in the design discipline. By the 1980s, thanks to – among others – work by Archer (1979), Cross (1982) and Schön (1983), there was consensus to move away from a scientific approach and explore the unique epistemological foundations of the designerly approach (Cross, 2001), where design questions are not determined from the beginning; instead, they shift through the practice (Pickering, 2002; Sweeting, 2016).

Schön (1983) notably demonstrates the convergence between cybernetics and design. He emphasised that practitioners must contemplate tacit norms, underlying judgments, emotions that influenced their actions, and their framing of the problem or role within the context when reflecting on their work. This mirrors second-order cybernetics, as Schön described the initial design act (first-order) and the reflective elements (second-order), which involve feelings, judgments, and the observer's role in professional practice. He detailed how the iterative interaction between the practitioner and materials generates new knowledge through exploration, experimentation, and critique of initial understandings of the phenomenon. Schön depicted the practitioner's reflective circle – making, observing, reflecting, and making again – as cybernetic, where the practitioner acts as an intelligent agent, a second-order cybernetic system, adjusting their activity in response to sensed outcomes. I expand on Schön's pivotal influence on my work in the next chapter.

The focus on the circular and iterative nature of practice is another parallel between cybernetics and design. Ever since the beginning of cybernetics, researchers embodied their ideas in machines and experiments, as demonstrated by Schöffer's (1956) sculpture, Pask's Musicolour Machine (1956) and Colloquy of Mobiles (1968), and many others (for an overview, see Reichardt, 1968). These experiments illustrate design approaches, with researchers constructing knowledge through design and embodying cybernetic theories in physical artefacts.

Figure 2.5 Left: Schöffer's CYSP-1 (a portmanteau of CYbernetics and SPatiodynamics) sculpture – the first artwork to reference cybernetics. Dubbed the "homeostat on wheels", CYSP-1 was designed to seek equilibrium when it gets out of balance and perform statistical exploration of all possible combinations of inputs. It reacts to sound, light, and heat, making 16 pivoting polychromed plates turn and move in various directions. Image credits: (Schöffer, 1956).

Right: Pask's Colloquy of Mobiles, reconstructed in 2018 by Pangaro and TJ McLeish. This interactive artwork consists of five computer-controlled mobiles that engage in conversations with each other through light and sound, resembling chit-chat at a cocktail party or a stylised courting ritual of a strange animal species. Visitors can also participate in the conversation using flashlights and mirrors. Image credits: (Pask and Pangaro, 1968).

Finally, Glanville and Krippendorff cemented the link between design and cybernetics. Glanville served as the American Society of Cybernetics president from 2009 until his death in 2014 while holding a professorship at the Royal College of Art. Glanville staunchly advocated design as the embodiment of cybernetics in practice and positioned cybernetics as the theoretical foundation of design (Glanville, 2007, p.1178). Krippendorff contends that language and semantics are central to cyberneticians and designers in a constructivist context. Echoing Ashby, Krippendorff (2019) links design and cybernetics by equating the designer with the observer. He emphasises that systems are continuously reconstructed by their constituent network of observers, simultaneously proposing and constructing reality through discourse.

In summary, the cybernetic approach to design facilitates interdisciplinary conversations on complex, ambiguous, and subjective domains, such as the case of enhancement technologies. As Dubberly and Pangaro (2015) put it, cybernetics can help designers understand complex challenges and navigate uncertainty through its dual nature of first-order and second-order systems. First-order cybernetics offers objective descriptions of rules-based systems, while second-order cybernetics introduces subjectivity by acknowledging the system's observer as a significant agent. Cybernetics serves as a framework for both the design process and the object being designed, capturing the dynamics of first-order and reflective second-order cybernetic systems.

2.4.2 What can Design Cybernetics Offer to Enhancement Technologies?

From the discussion above, it is clear how design and cybernetics are aligned. However, the question remains about how exactly this overlap is helpful for the topic I deal with in this research. As previously mentioned, cybernetics studies communication, control, and (self-)regulation in systems understood both as natural and artificial entities. Second-order cybernetics focuses on the observer's subjective role and implications for understanding and influencing these complex systems.

In both flavours of cybernetics, however, one of the cybernetician Ashby's most important contributions, the Law of Requisite Variety, is applicable. Although it was not developed in the era of second-order cybernetics – von Foerster introduced that term in 1974, two years after Ashby's death – its principle is valid in both frames of reference (Umpleby, 2009).

Ashby's Law of Requisite Variety (Ashby, 1957, p.207) states that the complexity of a system must match that of the environment it operates within for effective interaction. This means that a system should be complex enough to adapt to the complexity of its environment. In the context of enhancement technologies, enhancement is understood as providing new methods for the controller – or the agent – to interact with the opportunities provided by the environment (Sanzeni et al., 2022), as depicted in Figure 2.6. This epistemological shift assumes its significance when confronted with human biology: despite having high levels of sensorimotor complexity, human bodies did not evolve to interact with many of the signals potentially available in the environment, such as magnetic fields, large sections of the light spectrum, or most chemical compounds. In other words, many environmental affordances are inaccessible to humans.

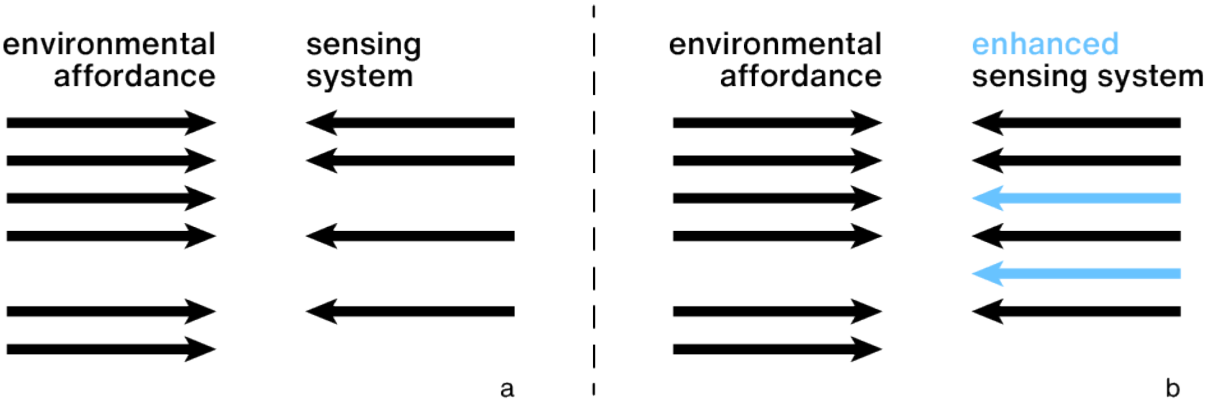

Figure 2.6 Representation of an enhancement system elaborated from Dubberly and Pangaro's (2007) depiction of Requisite Variety. Fig. A represents a non-enhanced agent interacting with an environment. The latter presents sensory cues, which the interacting agent does not present sensors to perceive. Fig. B depicts this thesis' postulate for enhancement technology: an agent is enhanced when presented with sensory systems that convey previously unreachable sensory information.

In addition to providing the epistemological scaffolding and a practical framework, Design Cybernetics provides a language that goes beyond the conventional notions of enhancement. Building upon Ashby's Law, which offers pragmatic guidance, we find a deceptively simple perspective: enhancement can be viewed as increasing the controlling agent's sensory variety. This concept forms a pivotal segue into exploring Affordance Theory, shedding light on how the environment offers perceivable possibilities for action. Design Cybernetics is also fundamental to my chosen method of Reflective Practice. Design Cybernetics emphasises feedback loops, externalising thoughts and reflecting on practice, all key components of reflective practice, as I will discuss in the next chapter.

2.5 Affordance Theory as a Companion to Design Cybernetics

Affordance theory was introduced by Gibson (1979), building on the ideas of Gestalt psychology. In its original sense, affordance refers to the physical properties of an object that indicate the actions and manipulations that an interacting agent can perform, as shown in Figure 2.7. This invitation to action is distributed across the object and the interacting agent.

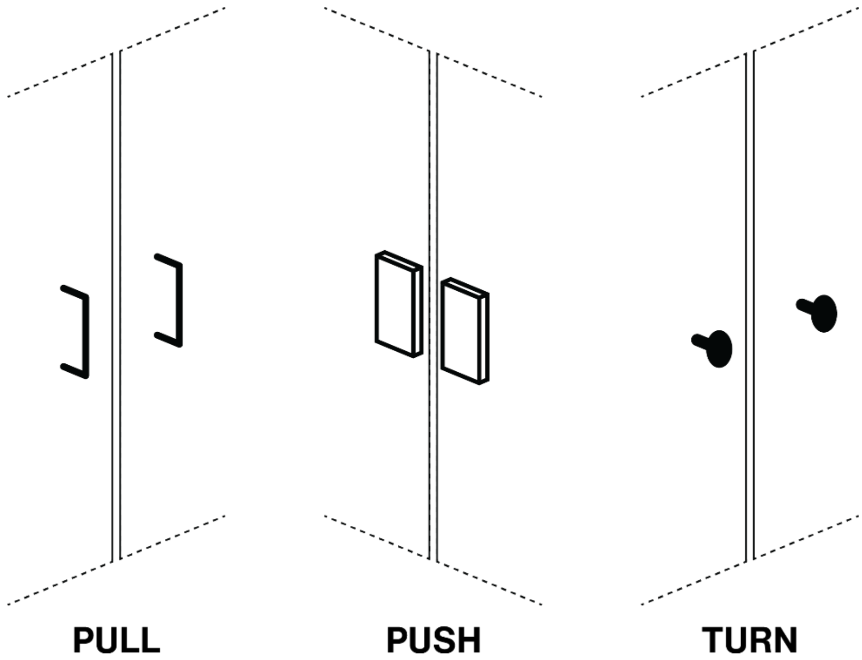

Figure 2.7 Example of affordances in doors. While a handle affords for pulling and a plate for pushing, a knob affords turning. All these potential interactions are embedded within the physical shape of the door and distributed with the interacting agent.

Norman's (2013) distinction between real and perceived affordances is crucial for enhancement technologies. *Real affordances* are all of the available actions that an object provides, whereas *perceived affordances* are narrowly defined as the actions that an agent perceives as feasible. In this thesis, I refer to the real affordances that are not normally perceived as *hidden affordances* to highlight that although these affordances are available in the world, they are unreachable by human or human-made agents.

Further, Norman introduced the concept of signifiers to distinguish real affordances from features that suggest how an entity should be utilised, such as arrows, colours, and directives. For example, a door's physical design and hinges afford a swinging action, whereas a handle signifies which side of the door an agent should pull to go through it. These distinctions between affordances and signifiers are essential for addressing enhancement technologies within the context of Requisite Variety. Although the environment provides numerous affordances, agents' physical bodies lack the variety in senses necessary to signify them. Therefore, enhancement technologies can be defined as additional sensory systems that signify the possibilities of the environment to the agent, including the hidden affordances embedded in it. This argument is consistent with the depiction in Figure 2.8 and the previous discussion.

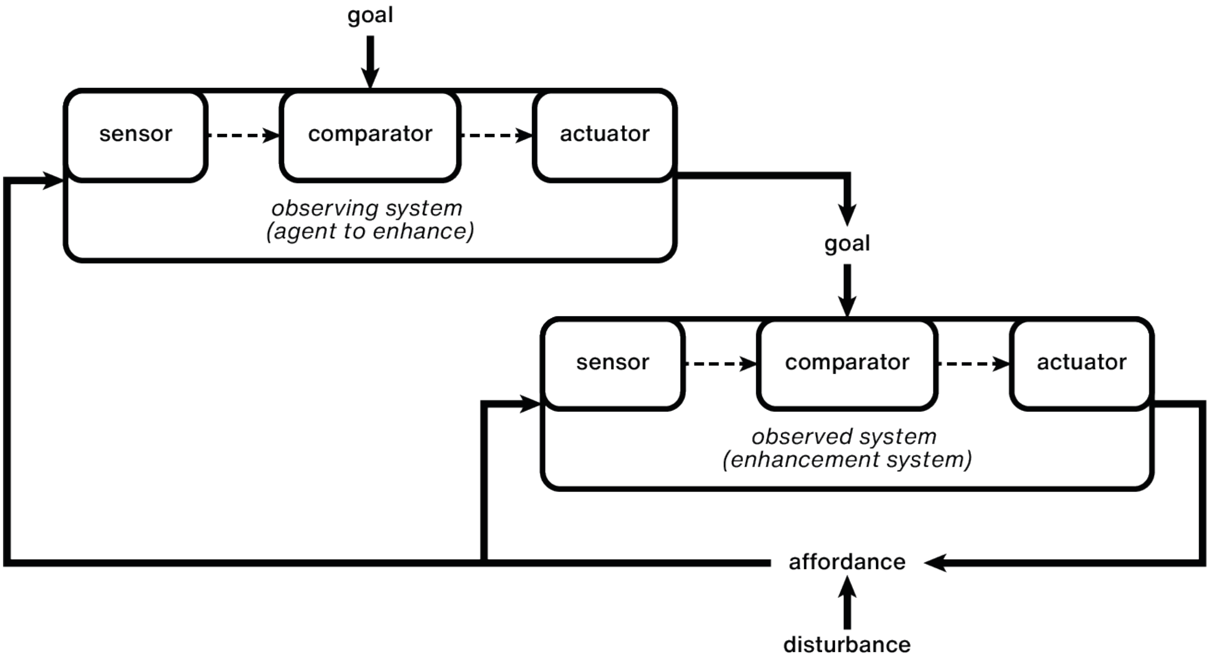

Figure 2.8 Dubberly and Pangaro (2007) presented a diagram that depicts enhancement systems as nested first-order systems. The illustration above (Sanzeni et al., 2022) shows a second-order feedback loop, where the agent who needs to be enhanced sets a goal for the enhancement system. The goal is to signify a specific hidden affordance in the environment. The enhancement system then uses the agent's existing biology to provide information about the hidden affordance to the agent.

The enhancement framework derived from the intersection of cybernetics and Affordance Theory allows researchers to clarify the fundamental assumptions of their discussion. Furthermore, this approach has several essential implications from an epistemological perspective. Firstly, it underscores the importance of facilitating one-way communication between the environment and the enhanced agent as they move within it. This emphasis on communication is not tied to any specific technology but instead suggests multiple ways to achieve the same interaction. Consequently, numerous avenues for enhancement can be explored in response to the same hidden affordance.

The distinction between affordances and signifiers strengthens the interactional nature of enhancement: a system must signify the changes in the hidden affordance to the agent to qualify as an enhancement. For instance, a wearable device that alerts an electrician of high voltage in the work area would qualify as an enhancement.[4] However, the enhancement system must convey the information in a way the agent can understand, leveraging the agent's pre-existing body. Therefore, enhancement systems operate as transducers, remapping unperceivable information into a format the agent can perceive. In contrast, tools such as multimeters, which measure voltage, current, and resistance by physically probing an electrical circuit, do not classify as enhancements.

As a result, the paradigm I provide here does not involve establishing a common baseline against assessing whether a particular technology constitutes enhancement. Instead, the agent's body and any pre-existing senses form the pragmatic starting point for designing enhancements (Sanzeni et al., 2022).

[4] Subdermal systems with these properties exist. Notably, a Reddit user (elgevillawngnome, 2012) implanted neodymium magnets in their fingertips to detect magnetic fields emitted by AC-powered appliances. Further from the rationale presented in section 2.7 for not pursuing subdermal or transdermal solutions, magnetic properties decay over time, eventually resulting in a complete loss of magnetic properties (Robertson, 2017).

In summary, my approach to enhancement via Posthumanism requires Embodied Cognition. Design and Cybernetics offer the epistemological scaffolding for describing and probing the circular interaction between agent and environment. I am specifically interested in hidden affordances – a concept I introduce to expand current discourses on Affordance Theory, as shown in Figure 2.9. I argue that allowing agents an increased possibility of interaction with the environment constitutes a practical approach to enhancement technologies. Going back to the three problems with using 'human' and 'enhancement' together, my research position offers two benefits:

1. No normativity exists: each agent and their body are the baseline. It is not necessary to define humanity to then define enhancement.
2. There is no 'better': reframing enhancement as allowing agents to increase their variety to access hidden affordances, there is no need to define the fuzzy concept of better. What matters is the agent's intentionality, i.e., which hidden affordance they want to access.

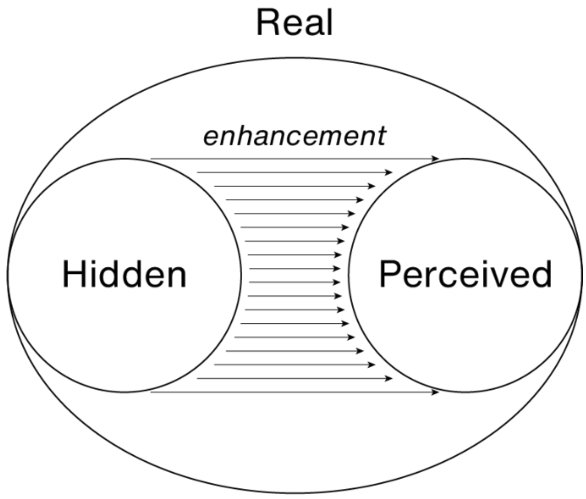

Figure 2.9 The three typologies of affordances. As introduced in my work, hidden affordances extend Norman's categorisation of affordances into real and perceived to signify all of the affordances an agent does not have the senses to perceive. I here reframe enhancement as the practice of allowing agents to perceive hidden affordances.

2.6 Enhancement in this Thesis

Following the introduction of the three modalities of enhancement emerging from the literature and my focus on enhancing individuals rather than groups, I will clarify what I mean by enhancement and enhancement technologies in this thesis. First, following the embodiment assumption, I conflate the enhancement of the senses with enhancing cognition.

Second, I narrowly define enhancement technology as devices that offer access to sensory information to the user that they would otherwise not be able to perceive. These sensory enhancements act as prosthetic transducers: they first sense information not available to the agent's body in the environment and then translate it into sensory information that is understandable to the agent. For example, reading glasses are not considered enhancements for my purposes, as they merely sharpen existing sensory information. Rather, a hypothetical wearable system allowing the agent to perceive infrared light would be classified as an enhancement.

In other words, enhancement in this thesis is not intended to 'do better something possible already' but instead to allow for broader capabilities, such as sensing information in the environment that would otherwise be inaccessible. In line with the definitions outlined before, this new sensory information is communicated via a prosthetic device that leverages the human or human-made body and pre-existing senses. Going back to the previous discussion on the difference between *augmentation* and *enhancement*, I argue that the former term refers to making-more-better. In contrast, the latter refers to offering new ways of seeing the world. In practical terms, my definition of enhancement technology can be achieved by making an existing sense sensitive to information that the human or human-made agent would be unable to reach.

2.6.1 Frameworks

While my previous definition of enhancement technology provides a narrow starting point, developing a framework that outlines the key questions to address when designing enhancement is essential. This is because the complex relationships between cognition, sensory information, and the body's performativity highlight the need for a conceptual architecture that integrates multiple disciplines and perspectives in a structured yet porous frame.

Frameworks enable decision-making while maintaining an interpretative approach to social reality; in other words, frameworks offer cohesive guidelines for interpreting and connecting situations in an indeterministic way. By providing a framework for designing enhancement technologies, I aim to facilitate a nuanced exploration of the subject matter without foreclosing alternative interpretations or possibilities. In this sense, the framework serves as a tool for navigation rather than a rigid structure that seeks to dictate outcomes, very much in line with the mythological figure of the steersman underpinning cybernetics.

For clarity, I define a framework in this thesis as a conceptual construct (Jabareen, 2009) aimed at moving beyond isolated efforts, such as mine, to articulate a frame for approaching enhancement through practice. The framework I present in this thesis stems from my reflective practice and does not provide incontestable facts but lays out my intentions and motivations, opening for other practitioners to have a "soft interpretation of [my] intentions" (Levering, 2002).

In fact, design solutions are one-of-a-kind and cannot be replicated exactly (Rittel and Webber, 1973, p. 163). In other words, design matters cannot be judged solely by how predictable or repeatable they are (Fischer, 2017, 2014, 2012). Designers bring unique perspectives and experiences, making their work innovative. Even if the same designer works on the same problem twice, their second attempt will yield a different outcome because they have evolved through their previous work.

In other words, the framework I articulate in this thesis is the epistemological middle ground between design instances (i.e., the three prototypes covered in chapters 4 to 6) and a cohesive and fully generalised theory. My research aims to propose knowledge that is more abstracted than particular instances (i.e., it is transferrable to other researchers) yet does not claim the same generality of a theory. Instead, the framework I propose in this thesis aims to be generative: the starting point for others to create new designs and refine and expand my practice.

Any doctoral research requires the generation of new knowledge as its output. Within doctoral design research, new knowledge often takes the shape of prototypes and frameworks (Danzon-Chambaud and Dumesny, 2023), where practitioners experiment with innovative designs, put them to the test and report back on how the weaving of these instances create more abstract knowledge that is not yet a general theory (Höök and Löwgren, 2012). My contribution follows this tradition, where I explore the intersection between the theories with the instances and how this design space is indeterministic, i.e., capable of effervescing many new designs.

I aim to strengthen the process of theory construction as described by Weick (1989). By rooting my work in clearly defined theories (embodiment, cybernetics and affordance theory) and a context (enhancement as sensory layering), I articulate five transferrable guidelines leading to a framework intended to guide other practitioners' "Disciplined Imagination".

Notes on Manifestos

At this point, the reader might ask why the word 'framework' is used instead of 'manifesto'. After all, both terms offer a conceptual guide to a complex situation, often articulating several points. These points guide decisions, actions, or approaches to a specific domain. Further, both are practical communication tools that concisely express ideas, values, or methodologies to the audience.

Yet, a manifesto is usually a document that declares passionately held beliefs and intentions, serving as a call to action for an organisation or movement (Obrist, 2010). In contrast, a framework primarily serves as a structured and critical approach to organising, analysing, and systematically guiding actions (Jabareen, 2009), remaining flexible and adaptable and inviting an iterative process of refinement based on new circumstances or insights.

Given the iterative nature of my research, driven by the conversation between theory and practice, I chose to use the word 'framework'. Unlike a manifesto, which is typically an outward transmission of ideas derived from conclusions or beliefs, a framework has a more reflexive, iterative character, potentially reshaped by new developments. Furthermore, this word has the ambition to invite expansion and revision of the approach I present in this thesis. I also want to emphasise how the very nature of a framework is indeterministic – a point in tension with the usually deterministic nature of technology development. As mentioned before, my intention is not to prescribe the solution to the enhancement problem, mainly because I do not believe one exists. I intend to present the structure for enhancing technologies' individual and nuanced development.

Further, in contrast to a methodology – usually closely linked to the desired outcome of a field of study – a framework offers a more flexible structure. It serves as a structured approach to addressing the complexities of enhancement technology, allowing for the systematic inclusion of various components, processes, and tools. The framework's loose yet coherent structure provides ample space for adaptability.

Principles, guidelines or heuristics?

While principles, guidelines, and heuristics are often used interchangeably, they serve distinct purposes in guiding design and decision-making processes. For an in-depth review and analysis of these three terms' usage in design, see Fu et al. (2016), but I discuss here the main similarities and differences between them to explain my choice of using the word 'guideline'.

Principles are fundamental propositions that guide decision-making (Mattson and Wood, 2014; Mcadams, 2003) and shape outcomes. These underlying laws explain how something works or why something happens and can be categorised into three types (Glegg, 1969): specialised techniques, general rules, and universal principles. Design principles are not simply lists of goals but rather methodologies to achieve those goals (Anastas and Zimmerman, 2003). They should be applicable, effective, and appropriate across various contexts (ibid.), guiding designers towards more effective outcomes (Perez et al., 2012).

In contrast, guidelines provide recommendations for context-specific design issues (Nowack, 1997), capturing and transferring design expertise (Greer et al., 2008) to new domains and instances. These intermediary interfaces between designers and expert knowledge (Kim, 2010) are continuously revised and updated to meet technical and environmental changes. A good set of guidelines combines specific and general guidelines (Bevan and Spinhof, 2007), addressing various design levels. They should be well-documented, including examples, tables of contents, and glossaries (ibid.). Most importantly, guidelines assist design practitioners by identifying issues to consider at the time of decision (Matthews et al., 1998).

Heuristics differ from principles and guidelines, as they are rules-of-thumb (Li et al., 1996) and common sense-based (Rechtin and Maier, 2000, p.25), relying on lived experience and intuition (Douglass and Moustakas, 1985) rather than strict analysis. These trusted, non-analytic guidelines aid decision-making, value judgments, and assessments for complex, inherently unbounded problems. Heuristics can be either descriptive (Papalambros, 2015) or prescriptive (Glegg, 1969), providing successive transitions from qualitative and provisional needs to descriptive and prescriptive techniques.

While principles may provide fundamental truths and guidelines offer specific recommendations, heuristics offer practical solutions (Koen, 1985, pp.27–28) for addressing complex problems within resource constraints. In other words, Heuristics provide "quick and dirty" (Yilmaz and Seifert, 2011) tips to reach acceptable solutions to a design problem. Heuristics should be simple, concise, and easily rationalised; they should stand the test of time and earn broad consensus (Rechtin and Maier, 2000, p.51). However, heuristics often lack a solid theoretical basis. In contrast, my PhD work aims to triangulate new theory, guidelines, and examples of innovative practice, providing a more robust and theoretically grounded approach.

Unlike principles, which are comprehensive and universal, or heuristics, which rely on intuition, guidelines offer a transferable and adaptive approach that is inherently partial and subject to revision. This flexibility allows them to be presented at the beginning and throughout the reflective design process, implying working through examples and encouraging criticality. Using guidelines, I aim to capture and reapply my design expertise, and my choice of guidelines reflects their potential to facilitate effective decision-making and problem-solving in the early design stages, where broad knowledge is beneficial, and adaptability is critical.

Notes on Technological Determinism and Enhancement

At this point, the reader might be asking themselves about (another) implicit tension in my research: I state that I am designing a framework – which is, by definition, non-deterministic. Yet, by focusing on wearable enhancement technology, I might be suggesting that technology determines social progress. This deterministic view of technology is commonplace in, for example, politics:

> *"Communism is Soviet power plus the electrification of the whole country."* (Lenin, 1920)
>
> *[Talking about AI] "Now I believe nothing in our foreseeable future will be more transformative for our economy, our society, and all our lives, than this technology. […] And that's why I make no apology for being pro-technology."* (Sunak, 2023)

Clearly, Sunak and Lenin have very little in common besides their belief that technologies determine society's structure – the textbook definition (Dusek, 2006, p.84) of technological determinism. This assumption can be valid in specific instances, such as the infamous low-clearance overpass purposefully designed by Robert Moses in the '20s and '30s to disallow buses (and, hence, poor, black and working-class people) from enjoying the beaches of Long Island[5]. Yet, how technology influences society should be examined on a case-by-case basis instead of making sweeping claims that technology per se determines society (Héder, 2021).

Figure 2.10 One of Moses' bridges across the Bronx River Parkway (Campanella, 2017).

My exploration of enhancement from a body-centric perspective does not necessarily imply technological determinism.[6] I focus on understanding how technology interacts with and enhances an agent's body rather than assuming that technology alone dictates societal outcomes. My framework acknowledges agents' choices regarding integrating these enhancements into their lives, considering personal goals, preferences and cultural influences. Further, my body-centric perspective encourages a critical examination of the potential impacts of enhancement technologies on agents. This approach does not assume a deterministic trajectory but invites reflection on enhancement's ethical, social and cultural implications. A critical element of my claim is my focus on wearable enhancements and how they provide additional layers of sensory information to the agent wearing them.

2.7 Sensory Layering and Wearable Enhancements

At this point, I have used the word 'wearable' several times without giving it a formal definition. In this thesis, *wearable* indicates electronic devices worn close to the wearer's outer surface. In this thesis, wearables are a component of an assemblage that interacts with other components to manifest emergent properties. In the case of humans, I develop wearables in contact with their skin, while in the case of human-made agents, I develop systems that anchor on and integrate with their bodies, as will be discussed in depth throughout chapters 4 to 6.

[5] The Moses case study was arguably inflated (Joerges, 1999) for political reasons. Nevertheless, I include it here as it is often brought forward as a case study for technological determinism.
[6] Some might argue that my attempts to avoid technological determinism are merely an illusion, akin to believing we have free will when, in fact, our choices may be predetermined. From this perspective, the relevance of my stance on technological determinism lies not in its accuracy as a reflection of reality but rather in its potential impact on shaping our collective future.

In practical terms, wearable devices enable *sensory layering* – a term I derived from traditional sensory fusion procedures from robotics (Duan et al., 2022; Mohd et al., 2022). Sensory layering integrates information deriving from sensor systems. However, instead of presenting the unified sensory data to a central processing unit (as standard practice in sensory fusion algorithms), it presents it to the human or human-made wearer, where it will be interpreted and integrated with the body's existing senses. Sensory layering, within this thesis, means the practice of adding layers of sensory information deriving from environmental affordances in addition to the agent's pre-existing sensing capabilities.

According to Dimou et al. (2017, p.70), wearable technology is a vast subject matter divided into six categories: entertainment, gaming, fitness, lifestyle, medical, and industrial. Since discussing such varied potential wearable incarnations is beyond the scope of this study, I decided to focus on wearables designed to improve the wearer's navigation and wayfinding capabilities. Navigation was chosen as a fundamental goal-directed skill shared by human and human-made agents that coordinates planning and executing movements (Montello, 2005) and can be studied in the temporal domain. In a broader sense, navigation can apply to any situation that requires determining position and direction. All navigation techniques involve evaluating the navigator's position in relation to known geographies, landmarks, or mental maps (Wickens et al., 2021, p.131). Navigation, in this sense, encompasses a wide range of activities, from maze-solving robots to pedestrian navigation. Furthermore, because navigation relies on multiple senses and the agent's knowledge of the environment, it provides a rich area for enhancement technologies. Finally, although previously investigated, wearable navigation systems are an under-researched area (Amorim et al., 2020).

The rationale for selecting wearable technology over, for instance, ingestible or implantable technology stems from my intention to respect potential users' sensitivities towards more invasive technologies: in 2012, a survey conducted by Imperial College in London (Bergmann et al., 2012) compared the acceptability levels of invasive versus non-invasive sensing techniques for patient monitoring revealed that the majority of those polled (85%) preferred sensors to be positioned outside the body, albeit in contact with it. In addition, the study's participants expressed a preference for small, unobtrusive, and discrete wearables.

Further, wearable technology is one of the fastest-growing innovation sectors in technology, projected to expand at a compound growth rate of 15.9% from 2020 to 2027 (Grand View Research, 2020). This growth is fuelled by public interest, as evidenced by Accenture's report, which noted that between 2014 and 2020, the use of wearable devices in the US population doubled (Accenture, 2020). Wearables offer a novel avenue for human-computer interaction because of their portable, embeddable, and ubiquitous potential.

Another advantage of wearable technology is how approachable the development of wearable systems can be for practitioners from disciplines other than engineering, such as designers like myself. Several platforms, such as the Arduino ecosystem, are explicitly designed to democratise access to wearable technologies. Finally, while wearable technology has been widely used in the healthcare industry, only a few applications outside fitness trackers have been explored in the literature (Niknejad et al., 2020, p.52), leaving room for developing enhancement systems and sensory expansion. Furthermore, wearable technology has been highlighted as critical for human enhancement because it allows for the seamless and non-invasive integration of the digital and physical worlds (Raisamo et al., 2019).

In the following sections, I will discuss recent literature addressing enhancement technology as narrowly defined above from both Robotics and Design practice. The following sections present a high-level introduction to the practice of enhancement technology. Chapters 4-6, in which I outline my practice, have literature reviews specific to each use case presented.

2.7.1 Wearable Robotics for Enhanced Navigation

Many wearable robotic systems for navigation have been developed recently, focusing on visually impaired people. The majority of the research has focused on vibrotactile feedback on the wearer, with the haptic interface placed on various zones of the body, such as the fingers (Aoki et al., 2009), hands (Bial et al., 2011), neck (Matsuda et al., 2020; Schaack et al., 2019), waist (Heuten et al., 2008; Krüger et al., 2020) and head (Berning et al., 2015; Kaul and Rohs, 2017; Landa-Hernández et al., 2013; Lee and Medioni, 2015). There are also some examples of full-body haptic feedback suits (Konishi et al., 2016; Mateevitsi et al., 2013; van den Boogaard et al., 2018). The premise is similar in these projects: given a person with visual impairments, a novel wearable haptic device is developed to assist the wearer in navigating the environment. However, van den Boogaard et al.'s (2018) work is notable as it is the only one explicitly mentioning human sensory enhancement as the goal of their research. These researchers developed a full-body suit capable of intercepting broadcast Wi-Fi signals, transforming their intensity into haptic patterns. The system aimed to allow the wearer to detect invisible force fields in the built environment, resulting in an embodied awareness of hidden objects (ibid, p.600).

Another example of human sensory augmentation can be found in Kiss et al. (2018), who developed a tactile display for eye-less navigation for motorcyclists. The wearable comprises twelve vibrating motors arranged on a belt strapped around the motorcycle driver's kidneys and actuated in fourteen different patterns to represent both turning left or right and proximity to the turning point (ibid, p.618). The empirical findings derived from Kiss et al.'s paper are important for my thesis: wearable systems can layer directional information on the human body's pre-existing senses. Notably, compared to a visual and audio-based navigation system in a real-world test, Kiss et al.'s wearable system outperformed the commercially available systems by being less distracting and reliably communicating turning information (ibid, pp.617-618).

This last example from Kiss et al. suggests the influence of Bach-y-Rita's (1987) seminal work on brain plasticity or the brain's intrinsic potential for adaptive changes in response to a rapidly changing environment on them. Bach-y-Rita's research has demonstrated that augmentations such as artificial receptors, coupled with the human brain, have yielded similar perceptual capacity levels compared to the substituted sense in both auditory-visual and tactile-vision sensory substitution (Bach-y-Rita and Kercel, 2003), as shown in Figure 2.11. Although sensory substitution was initially defined as simply 'translating' one sensory property onto another (Bach-y-Rita et al., 1969), its definition was extended to encompass any act of translation of one sensory modality – the source – to another – the target (Fakhri and Panchanathan, 2019). Fakhri and Panchanathan's modern definition is particularly relevant to enhancement technologies, as it implies that sensory substitution can also enhance the abilities of individuals who do not have sensory impairments by providing them with new or alternative ways of experiencing the world. For example, a sensory substitution device might convert auditory information into visual information, allowing a person to "see" sound or to perceive music in a new and more immersive way. In other words, sensory substitution devices should be viewed as new tools for expanding sensory experiences: these sensory substitution devices transcend their sensory origins and have the potential to shift the boundaries of traditional senses (Auvray and Myin, 2009; McGann, 2010).

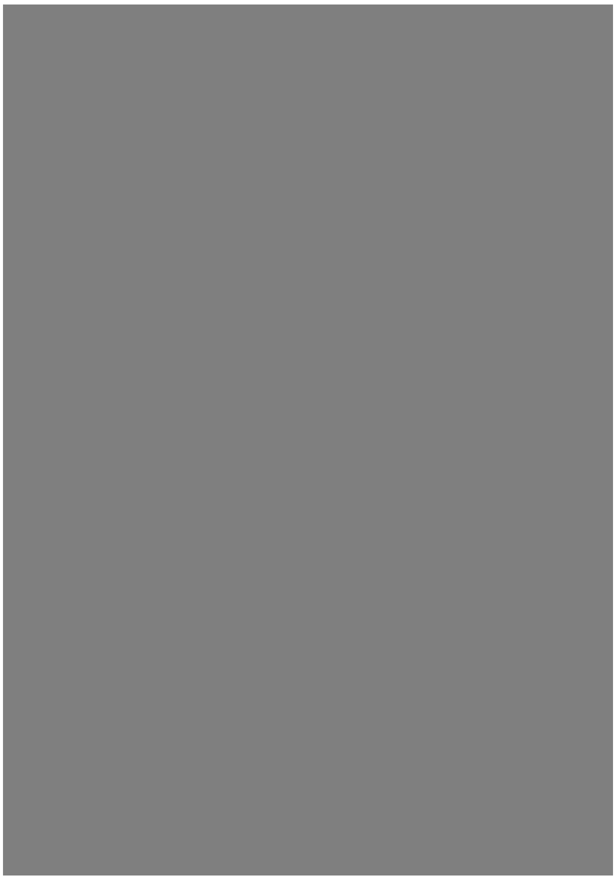

Figure 2.11 One of Bach-Y-Rita's (1971) first sensory substitution devices was the TVSS (Television Substitution System). It consists of a TV camera, commutator, and 400 vibrotactile stimulators arranged in an array on the subject's back. Following several hours of training, blind participants accurately recognised objects on a table, assessed distances, and located items spatially using "visual" cues like depth, perspective, parallax, and size constancy.

While sensory substitution is helpful in medical devices to assist users with physical impairments, its impact in the field of enhancement technologies more broadly is currently limited. This limitation stems from a lack of a straightforward approach to implementing systems to enhance the wearer. Nevertheless, some early, albeit implicit, examples of sensory layering emerge in the literature. One example is the haptic wristband developed by Pescara et al. (2019) to track volatile markets such as foreign exchange currencies and cryptocurrencies. Another example comes from Novich and Eagleman (2015), who developed a wearable vest with vibrotactile motors in the lower back for encoding spatial and temporal data (ibid, pp.2781-2785), as shown in Figure 2.12. Because these researchers view the brain as a black box, the epistemological assumption in both projects is particularly intriguing. The term 'black box' is used here as a metaphor developed by the cyberneticians Ashby (1957) and Wiener (1961) to describe a method of understanding a complex system in which the steps between inputs and outputs (or perception and action) are invisible. The concept of black boxes was first introduced in cybernetics to model complex systems that receive inputs and, as a result, produce outputs without necessarily knowing their inner workings (Glasersfeld, 1979). A black box is typically characterised by its inputs and outputs, but the processes or mechanisms by which it operates are unknown or considered irrelevant. For example, an aeroplane might be considered a black box because it can be evaluated based on its performance and safety without necessarily understanding the complex mechanisms that enable it to fly.

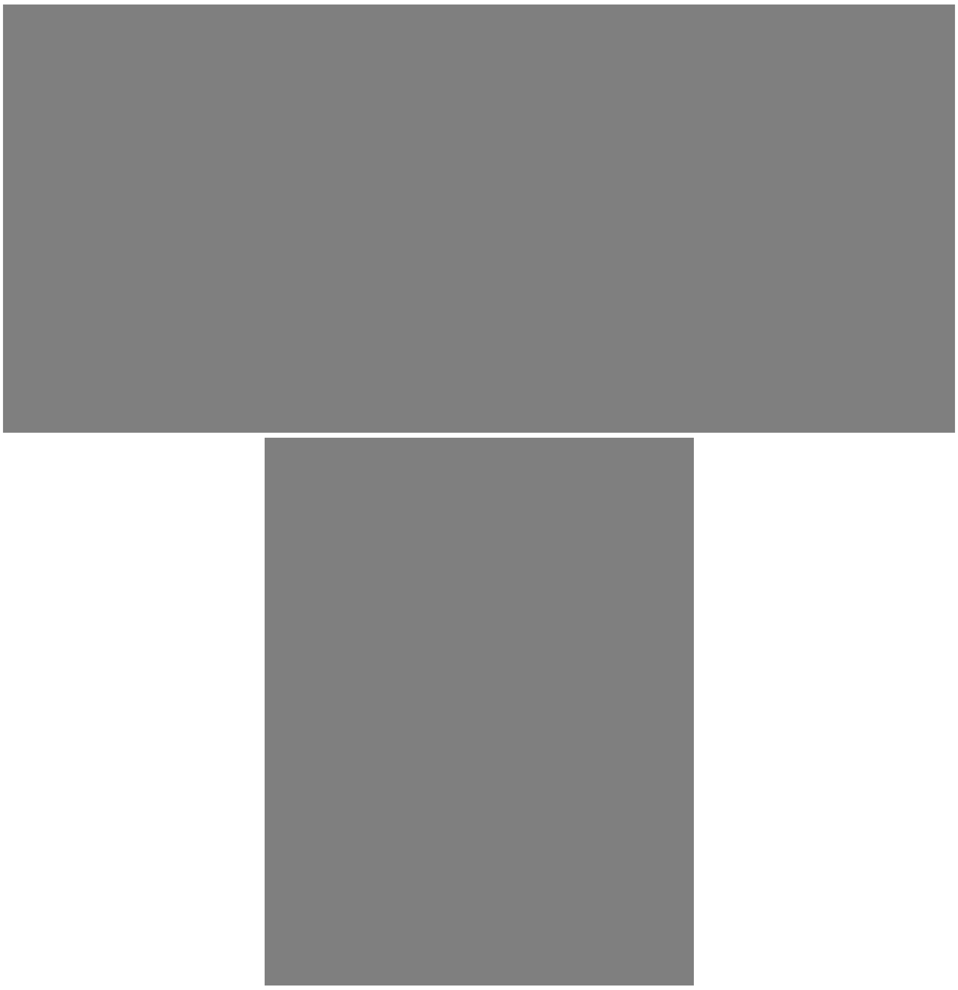

Figure 2.12 Top: Novich and Eagleman's (2015) vibrotactile vest, relaying information to the wearer via vibration from small motors placed on the lower back. Bottom: Eagleman (2015) wearing another iteration of the vibrotactile vest during his TED Talk.

The black box metaphor is particularly apt for approaching the human mind as neuroscience researchers classify brain computation as one of the possibly unsolvable questions in the field (Adolphs, 2015). However, the human mind can still be studied and understood based on inputs, outputs and overall behaviour. This point is particularly relevant to my research's pragmatic aims: we do not necessarily have to 'solve' the inner workings of the human mind to start approaching the subject of enhancing the senses. Rather, by considering the human brain – or even a human-made agent's central processing system – as a black box, we can design sensory enhancements as systems that augment the black box's inputs.

In essence, by following the concept of black box, its abilities as a generic input-output device can be effectively used to enhance the wearer's knowledge by encoding normally inaccessible information (such as the previous example of Wi-Fi signals) and presenting it to the wearer through sensory substitution. This is a common point of agreement in discussions about the future of wearable technology. For example, Ormandy (2019, pp.106-108) contends that for wearable systems to be effective, they must be designed with a body-first approach, incorporating a minimal number of sensors configured in multiple modalities, allowing the brain to assimilate additional information embedded in the environment. Ormandy's point reinforces Sullivan's (2016, pp.115-118) argument that wearable technologies are uniquely positioned to influence the world's embodied experience by potentially mutating sensory substitution into sensory augmentation.

In addition to haptics, other systems have been developed to aid navigation by utilising other senses. For example, visual-auditory substitutions for visually impaired people have been thoroughly researched: Fristot et al. (2012) created an indoor navigation system by mapping depth camera inputs and outputting varying distance-based melodies; Blessenohl et al. (2015) improved Fristot et al. system's safety and reliability. Heller and Schöning (2018) further investigated the potential of audio-based navigation wearables, demonstrating that embedding navigation cues in multi-track audio recordings effectively guides users to the sound source. Finally, heat-based feedback was investigated to convey spatial information and real-world navigation (Berning et al., 2015; Tewell et al., 2017). It should be noted that the research efforts in all of the preceding examples are aimed at visually impaired individuals, and no potential applications for more generally applicable enhancement have been identified.

While some guidance on human enhancement has been published in Robotics, roboticists rarely address the subject matter directly (Grinbaum et al., 2017; Salvini, 2014). One of the few comprehensive analyses on human enhancement and robotics identifies gaps concerning the potential social impacts of robotic enhancement technologies and the need for further governance and policy discourses (Djebrouni and Wolbring, 2020, p.6). Further, the authors suggest the term 'ultrabilitation' or the idea of going beyond the recovery of 'normal functioning' for disabled people (Buetow et al., 2019). However, this approach does not offer a transparent approach to enhancement technologies since it relies on an implicit conception of 'normality'. As argued in the previous sections, my research addresses this assumption by erasing its need: I articulate enhancement technologies through the concept of sensory layering – or adding sensory systems on an agent and integrating them with the wearer through feedback loops. In this framework, defining 'normality' becomes unnecessary, as the focus is on the individual agent and not on an abstract idea of species. In other words, the individual agent and its current senses are the 'normal', and wearables constitute enhancements if they can provide novel sensory information and be tightly coupled with the wearer.

My research is positioned at the intersection of wearable robotics and design research, leveraging each field's strengths: from the first, its pragmatic approach to building application-specific systems and from the latter, its forward-looking and exploratory nature. As stated above, I focused on agents' physical shape and sensorimotor contingencies. In line with Sullivan's (2016) and Ormandy's (2019) argument that human sensory augmentation should be approached from a body-first perspective, I am developing wearable prototypes to expand the agent's ability to sense its environment. Design here is an exploratory and reflective practice, as expanded in the next chapter, to empirically develop wearable systems and examine the augmented agent's interactions within and with the environment. To quote Vincent Beaubois, "The designer does not know what will happen, but he/she knows that something *will* happen" (2015, p.186, emphasis added)[7].

[7] This remark is contextualised within a discussion on the influences of Deleuze and Guattari in Design. The statement cited here does not imply that designers cannot predict or, indeed, are unaware of the consequences of their design outputs. On the contrary, Beaubois argues that the designer creates with an expectation in mind, which is inevitably challenged when the artefact is inserted within a sociotechnical context. In my research, I develop wearable systems with the expectation of offering access to affordances that are typically outside of an agent's sensory reach. I do not, though, claim universality and immutability of my outputs: when they become part of the world they might produce unanticipated effects. Part of my argument on the importance of open-source enhancement is in mitigation of these unanticipated effects: transparency fosters trust (Wortham et al., 2016) and facilitates accountability (Felzmann et al., 2020; Hulstijn and Burgemeestre, 2015), among others.

2.7.2 Design and Enhancement Technologies

As indicated in the introduction of this chapter, design has dealt with enhancement technologies. Although the design field has been primarily concerned with morphological practices related to human enhancement, a limited number of projects have looked into sensory substitution or layering, as defined at the beginning of this section. For example, the Berlin-based design studio Beta Tank developed two projects: the Mind Chair (2008) and the Eye Candy (2007), which explicitly addressed Bach-Y-Rita's brain plasticity hypothesis. The former project consists of a polypropylene chair capable of transmitting moving images to the person sitting through an array of solenoids on the chair's back. The latter is a lollipop-shaped product that transmits visual information to the user's brain by actuating an array of resonators when placed on the tongue, as shown in Figure 2.13. The Eye Candy concept was developed in collaboration with Wicab, a medical engineering company specialising in sensory substitution, which eventually produced a commercial product based on this exploration, the BrainPort Vision Pro (Richardson et al., 2020), shown in Figure 2.14.

Figure 2.13 Beta Tank's Eye Candy project (Burstein et al., 2007), a speculative lollipop-shaped device that could transmit images to the brain through the tongue.

Figure 2.14 Wicab's (2020) BrainPort Vision Pro headset. The actuator array positioned under the wearer's tongue was conceptualised from Beta Tank's Eye Candy project.

We can see more explorative approaches to morphological practices inquiring about human beings' future through design methodologies. Matt Pyke's work stands out for its vision of the human body: he explores the ever-changing human morphologies in his installations, speculating on their potential. The Transfigurations (2011) and its most recent iteration (2020) show a looping animation in which a humanoid figure morphs between different 'costumes', each representing a technological advancement regarding its predecessor – from primitive – such as rocks and shards – to current materials – such as voxels, or three-dimensional pixels. The topic of fluctuating morphologies characterises his work and is explored in relation to architecture in Walking City (2018), in mixed reality with the iOS app Super You (2021), and, finally, hinting at a future human capable of flying in Do We All Dream of Flying? (2020). The most relevant example of human enhancement in Pyke's work is Future You (2019). Here, real-time motion tracking is employed to track people's movements, which are then analysed through Machine Learning. The more the user interacts with the installation, the more optimised their projected morphology is to increase agility.

Advancements in synthetic biology present a clear motif in contemporary design and art practice: from ORLAN's Harlequin's Coat (2008), a critical piece about cultural cross-breeding and the implications and potentials of hybridisation, to Ana Rajcevic's Animal: The Other Side of Evolution (2012), where the questions around the aesthetics of trans-speciesism are explored, to Neri Oxman's Vespers series (Oxman, 2016a, 2016b, 2016c), a series of 3D printed death masks exploring wearable customisation for both the body and the environment, many designers have critically looked at the implications of technology for humanity's future. Changing and envisioning new human bodies is a rich source for design speculations: Agatha Haines explores a near-future scenario in which advancements in aesthetic surgery allow people to design their babies, anticipating potential medical, environmental or mobility issues (2013a). In Circumventive Organs (2013b), Haines envisions synthetic hybrid organs that combine selected animals' properties – electric eels, rattlesnakes and leeches – to create fictional organs designed to support human life automatically. The envisioned solutions provide automatic defibrillation, excessive mucus removal and blood thinning.

Figure 2.15 Speculative organ (Haines, 2013b) resulting from splicing human genes with leeches, allowing stroke prevention by thinning the blood thanks to anticoagulants naturally present in leeches' salivary glands.

The vast majority of these projects rely on discursive (Tharp and Tharp, 2019), fictional (Bleecker, 2009; Sterling, 2013a), and speculative (Dunne and Raby, 2013) practices to explore the future of human beings. These methods are explicitly designed to inspire debate and awareness-raising on the specific issues they address, but they do not claim to solve the issues raised. Furthermore, discursive and speculative design practices deliberately separate themselves from industrial practices, preferring museums and exhibitions as an outlet, limiting their impact on the broader community (Sanzeni et al., 2019). Although these artefacts are compelling (and polarising) design pieces, most are ill-equipped to look to the future programmatically, grounding the debate on recent technological advancements, as discussed in chapter 0.

Nevertheless, several design projects stand out in pragmatic human enhancement. Marc Owens employs a head-mounted interface and a body-mounted camera in Avatar Machine (2008) to simulate a wearer's third-person gameplay experience. Shirota et al. (2020) reshape human ears and noses to change their innate abilities to extract environmental information. Aghakouchak and Paneta (2016) built a soft-wearable system using live 3D scanning technology to explore virtual environments within physical settings. These three projects share the interfacing modality with the body (they are all wearable devices) and emphasise current technology, albeit drastically different in scope. These pieces challenge the human body's future and physically illustrate how future interactions could appear. My practice shares these projects' approaches to enhancement technologies and extends them by developing a series of design guidelines for designers and roboticists approaching the subject matter.

2.8 Conclusion

To summarise, designing body-centric enhancement technologies is reframed for my research as *the practice of creating detachable body-moulded sensory systems aimed at expanding the wearer's near-body space*. These systems effectively augment the wearer's knowledge of the environment in which it is embedded by presenting environmental affordances previously unseen. This reframing creates exciting design challenges, where the designer can create many sensory systems to uncover hidden affordances. These *hidden affordances* are the forces outside human organs' sensitivity, such as magnetic information or ultraviolet and infrared light. Further, this point implies that robotic systems should similarly be designed with sensory modularity in mind, where a new sensor can be seamlessly added to the system to increase its comprehension of the world.

My approach to enhancement technologies, as described above and throughout this thesis, aims to extend and ground the theoretical debate by focusing on the body and its interaction with the environment. Firstly, I challenge the implicit nature of 'normal', highlighting how assuming what normal means is problematic as it involves establishing a standardised benchmark for characteristics, behaviours or conditions. I then expand the theoretical debate by focusing on one dimension: the body and how it senses its environment. To achieve this goal, I aim to provide a new perspective rooted in cybernetics and affordances through which theory can be comprehended and analysed, thus opening up novel paths for exploring enhancement. In the next chapter, I introduce the methodology I used to guide my practice.

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3 Methodology: Developing Enhancement Technologies Through Practice

My research interweaves – in a non-linear way – reading, theorising, making, reflecting, and synthesising working guidelines. The practice-led research I present in this thesis aims to generate transferable design guidelines to guide practitioners in approaching enhancement technologies. Following this point, I designed the three case studies as experiential prototypes – critical pieces designed to reflect on an instance of enhancement technology. It is also important to note that the outcomes of the case studies each embody one of the possible answers to a design brief rather than claiming universality. This point again reflects the role of the design guidelines: to act as a generative framework for practitioners rather than a fixed set of rules. These guidelines were conceived to be generalisable, enabling other designers' practice and perhaps being moulded and reshaped by others' practices.

In this methodology chapter, I aim to demonstrate how, as a design researcher, I can contribute to enhancement technologies as defined previously. In my research, I use aspects of Critical Design and Reflective Practice to illustrate how practitioners can effectively combine expertise from design and robotics to develop new enhancement technologies, especially in the context of wearable navigation systems. First, I introduce these two methods, surveying their associated literature and their relevance to my subject matter. Then, I introduce and discuss the five design guidelines I employed throughout my research, why I favoured reflective practice over user-testing, and the three design briefs representing my practice.

My approach comes from my past experiences as a service designer. Service design is particularly suited to ill-defined problems because of its systemic approach to the practice and because it approaches socially situated issues (Suoheimo et al., 2021). The service design methodology orchestrates dynamic systems, spanning products, systems, and stakeholders. In this landscape, the designer considers the different elements of the system and then designs some touchpoints helpful to reveal the value and the interactions of an intangible idea – e.g., enhancing agents with wearable sensory extensions. A *touchpoint* indicates a contact point between a service and its users. A touchpoint can be embodied in physical artefacts, environments, or other sensory-specific experiences (Mager, 2008, p.356). Touchpoints are central to service design practice as they provide a tangible interface to an intangible service – bringing it to life (Secomandi and Snelders, 2011). Within my research's context, the touchpoints' role is to explore and chart possible implementations and outcomes of enhancement technologies (Sanzeni et al., 2019).

My research aims to demonstrate my approach by designing tangible future interactions with technologies. The projects documented in the following three chapters were designed to address specific human and human-made navigation challenges employing a range of sensory inputs. However, the underlying concepts aim to be transferable to other contexts relevant to enhancement technologies. My research parallels the approach of service design to complexity. In dealing with complex systems, service design seeks methods that cut across knowledge domains (Johnson et al., 2007; Young, 2009).

3.1 Critical, Speculative and Fiction Design

This thesis fits into the tradition of Critical Design, although distancing itself from it in some areas, as mentioned in the previous chapter and argued in this section. Speculative Design and Fictional Design belong to the tradition of Critical Design. This branch of design developed between the 1990s and the new millennium within the Royal College of Art in London, largely thanks to the practice of Anthony Dunne and Fiona Raby.

The beginnings of Critical Design can be traced to the late Nineties (Dunne and Gaver, 1997) when design practice was framed as able to produce thought experiments named "value fiction" (ibid, p.361). The authors described this practice as imagining and designing objects based on current technologies that users would not accept because the values they embody are not widely shared. Here, the public is presented with a polished prototype as if it was a finished product. The public's feedback and reaction become a central part of the project, as it aims to understand how and where these unusual approaches to technology would fit in their lives.

The ethos embodied in this first exploration was then carried over in other Dunne and Raby writings: Hertzian Tales (1999), Design Noir (2001) and Speculative Everything (2013). The literature highlights how Critical Design follows the ideals of Radical Design developed between the sixties and seventies by Archigram, Archizoom, Superstudio and Studio Alchimia in Italy (Dunne and Raby, 2013, p.6; Mazé and Redström, 2007). These studios were born as an explicit critique of design and architecture's relations to the context they operated within, which often implied utilitarianism and consumption (Mazé and Redström, 2007). In addition to its affinity with Radical Design, Critical Design relies on John Thackara's (1988, p.21) reflections on the relationship between product design and capitalist production, in line with Papanek's (1985) scathing critique of product design as the "most dangerous profession in the world".

In line with these thinkers, Critical Design shifted the focus from the product to the user's reaction to a provocation – underlining the ethical, social, environmental and political implications that derive from it. In other words, subjectivity is crucial in Critical Design. Within the practice, designers externalise their points of view in their provocations. Background study on a subject is crucial, but the practitioner's reflection ultimately decides the artefact or provocation. The output from a Critical Design process is an artefact encapsulating an idea, a reflection or an alternative – which parallels my work.

Beyond the artefacts, Dunne & Raby's Critical Design uses speculation as a catalyst to build scenarios and narratives in which new technology and its impact on the environment in which it develops are imagined and embodied in a range of media. The authors propose Speculative Design as the vehicle to conduct this type of practice. Following the definition by Auger (2013):,

> *"Speculative design combines informed, hypothetical extrapolations of an emerging technology's development with a deep consideration of the cultural landscape into which it might be deployed, to speculate on future products, systems and services. These speculations are then used to examine and encourage dialogue on the impact a specific technology may have on our everyday lives. The familiar and engaging nature of the designed output is intended to facilitate discourse with a broad audience: from experts in the field such as scientists, engineers and designers to the consumers and users of technological products and systems."*

Speculative Design is conceived as a form of broadcasting and publishing. Auger's definition echoes Dunne and Gaver's (1997) first publication on the matter, where they discussed a pillow which could display radiating magnetic fields: "the Pillow was not made to be isolated in a gallery space (making its exhibition problematic), in which the experience of seeing it and the questions it raises can be compartmentalised and separated from everyday concerns. Instead, the Pillow is designed to live in the home, raising its issues as a routine part of day today life". My own work is not exhibited, very much in line with the initial intention quoted above. Despite making my work public through this thesis and occasional publications, it is more solitary and reflective, as I will discuss in the next section.

Figure 3.1 Dunne and Gaver's (1997) Pillow prototype. The prototype comprises a translucent plastic block containing an LCD and eight circular holes. A clear, inflatable plastic pillow covers the block. The LCD displays coloured patterns corresponding to the arrangement of the eight holes, with the colours fading in and out periodically.

In addition to Speculative Design, Sterling (2005) and later Bleecker (2009) introduced Design Fiction to make the designed content visible to the public, thanks to its ability to build engaging and credible narratives. Techniques used to support storytelling include the creation of physical artefacts through rapid prototyping and communication artefacts (Kelliher and Byrne, 2015). In the words of Bleecker (2009, pp.7-8):

> *"Design fiction is a mix of science fact, design and science fiction. It is a kind of authoring practice that recombines the traditions of writing and story telling with the material crafting of objects. Through this combination, design fiction creates socialized objects that tell stories – things that participate in the creative process by encouraging the human imagination. The conclusion to the designed fiction are objects with stories."*

One of the main concepts for Design Fiction – and, arguably, for Speculative Design – is the diegetic prototype (Bosch, 2012; Kirby, 2010). Diegetic prototypes are physical objects that evoke a narrative, a future context. Consequently, it is necessary that:

1. The future scenario to which that prototype belongs is in continuity with the present,
2. It is plausible within the narrative it wants to illustrate,
3. The prototype is a provocation, eliciting a debate to continue reflection.

In Sterling's words, Design Fiction is "the deliberate use of diegetic prototypes to suspend disbelief about change" (Sterling, 2013a). The outputs of Design Fiction are self-contained worlds (Lindley and Coulton, 2015) that extend the traditional practice of prototyping by demonstrating both the concept in question and the context in which it is positioned (Lindley et al., 2014).

Although Critical Design is a renowned practice recognised by many exhibitions, such as those held in Milan (Mitrovic and Šuran, 2016), London (V&A, 2018), Beirut (Beirut Design Week, 2017) and New York (MoMA, 2017), the literature highlights two main criticisms of this approach. The first criticism identifies Critical Design as an artistically-inclined version of Interaction Design, in which the adjective 'speculative' becomes synonymous with the unfeasibility of its projects (Dubberly, 2010; Sterling, 2013b). The second criticism accuses Critical Design of being unable to develop self-criticality, given that it starts from the position of white, European, colonising and privileged practitioners (Prado and Oliveira, 2015; Thackara, 2013).

I add a third to these two arguments: Speculative Design artefacts are often designed primarily for looking at, not interacting with. This point introduces another tension in my research: If my research focuses on the body and its interaction with the world, how can I use a method that does not require the designed artefact to be on the body at all? In other words, Critical Design tends to crystallise complex – sometimes referred to as *wicked* (Rittel and Webber, 1973) – problems into diegetic prototypes, as explicitly stated in Speculative Everything (Dunne and Raby, 2013, p.2):

> *"[Critical Design] thrives on imagination and aims to open up new perspectives on what are sometimes called wicked problems, to create spaces for discussion and debate about alternative ways of being, and to inspire and encourage people's imaginations to flow freely. Design speculations can act as a catalyst for collectively redefining our relationship to reality."*

These design speculations – or diegetic prototypes – are fictional pieces designed to spur debate in specific contexts, traditionally galleries and museums. Although captivating, these design practices collapse a possible future scenario in a limited number of critical pieces. I argue that this approach is limited, as it relates only to a select group of individuals. Going back to Gaver and Dunne's (1997) seminal essay, the researchers explicitly stated that the aim of critical design pieces should not be exhibited in the isolation of galleries and museums, as this venue would allow the public to compartmentalise the critical aspects of the object and remove them from their lived experience. Rather, critical design objects should live in everyday life, constantly reminding them of the issue they address.

Therefore, following Dubberly's (Dubberly, 2010) and Sterling's (Sterling, 2013b) taxonomy of designed objects, I aim to create desirable and buildable artefacts in my PhD research to overcome the limitations of Critical Design practices, as illustrated below in Figure 3.2. My design approach enriches the subject matter in this context: rather than speculating, interviewing, and debating, new knowledge is generated through the pragmatic act of making, iterating, documenting, and reflecting on the practice – as I will discuss in the next section. This practice-led approach to the subject matter of enhancement technologies allows for concrete and grounded conversations.

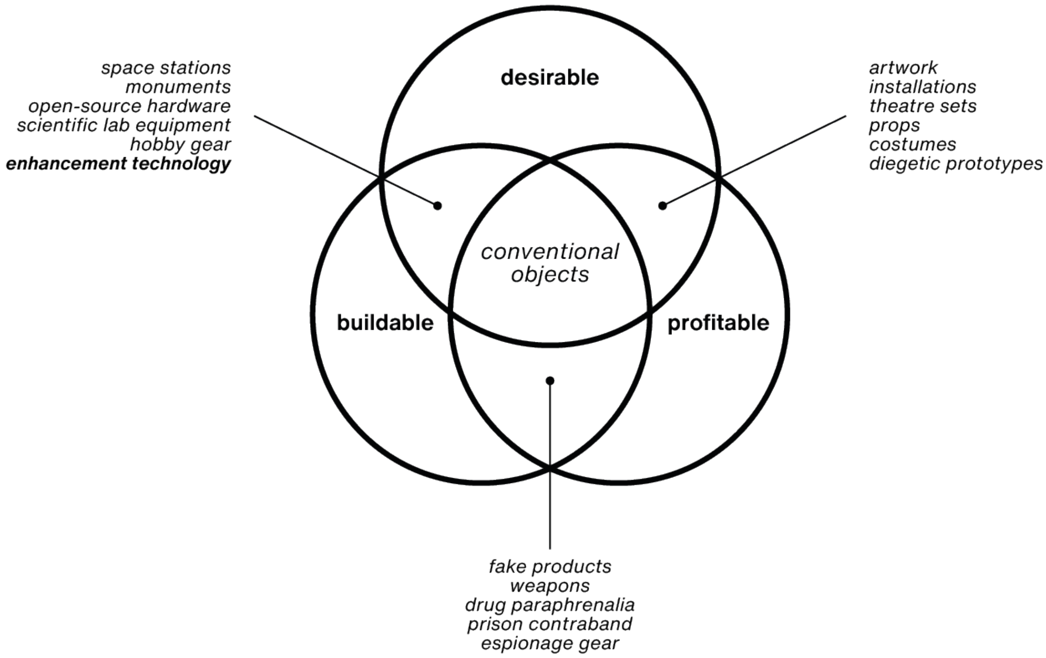

Figure 3.2 Enhancement technologies contextualised in Sterling's Anticonventional Objects (Sterling, 2013b), itself an elaboration of Dubberly's "Designing Successful Products" (2010). Whereas Critical Design practices exist at the intersection of desirable and profitable objects, this thesis contends that enhancement technology should be desirable and buildable. Critical prototypes, such as those presented in this thesis, must go beyond an installation or prop format, according to Prado and Oliveira (2015), to effectively penetrate the public debate on enhancement.

My research straddles the common design and Human-Computer Interaction tension between what *could be* – desirable objects – and what *is* – buildable objects (Steen, 2011). I am certainly not the first researcher to work in this tension: Buchanan (1992, p.6) famously called for an integrative approach to knowledge-making within Design to extend the field "beyond the library or the laboratory".

The critical relevance of reaching a larger audience is reflected in Kaspersky's research on the public's attitude toward enhancements (Opinium Research, 2020), revealing that concerns about these technologies are widespread globally. This position is further reflected in critiques of Critical Design practices, which stress the need for bringing critical prototypes to a broader audience to include stakeholders of diverse backgrounds (Prado and Oliveira, 2015) and make the subject matter experientially available for public scrutiny (Smith et al., 2016, p.7).

My approach, in other words, uses functional design artefacts to explore new framing and meanings of enhancement – as I will discuss in more depth in chapter 3.3.2. In this way, my practice echoes Gaver's Ludic Design (Gaver, 2001, 2006; Gaver et al., 2010, 2004), which argues for more playful, evocative, and culturally embedded designs by emphasising the creation of artefacts and experiences that nurture curiosity, exploration, and personal interpretation. His artefacts, as Gaver notes, should avoid clear narratives of use and instead offer "under-defined" design scripts (Akrich, 1992; Fallan, 2008), leaving room for personal interpretation.

Gaver's approach is grounded in the idea that humans are not only *homo faber* – creatures who build – but also *homo ludens*, playful beings who engage in activities that are not always goal-oriented (Huizinga, 1955, p. 13) but reflect and engage through experience mediated by artefacts (Sengers et al., 2005). In this context, Gaver's work illustrates how ambiguous and evocative design can inspire meaning-making. These probes (Mattelmäki, 2006) elicit fragments of meaning, which can inspire, in turn, new designs. This point is fundamental for my practice: my case studies do not detail incremental developments within a single domain but explore a range of contexts and are linked to each other by their relationship to my research questions.

3.2 Reflecting for Enhancing

Having positioned my work in relation to the literature and to Critical Design, I will set out the methods of my own practice within this research. I stress that my research was an exploratory process of simultaneous problem-framing and problem-solving. This process is nonlinear and akin to cybernetic ways of knowing, where there is a constant feedback loop between setting a goal (i.e., designing enhancement technology), building a prototype and using it to re-define the goal itself. In other words, my research materialises theoretical concepts to explore and reflect on the theory itself.

My work resonates with Reflective Practice and Pragmatism in Design. Although comprehensively reviewing these two domains is outside the scope of my work – and others have dedicated significant time and resources to do just this – the next section introduces the concepts and their relation to my research.

3.2.1 Reflective Practice

Reflective practice (Schön, 1983) is a method of learning and improving by actively thinking about one's experiences. It involves critically examining and evaluating one's thoughts, actions, and beliefs to gain a deeper understanding. Reflective practice can be helpful in a wide range of fields, including education, healthcare, and business, as it can help individuals to develop new skills and insights and to improve their performance.

Although Schön's work is the most referred to within the design community, he is not the first to introduce the term; in fact, Dewey (1910) is widely considered the founder of Reflective Practice. For Dewey, reflection is a rigorous process of meaning construction based on a deep understanding of the connections between experiences, with the goal of continuous interaction that encourages personal growth. This reflective process begins with an experience, yielding a spontaneous interpretation, followed by possible questions about it. From these questions arise potential explanations, transformed into probable hypotheses that may or may not occur (Rodgers, 2002).

Schön (1983) proposed an epistemology that values the "special expertise" (p.5) or "artistic, intuitive processes" (p.49) developed through professional practice. This knowledge is often implicit in patterns of action, making it difficult to explain or articulate. Practitioners must respond spontaneously to uncertainty, instability, uniqueness, and value conflict, relying on an intuitive feeling cultivated through experience. Schön's concept of "reflection-in-action" involves bringing awareness to one's actions during performance, noticing, thinking, or observing something about the action.

Schön's theory challenges Dewey's rational approach to reflection, which prioritises theoretical knowledge over practical experience. Instead, Schön privileges experiential knowledge as a superior form of knowing developed through direct experience and intuition. This perspective rejects the notion that practice can be reduced to a set of predetermined plans or data-driven decision-making processes. Rather, practitioners' knowledge exists in their "knowing-in-action".

Although my work aligns closely with Schön's interpretation of Reflective Practice, I still employ some of Dewey's reflections, especially on Pragmatism, as I will elucidate in section 3.2.4. Regardless of the differences between these two authors, we can state that reflective practice involves processing knowledge and understanding, often in response to complex or ill-structured ideas, such as enhancement. Further, "reflective practice" is broader, encompassing the habit of reflecting on one's activities to improve practice. However, there are diverse definitions of reflection in the literature, often focusing on outcomes rather than processes (Moon, 2007).

Schön divides reflection into reflection-in-action (RIA) and reflection-on-action (ROA). RIA occurs during the action itself, where tacit knowledge is implicit in the action models. Reflection during action helps to overcome the dilemma between rigour and relevance and is influenced by surprise and experience. The speed of RIA depends on the duration of the situation. On the other hand, ROA occurs after the action has been completed to review and understand the actions performed in that situation. This process involves a more in-depth examination of the action and can lead to interactively defining ends and means, similar to a researcher operating within the context of practice.

Through my research, I have employed both RIA and ROA. During the development of each case study, I engaged in RIA, reflecting on my thinking and decision-making processes as they unfolded. This allowed me to refine my understanding of the phenomena under investigation and adjust my approach accordingly. Meanwhile, upon completing each case study, I conducted ROA by reflecting on my actions during prototyping, analysis, and interpretation. Through this process, I have critically evaluated my methods, identified areas for improvement, and distil key insights that inform this thesis and the design guidelines I present later in this chapter. This practical application of reflective practice in my research demonstrates its effectiveness and potential for other researchers.

To better define and refine my practice, I employ reflection to express and articulate my tacit knowledge. Through this process, I can uncover and make explicit the implicit assumptions, values, and beliefs underlying my actions, providing the reader with greater insight into my thought processes and decision-making habits.

3.2.2 Tacit Knowledge and Externalisation

Tacit knowledge (Polanyi, 1966) is knowledge that is difficult to express or articulate in words. It is often acquired through experience and practice and may be personal and subjective. Examples of tacit knowledge include a craftsman's understanding of using a particular tool or a musician's ability to improvise a melody.

Tacit knowledge and reflective practice are related in that reflective practice can make tacit knowledge explicit (Ravanal Moreno et al., 2021) and more accessible to others. By critically examining and evaluating one's experiences, a practitioner can gain a deeper understanding of their tacit knowledge and find ways to communicate it to others. In this way, reflective practice can be a valuable tool for sharing and disseminating previously tacit knowledge, an arguably fundamental activity in doing a Design Research PhD.

As a design practitioner, I often rely on sketches and low-fidelity prototypes to iterate between ideas. Although this feedback process might be taken for granted, it is rooted in the aforementioned theoretical traditions of Tacit Knowledge and Reflective Practice and the iterative cycle of making, reflecting and re-making. Specifically, the conversational aspects of the designer and artefact are highlighted in Glanville and Pak's (2010) work, which stresses how design practice benefits from thinking-while-doing. In other words, designing tangible artefacts allows externalising internal representations (Dix and Gongora, 2011). In practical terms, externalising the problem of enhancement technology helps ground the conversation, as much as taking out pen and paper helps add up 333374 with 6861783072 – a fundamental act that cybernetics and design share (Glanville, 2009).

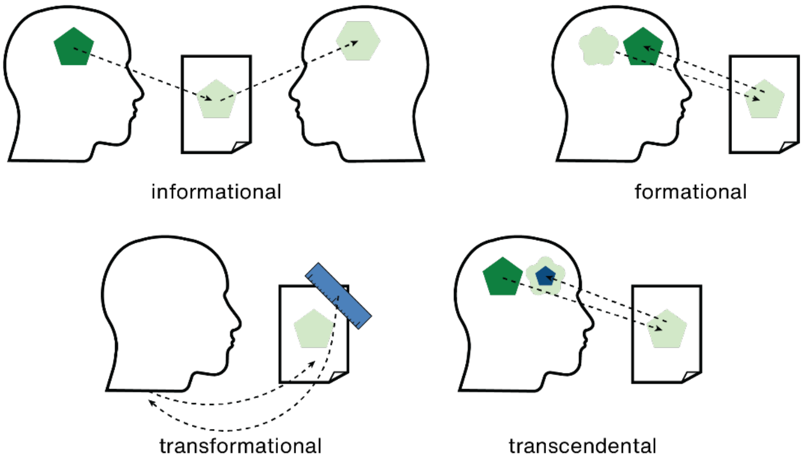

Figure 3.3 The four modalities of externalisation (Dix and Gongora, 2011). Informational externalisation *aims to convey existing thoughts or ideas from one person to another through written or visual means. Examples include engineering blueprints or packaging mock-ups.*

Formational externalisation *involves creating new ideas and knowledge through externalisation rather than simply presenting preexisting thoughts in an external form. An example is sketching.*

Transformational externalisation *provides an external representation with properties that aid understanding or planning. Examples include using a ruler, recording and playing back conversations, or touching a 3D print to verify its shape and smoothness.*

Finally, Transcendental externalisation *allows for examining thoughts and ideas as if they were external objects, making it easier to analyse their structure, strengths, and gaps. Mind maps, diagrams and academic papers are examples of this type of externalisation.*

My research used physical prototypes to externalise my thoughts about enhancement technologies. This method reflects the design tradition, where physical prototypes are essential because they are research tools to understand if and how a product, system or service works (Ulrich and Eppinger, 2011). Prototypes are also communication tools that express complex design ideas (Beaudounin-Lafon and Mackay, 2007, p.1007). Finally, prototypes are milestones to demonstrate the achievement of tangible results that move the design concept closer to production (Lauff et al., 2018). Specifically, following the externalisation modalities from Figure 3.3, my practice is both transcendental and formational, as by making wearable enhancements, I reflected on and reframed the fundamental assumptions, enabling the creation of a framework.

The literature identifies different classification modes and methods related to physical prototyping (e.g., Bogers and Horst, 2014; Buchenau and Suri, 2000; Lim et al., 2008; Michaelraj, 2009; Ulrich and Eppinger, 2011). In particular, Ruecker (2015) identifies three categories of prototypes: production-driven, experimental and provocative prototypes. Production-driven prototypes aim to develop a new product and often are incremental refinements of a pre-existing product, system or service. Experimental prototypes aim to produce knowledge about an idea that the prototype embodies so that it may be examined, understood, and tested. Finally, provocative prototypes do not lead to a product's development but are designed to provoke a reaction in the user. Provocative prototypes make a statement that challenges the expectations of the user.

According to the taxonomy presented by Ruecker (2015), development prototypes fall outside the scope of my thesis. In line with previous arguments, the problem of enhancement technologies is still in the incubation phase outside an industrial production context. However, experimental and provocative prototypes can be valuable tools for analysing and reflecting on the subject matter through practice.

An experimental prototype's purpose is to address a research question, explore and communicate it, and eventually evaluate the outputs of the design process. In this context, experimental prototyping is close to the concept of Experience Prototyping (Buchenau and Suri, 2000) discussed in this chapter's introduction. As part of this process, prototyping allows for understanding user experiences and the reference context, exploring and evaluating design ideas, and communicating the ideas developed. In Buchenau's words, "Experience Prototyping allows us to engage with new problems in new ways" (ibid., p.425).

The concept of provocative prototype can be found in Boer et al.'s (2013) research. The authors introduce Provotyping – a neologism that elides the words provocation and prototyping – as a tool for analysing current conditions and, at the same time, developing solutions through which to modify the same conditions. Returning to my earlier discussion of Critical Design, provocative prototypes embody criticalities. From them, alternative solutions are developed that challenge current cultural, social and economic models and established design practices.

In summary, externalisation can be framed as *working through* answers to the subject matter rather than *thinking it through*. As Hartmann et al. (2006) posit, design practice interacts with theory through a series of "conversations with materials" – such as sketching, 3D modelling, 3D printing and the craft involved in assembling a finished experiential prototype. In other words, design can be articulated as thinking-by-doing, where reflection on the work closes the loop between producing artefacts and producing new knowledge through the artefacts (Cross, 2006; Findeli et al., 2008; Jonas, 2007). Framing the loop between theorising and making as a conversation is further reflected in design cybernetics, which defines a conversation as the practice of making values explicit (Dubberly and Pangaro, 2019; Sweeting, 2015). In other words, the design-researcher makes theory *through* a pragmatic conversation with practice (Redström, 2017). I then reflect and collate my experiences, embodying them in a set of guidelines.

3.2.3 Experience Prototyping

Experience prototyping is the primary tool for validating the envisioned guidelines. This method derives from service design practice, where it is often impossible to prototype a complete service from end to end. Instead, service designers prototype some service instances, or touchpoints, to probe how the service's audience understands and reacts to it. As described before, these touchpoints are designed to understand, explore or communicate what it might be like to interact with a specific product, system or service (Buchenau and Suri, 2000). Experience prototyping overlaps with Critical Design, as it exemplifies larger systems and issues with a few designed pieces.

Experience prototyping is usually understood to deliver low-fidelity mock-ups of the intended experience. Given the highly nuanced and sensitive nature of enhancement technologies' subject matter, I choose not to develop low-fidelity design explorations, as they would lack the required subtleties to have fruitful conversations (even with myself). I instead developed fully functional prototypes intended to be reproducible by practitioners. In other words, I chose to translate philosophical discussions on the nature of enhancement and humanity – such as the ones outlined in the previous chapter – into a set of actionable artefacts that enable the wearer to experience the subtle matter of enhancement technologies.

Although useful for epistemological underpinning, Design Cybernetics and Affordance theories – discussed earlier – do not offer pragmatic guidance on approaching the complexity stemming from the embodied approach to enhancement technologies. However, Ashby's Law of Requisite Variety provides a starting point for approaching this complexity. Adapting this Law to enhancing technologies' specific context, the human or human-made agent senses' receptivity must be equal to or higher than the elements to sense. Rephrasing Ashby's postulate in this context helps design new sensory systems. If the agent wants (or needs) to access a hidden affordance in the environment, it must have the physical ability to sense it. For example, suppose a human agent wants to enhance its vision by sensing ultraviolet light. In that case, it must be presented with a sensory expansion system that integrates this new environmental information with its body.

Several wearables have targeted the integration of new environmental information with the wearer. Augmented Reality glasses, such as the Google Glasses (2013), Microsoft HoloLens (2016), and Epson Moverio BT-300 (2016), have been on the market for almost a decade; smartwatches, fitness trackers and several application-specific wearables are readily available for purchase in stores. However, as argued in sections 2.3.1 and 2.6, these wearables are tools that are not well-integrated with the wearer's body and lack the necessary design sensitivity for persistent integration. Instead, systems can effectively become new senses to the wearer if designed as persisting wearables tightly coupled with the body, effectively expanding its body schema in the near-body space.

From the notions of near-body expansion, Law of Requisite Variety and feedback loops, I have defined enhancement within this thesis as expanding an agent's senses in its environment to access hidden affordances. In the context of this research, sensory extension is achieved by designing wearable systems tightly coupled with the agent's body. I define this practice as sensory layering because it expands the wearer's knowledge of the environment by adding unobtrusive layers of novel sensory information conveyed through the wearer's pre-existing senses, as discussed in section 2.7. Reframing enhancement technologies in this way is in line with design practice aspirations. In Don Norman's words:

> *"The power of the unaided mind is highly overrated. Without external aids, memory, thought, and reasoning are all constrained. But human intelligence is highly flexible and adaptive, superb at inventing procedures and objects that overcome its own limits. The real powers come from devising external aids that enhance cognitive abilities"* (Norman, 1993, p.43).

In this research, I embody my explorations in enhancement technologies in wearable systems. I chose to position my practice within wearables for the reasons pointed out in section 2.7. In addition to those points, by definition, wearables are in contact with or in proximity to the body. Hence, they are a logical candidate for exploring enhancement technologies from an embodied perspective. Further, designing functional prototypes allows me to externalise my thoughts and approach to the subject matter.

As argued above, my practice-based approach to enhancement is centred around integrating reflective practice, tacit knowledge brought forward through externalisation, and experience prototyping. My approach recognises that meaning arises from the consequences and implications of contextual experience rather than from abstract theories. By continuously evaluating theories against the backdrop of practical applications, I acknowledge that even the most well-intentioned theories may not remain valid under changing circumstances. Instead, I focus on developing temporary stability through iterative prototyping, refinement, and testing of ideas, thereby embracing the emergent nature of the world. This situated perspective on human activity emphasises reciprocal capabilities of action and reflection, which inform my design approach. I bring tacit knowledge to the surface through reflective practice and externalisation, transforming it into explicit guidelines for future design decisions. My approach, as evidenced in the next section, is Pragmatic.

3.2.4 Research Approach: Pragmatism

As argued in 3.1, Critical Design artefacts, although helpful in stimulating much-needed design debates, are ill-suited to a programmatic approach to humanity's future (Sanzeni et al., 2019), as they do not integrate knowledge-making into the physical world, remaining instead confined to exhibition spaces. Buchanan (2009, p.417) expands on the integrative approach in his historical perspective on design, individuating Gropius and the Bauhaus as proponents of a pragmatic design strategy for achieving tangible outcomes through practice. He further pointed out Dewey's work as a foundation for developing Interaction Design (ibid., pp.418-419). Dewey's pragmatism builds on the idea that knowledge and beliefs are not static entities but are constantly evolving and changing as they are applied and tested in practice (Dewey, 1910, p.6).

Recent contributions indicate that Dewey's pragmatism has been a fruitful design research and practice framework (Dalsgaard, 2017, 2014; Dixon, 2020; Östman, 2005; Wakkary, 2009). Notably, according to Dixon (Dixon, 2020, pp.77-81), Dewey's pragmatism holds that it is the designer's responsibility to identify criteria to recognise a satisfactory outcome and declare the end of the design process. The designer also defines the scope of the problem and uses rules (or, in my case, design guidelines) to guide their work and externalise prototypes. This approach recognises that the knowledge gained through the design process is progressive and informs future work. In other words, no design inquiry is final, and new problem formulations can emerge and lead to new design solutions. This point strongly influenced my research, culminating in developing five pragmatic guidelines for designing wearable enhancements, as detailed in section 3.3.

3.2.5 How to Evaluate Practice-Based Research?

The framework presented in this thesis is rooted in a dialogue between design practice and theories, as practice-led research in design is particularly suited to addressing future and uncertain scenarios (Chow, 2014; Prochner and Godin, 2022), such as enhancement technology's problem and opportunity space. Nevertheless, there is little consensus on evaluating the quality of practice-led research (Prochner and Godin, 2022), especially as it would lead to evaluation following prescribed, *a priori* and repressive standards (Gaver, 2012). After reflecting on my practice, I tend to agree with Prochner and Godin's (2022) viewpoint of evaluating design practice within a pragmatic framework based on Dixon's (2020) contextualisation in design research of Dewey's philosophy.

Dixon (2020, pp.77-81) explains that Dewey's pragmatism suggests that designers must establish criteria to determine a satisfactory outcome and declare the end of the design process. The designer defines the problem and uses guidelines to guide their work and create prototypes, with the understanding that new knowledge gained can inform future work and potentially lead to new solutions. However, it is worth noting that this newfound knowledge may also lead to a change in the (self-imposed) brief, research question, and/or criteria. This freedom to revisit the brief, question, and criteria may seem alarming. Yet, it is one of the clear benefits of my solitary, reflective practice: I am beholden to no one and have not promised anything to a client or user.

Following Dewey's and Dixon's arguments, Prochner and Godin (2022) postulate that several research quality indicators emerge through a pragmatic lens. Firstly, practice-led research must be recoverable and transparent. Recoverable practice implies that the research results were made available to others by explaining how to reach the conclusions, so the audience can critically follow the practice's unfolding. Similarly, transparent research articulates a genealogy of thought that led to the design intervention. In this thesis, I first articulate the theoretical premise of my position, embodiment, tracing then how an embodied approach to enhancement technology led me to employ the lens of cybernetics and affordances to design wearable systems. Further, in each project, I explained the reasoning and doing that led to the three systems developed during this research. In addition, releasing the projects' outcomes as open-source hardware and software strengthens the reader's ability to scrutinise and critically evaluate them.

Although the problem space was narrowed down in the preceding text, I have yet to bring concrete and pragmatic guidance on designing wearable enhancements. Therefore, I developed a set of design guidelines to help other practitioners follow my methodology. I chose to compose a set of design guidelines as they capture design knowledge (Fu et al., 2016) without prescribing specific action.

The authors, although preferring the word 'principle', note in their review that the words principle, guideline and heuristic are often used interchangeably. They posit that a principle is "A fundamental rule or law, derived inductively from extensive experience and/or empirical evidence, which provides design process guidance to increase the chance of reaching a successful solution", a guideline is "A context-dependent directive, based on extensive experience and/or empirical evidence, which provides design process direction to increase the chance of reaching a successful solution" and a heuristic is "A context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution". As mentioned throughout this thesis, my work does not claim universality and, hence, cannot be classified as a principle. My work straddles Fu et al.'s (2016) definitions of guideline and heuristic, as it is both based on design and reflective practice. For simplicity, I use the term 'guideline' in this thesis. Some specific ways design guidelines can be helpful to other practitioners include:

- Providing a reference point for designers to consult when making decisions about a design in its early stages (Greer et al., 2008). Guidelines can help designers evaluate different design options and choose the one that best aligns with them.
- Facilitating communication and collaboration among designers, avoiding repetition and enhancing transferability (Singh et al., 2009; Weaver et al., 2008). Design guidelines can provide a shared vocabulary and understanding for designers working on a project, allowing them to discuss and evaluate designs more effectively.
- Guiding the development of design solutions that are effective and appropriate for the intended audience and context (Chong et al., 2009). Design guidelines can help designers consider agents' needs and goals and create designs that align with these needs and goals.

Developing design guidelines facilitates reflective practice by compelling me to articulate and formalise my tacit knowledge. By distilling my internalised expertise into explicit guidelines, I am forced to intentionally consider and refine my thought processes, making my assumptions and decisions more transparent. This externalisation of my knowledge enables me to better understand the underlying rationales behind my design decisions, allowing for a more systematic and reflective approach to design practice. It allows others to learn from my experience recorded in this thesis. As I formalise my guidelines, I must confront any ambiguities or inconsistencies in my thinking, leading to a deeper understanding of what constitutes pragmatic design guidelines.

3.3 Guidelines for Designing Wearable Enhancements

The reframing of enhancement technology through embodiment, cybernetics, and affordance theory in the previous chapter clarifies how enhancement is defined in this thesis as the practice of presenting to an agent hidden affordances in the environment. Nevertheless, it does not offer designers guidance on approaching the subject. It could be argued that designing wearable systems that simultaneously consider agents, environments, and interactions might be too broad a scope to produce useful results. This issue is not new for designers, as the field's recent history shows that the typical designer had to strongly specialise in a well-defined knowledge domain, given the quantity and complexity of the knowledge involved. The knowledge of unfamiliar disciplines required – whether in robotics, design or another constituent field – could give the aspiring innovator the false impression that they cannot engage with enhancement technologies.

I aim to assist designers interested in approaching enhancement technologies, reducing the effort required to design wearable enhancement systems. To this end, I outline design guidelines deriving from my research's foundations: design cybernetics and design practice. I did not formalise these guidelines at the outset of my research. Instead, my initial research pertained to developing exoskeletons to enhance human strength and mobility. However, reading through the literature on enhancement and, specifically, critical posthuman theorists, I realised, as documented in chapter 2, that many of enhancement's underlying assumptions were not addressed.

I observed patterns in my thinking and doing through many iterations of my experiential prototypes – which will be discussed in chapters 4 to 6. For example, I would first establish whether I was working with a human or a human-made agent. I would then brainstorm which hidden affordances would be beneficial for them to access and why. I would then dive into the practicalities of designing the prototype. These unconscious steps I took were eventually formalised in Guidelines 1 to 3.

Beyond the first three guidelines, while working on my second prototype, I realised the fundamental importance of positioning the wearable on a human body. I will give greater detail in chapter 5. However, as an overview, Zeagler's (2017) research updating Gemperle et al.'s (1998) work on designing for wearability clearly outlined a rationale for choosing on-body wearable positioning. For example, if a wearable is placed in a location that is difficult to reach or see, it may be less usable and convenient for the wearer. Similarly, a wearable placed in an uncomfortable or irritating location may cause discomfort or injury. Additionally, the location of a wearable can affect its ability to collect and transmit data accurately and its aesthetic appearance. This prototype allowed me to formulate Guideline 4, as detailed in the next section.

The outlier was Guideline 5, which underpins the fundamental importance of open-source hardware and software. This guideline – albeit informally – guided my research from the beginning. The reason is straightforward and pragmatic: I do not have formal training in electrical engineering, programming or robotics. I was able, nevertheless, to learn and action my knowledge, thanks to countless open-source designs. Specifically, I built an open-source robotic arm for the first two months of my research (InMoov, 2015), as shown in Figure 3.4. This project was developed by Langevin, a French sculptor and designer, and freely released. This experience impressed me with the open-source values of collaboration, sharing, and transparency, arguably central to advancing knowledge and the common good. Open source also challenges traditional models of ownership and control and promotes the idea that knowledge and resources should be freely available for the benefit of all.

Figure 3.4 Still from the GenerationRCA video (2019). The image depicts my first robotic exploration, where I 3D printed and assembled an open-source robotic arm, which I extended with custom electronics to control it using my muscle contractions.

I learned the practical skills of reading schematics, designing printed circuit boards and programming thanks to the documentation and support available through the open-source community. Therefore, I felt that open-source hardware and software would be a necessary consequence of my own design outputs, despite being offered the opportunity to do otherwise. In chapter 6, the reader will be introduced to a novel headset that employs bone and soft tissue conduction to convey high-fidelity audio to the wearer without occluding the ear canal. I was offered the opportunity of patenting the device, and decided not to pursue this route as it would defeat a key purpose of my research. As I stated several times in these first two chapters, part of my critique of Critical Design is that it falls short in its aspirations of being available to and usable by a wide audience. This experience showed me the necessity of spelling out that designers should where possible focus on accessibility to wider audiences.

3.3.1 The Five Guidelines of Designing Body-centric Sensory Enhancements

As discussed above, a design guideline in my research is a context-dependent direction deriving from externalising tacit knowledge that guides achieving a satisfying but not necessarily optimal solution. These guidelines cut across the specialist domains of knowledge such as robotics and design and are intended as the starting point for developing experience prototypes rather than a fixed checklist that would lead to predictable results. I devised these prototypes to help me envision, embody and probe how modern technologies can be applied to an agent's body to enhance its cognitive abilities and knowledge of the world in which it is embedded.

I briefly introduce the five guidelines emerging from my practice here before I discuss them in more depth in the later chapters.

Guideline 1: Establish hidden affordances.

When approaching a wearable enhancement system design, the designer should scope which hidden affordances the wearer would like to access. To help scope the possible affordances, the designer can refer to the biological world. Many animals present sensory systems that humans do not have, such as turtles, dogs, and bees which sense the Earth's magnetic field to navigate their environment (e.g., Hart et al., 2013; Liang et al., 2016; Lohmann, 1992). Sharks and bumblebees can easily perceive electric fields to reach their prey (or flower) (England and Robert, 2022). Other hidden affordances could include chemical interactions in ripening fruit, radiation, infrared, and ultraviolet light emissions. In determining which hidden affordance to design for, the designer must consider the intended agent, human or human-made. This guideline can be phrased as a question: What previously hidden information can the agent acquire from the environment?

Guideline 2: Determine which sense to layer.

I argued previously that enhancement technologies should increase the wearer's sensory variety to better interact with an information-rich environment. To this point, the designer should consider the pre-existing sensory variety in the agent to enhance. As presented here, the essential argument of sensory layering is that each agent's body is unique, and new senses should be layered onto pre-existing sensory systems. Translating this guideline to practice, the designer should approach the agent's body with sensitivity, considering what senses are pre-existing and developing wearable systems that leverage them. Capitalising on existing senses is a fundamental aspect of sensory layering (Eagleman and Perrotta, 2023). Learning from others' experiments on expanding the body schema, it is clear that the wearer's body may need training to adjust to the new sensory layer. This guideline is formulated so the designers can ask: Which of the agent's pre-existing senses should I address with data acquired via the wearable system?

Guideline 3: Establish sensory feedback loops.

Once the hidden affordance and the sense to layer are established, the designer must determine the feedback loop that conveys the new environmental information to the wearer. These feedback loops are necessarily body-dependent and, as such, should leverage the body's characteristics. Possible feedback loops can be based on haptics, visual feedback, changes in temperature, inflation or deflation of soft robots, audio feedback, or other means. The feedback loops should be established following the previously discussed forms of sensory substitution. The designer aims to create a wearable communication interface between the agent's body and the hidden affordance. This communication interface should feel natural and unobtrusive, providing the wearer with real-time access to the chosen hidden affordance.

Most interactions between the agent and the wearable system involve microinteractions (Aleksy et al., 2016). These are contained interactions lasting less than four seconds (Ashbrook, 2010) that accomplish a single task by interacting with a single piece of data (Saffer, 2013, p.5). For this reason, particular attention should be paid to the interaction model between agent and wearable. Levin (2014, p.104) introduced three interaction models relevant to these applications:

1. **Manual:** occurs when the agent initiates the interaction. E.g., when a human agent taps on a smartwatch to view a notification.
2. **Semi-automatic:** occurs when the agent is alerted by the wearable to a system change that requires their attention. E.g., when a vehicle shows warning labels on the dashboard.
3. **Fully automatic:** when the wearable interacts with the agent without direct input. E.g., cloud-enabled electroencephalogram systems (Kelati and Tenhunen, 2018).

Guideline 4: Determine the wearable enhancement system's placement on the body.

When the wearable enhancement system's placement corresponds with its intended function and feedback loop, the design will perform as intended and be more comfortable to wear, use, and interact with. Several considerations are emerging from the literature (Gemperle et al., 1998; Zeagler, 2017):

- **Movement**: the sensing unit should be placed on the agent's body-part of interest to capture information accurately. For example, if the designer is interested in tracking an agent's posture, they should position sensors near the centre of mass, such as the waist in humans (Karantonis et al., 2006).
- **Proxemics**: the wearable's placement should follow the agent's perceived size of their body. Wearables should be located within an intimate distance (Hall, 1988, pp.117–118) – e.g., 0-5 inches from the skin. Wearables can extend beyond this range in some areas of a human agent's body as long as they do not interfere with their ability to move freely (Zeagler, 2017).
- **Reachability**: when designing for human agents, the wearable should be designed for self-donning (ibid) rather than requiring installation by a second agent.
- **Social acceptability**: designers should avoid placing wearables in interaction areas critical to the agent's body interaction with other agents (e.g., genitalia). Special care should be used when video-based sensors, such as cameras, are selected, as they raise questions on privacy from third parties.
- **Thermal tolerance**: heat-generating elements, such as processors and batteries, should not be placed close to the skin.
- **Weight**: the wearable should not hinder the agent's movement or balance. As a helpful heuristic, the wearable should be placed close to the agent's centre of mass.

Since wearables are inherently positioned on the body, the designer should focus on the agent's sensitivity. These considerations should focus on delivering the best wearer experience possible. To achieve this, the designer should consider the specific agent's tolerance to wearing a piece of technology. From there, ergonomics, materials, hardware, and software can be designed to integrate seamlessly with the wearer. This guideline can be interpreted in two ways, depending on designing for a human or a human-made agent. In the former case, the designer should include the wearer throughout the design process to establish comfort levels, whether the feedback loops suit the wearer, and develop a highly compatible solution for their body. In human-made agents, the designer's sensibility should be directed towards mechanical compliance, minimising potential conflicts between sensory systems and ease of integration with a pre-existing system.

Guideline 5: Design for accessibility and distribution.

As noted in the introduction chapter, one of the key sources of anxiety for people when discussing enhancement is how opaque these technologies are. Wearable systems in the market are usually black boxes, where the wearer does not have access to or knowledge about the system's inner workings. Although arguably justifiable for protecting intellectual property, this approach hinders trust and transparency between the wearer and the wearable, especially for human agents. Designers and roboticists should develop wearable enhancement technologies with accessibility and openness in mind to begin addressing this issue. An open approach to developing enhancement systems would allow more designers, roboticists and other researchers to approach the subject. It would allow for a better understanding of the envisioned solutions, both in design and technological terms, leading to better-informed decision-making about the feasibility and expected results. Finally, well-documented designs and implementations are excellent tools for education, offering a compelling introduction to interdisciplinary research and practice.

The reference framework for this last guideline stems from the sociotechnical phenomenon of Open-Source Hardware. This emerging movement takes the approaches of open-source software – namely, (i) identify a suitable subject matter, (ii) build on top of previous open-source projects, (iii) if possible, solve the problem by leveraging on parallel work of contributors, (iv) iterate fast and (v) document and circulate your findings (Weber, 2004, pp.73–82) – and extends them into the physical world (Balka, 2011, p.4). Generally speaking, open-source practices for hardware and software share a willingness from the contributors to support a distributed, informal and individual-scale production. This approach presents the advantages of democratising technological production and lowering the environmental impact by enabling local production (Bonvoisin et al., 2017). Furthermore, it is documented that open-source approaches positively impact the economy, with an estimated between 50 and 80 billion Pounds in the EU (Blind et al., 2021, p.202).

Guideline 5, therefore, addresses two key aspects of openness. First, users of enhancement technologies need to be adequately informed about what the technology is doing and how it works, empowering them with the knowledge to make informed decisions. Second, openness facilitates the ability of new practitioners to build effectively on prior work, largely removing the implicit connotations connected to the meaning of enhancement, as discussed in chapter 2.2.

3.3.2 To User-Test or Not to User-Test?

At this point in the thesis, the reader might expect an account of the methods employed to collect feedback from individuals interacting with the wearables I prototyped. However, in my research, I focused instead on employing the reflective practice methods outlined in section 3.2. Therefore, this section outlines some recognised methods and benefits of user testing, but emphasises its disadvantages and the rationale for not employing it in my research.

User testing is a method of evaluating a product or service by testing it with representative users. The main advantage of user testing is gaining insight into how users interact with a product or service. Designers can identify usability issues, pain points, and areas for improvement by observing and receiving feedback from actual users via several standard methods.

Usability testing (Albert and Tullis, 2013; Dumas, 2002) involves observing users perform specific tasks and collecting data on their performance and experience, which can be conducted in-person or remotely. Similarly, in-person and online interviews (Kozinets, 2015; Sellen, 1995; Thunberg and Arnell, 2022) entail conducting one-on-one or group interviews to gather user feedback, offering the flexibility of structured or unstructured questioning. Surveys (De Vaus, 2013) involve distributing questionnaires to users to collect responses about their experiences. These questionnaires can be administered online, by mail, or in person and effectively provide quantitative and qualitative data. Focus groups (Barbour, 2010) bring together small groups of users to discuss and provide feedback on a product or service, with a facilitator moderating the discussion and encouraging participation. Lastly, diary studies (Blandford et al., 2016; Carter and Mankoff, 2005) require users to log their experiences over a set timeframe, yielding insights into user behaviour in their everyday environment.

However, user testing is fundamentally an evaluation methodology rather than a creative one (Cooper et al., 2014, p.140). In other words, user testing can be characterised as *knowledge sharing for refining existing knowledge*. Similarly, as Norman and Verganti (2014) posit, human-centred approaches to innovation (including user testing) are often driven by a focus on efficiency and cost-cutting and can lead to products similar to existing ones but with slightly improved features or functionality.

Radical innovation, on the other hand, does not necessitate a formal assessment of individual or societal needs (Norman and Verganti, 2014, p.79). Design-driven innovation, in particular, seeks to propose radically new meanings and languages, as shown in Figure 3.5. These new meanings frequently imply a shift in social understanding (Verganti, 2008). Moreover, such innovations are open to creative engagement and inherently susceptible to unexpected or unintended uses by their audience (e.g., Gaver et al., 2007). Gaver's open-ended user trials are a notable example of how design can embrace these unanticipated uses. Unlike traditional user testing, which optimises towards a predefined goal, Gaver's approach is deliberately ludic – as discussed above. These trials are not about closing down options, but rather about opening them up, allowing users to interact with the design in ways that may diverge from the designer's original intent, thereby uncovering novel applications and meanings. In other words, the contextual reframing (Paton and Dorst, 2011) of the designed object surfaces new meanings.

Figure 3.5 Norman and Verganti's (2014) refinement of Stoke's (Stokes, 1997, p.73) Design Research Quadrangle. Whereas human-centred research concerns people's current understanding of products, inevitably leading to enhancing existing product/system/service categories, design-driven research (i.e., what I am presenting in this thesis) aims at "envisioning new meanings" to then apply to enhancement.

Although I do not claim radical technological innovation in my research, I argue for introducing a new framework (i.e., new meaning) for designing enhancement technologies, as shown in Figure 3.6. While user testing tends to focus on immediate reactions to the design object or service at hand, I am interested in the epistemological shift from ‘normal’ as the reference for enhancement to the agent’s body. Further, whilst user testing is useful when determining the pragmatics of functionality and aesthetics, these two elements are not the focus of my research.

Figure 3.6 Norman and Verganti’s (2014) Two Dimensions and Four Types of Innovation. In this research, I do not propose radical technological change; rather, I use novel combinations of off-the-shelf technologies, as argued in the following chapters. My framework proposes a new stance when addressing enhancement – falling in the ‘meaning-driven innovation’ category.

With a focus on designing for a broad audience, as evidenced in Guideline 5, my reflective practice aligns with, for example, the tradition of knowledge generation of the Royal Society and the Académie des Sciences from the 17th Century onwards. Specifically, the Royal Society decided “to adopt the plain language of artisans rather than that of wits” (Knight, 2002) to encourage the development of the sciences.

In summary, knowledge generation does not always hinge on applying user testing methods in the design process. User testing is particularly well-suited to situations where designers need to identify specific pain points, usability issues, or areas for improvement based on user feedback. In such contexts, the iterative testing, feedback, and refinement process allows for incremental enhancements that align with user expectations and needs.

However, my work pursues a different trajectory. First, user testing is inherently evaluative, focused on refining and validating existing knowledge rather than enabling the creation of new frameworks. This point makes it less compatible with my goal of proposing a new framework for enhancement technologies. Secondly, user testing prioritises short-term, surface-level interactions with the design object, contrasting my interest in exploring deeper epistemological shifts. Third, while user testing emphasises the pragmatics of functionality and aesthetics, these are not the primary concerns of my research, which instead prioritises the interaction between broader theoretical questions and design practice. Finally, user testing often leans toward developing solutions that meet the immediate needs of a broad audience, whereas my approach, rooted in reflective practice, seeks to generate new meanings and languages that may challenge conventional understandings and norms.

3.3.3 Design Tensions and Briefs

At this point, the reader will realise that much of my research lies between tensions: the human and the human-made, enhancement and augmentation, Cartesian dualism and embodiment, to name a few. This concept of design tensions is central to my approach. Design tensions refer to exploring and balancing conflicting forces or ideas within a design process– the gap between *what is* and *what should be* (Card et al., 1990). Unlike other methods, which often focus on clearly defined problem spaces, I engage with these tensions as fluid elements that shape the design process rather than merely constraints to be resolved.

However, framing design as an exploration of tensions and their resolution contradicts many contemporary design practices. These approaches, referred to as Design Spaces (Card et al., 1990) or the Fundamental Method of Design (Jones, 1992; Matchett and Briggs, 1966), often focus on directing attention towards a bounded set of choices, typically presented as tables or categorisations, as shown in **Error! Reference source not found.**.

Figure 3.7 Elaboration of Harrison et al. (2006) sandwich solutions Design Space. This design space illustrates the bounded choices in creating sandwich combinations, with each cell representing a unique combination of bread, filling, and condiment. While the space can be expanded to accommodate additional options, it struggles to represent more complex relationships or n-dimensional solutions, such as a club sandwich. The tabular format emphasises exploration within the defined design space but may downplay the importance of selecting a specific solution outside its boundaries.

The Design Spaces approach emphasises navigating within a defined scope, where the choices are independent, and the goal is to explore combinations of elements within that space. This method helps develop solutions by systematically exploring and refining options, often through categorisation or bounded sets of choices. While this approach has its strengths – namely, it allows for approaching problems as a combinatorial exercise – it also has limitations. It can neglect complex relationships between social and technological aspects of system design and struggle to represent more than two dimensions or complex interrelationships.

In contrast, my approach focuses on design tensions, which are not confined to a predefined space. Design tensions help identify and navigate the competing considerations that can shape a system's success or failure. This method is unbounded, non-categorical, and extensible (Tatar, 2007), allowing for a more expansive analysis that integrates various paradigms to inform design choices, such as the guideline-informed framework I present in this thesis.

So, how do I frame my research pragmatically if I am not exploring design spaces but design tensions? I chose design briefs as the frame for my thinking, prototyping, and reflection. As mentioned, my design briefs are self-imposed and serve as a guiding structure that allows me to explore the design tensions within my work. This autonomy in setting briefs allows my practice-based exploration to articulate the key tensions I wish to explore, which are most pertinent to the enhancement problem. Further, self-imposed design briefs are quite relevant to my position as a researcher: I conducted this research without the backing of a funding body, allowing me to fully self-direct the research.

As argued in this thesis, the problem of enhancement is not bounded but, very similarly to the cyborg and the assemblage, is a porous entity that can be approached from many vectors. By providing five guidelines, I offer an initial substrate for other practitioners to examine the matter from their perspective. The guidelines, in a specific context bounded by the brief, determine the tension space for my investigations, as shown in **Error! Reference source not found.**.

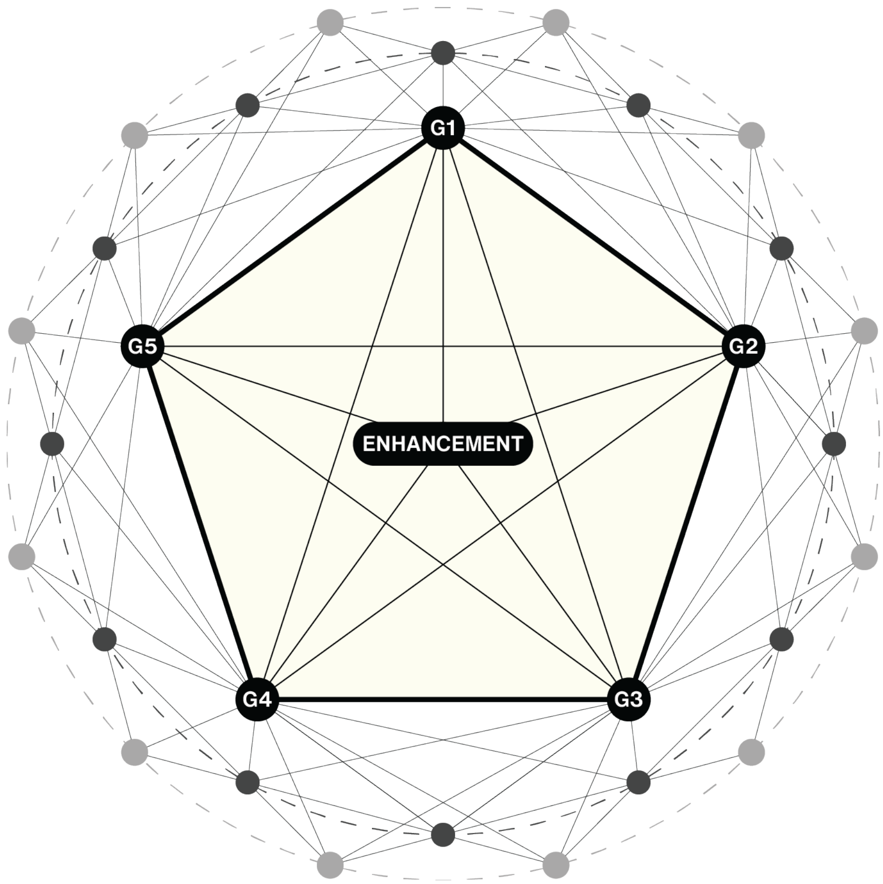

Figure 3.8 The design tension space bounded by the guidelines (G1 to 5) and by the design brief (in yellow). The orbiting circles show that there are – potentially – unlimited other guidelines, tensions and concerns surrounding the enhancement problem, which were not the focus of my research.

My definition of a design brief in this context includes four elements: objectives, requirements, constraints, and criteria. The *objectives* define the primary goals of the design, such as ‘design a new sensory layer for robots’ or ‘create a wearable device for affording hidden health metrics’. The *requirements* specify the conditions or constraints necessary to achieve these objectives, such as ‘the new robotic sense should use pre-existing communication protocols' or 'the wearable device should have a battery life of at least 24 hours'. *Constraints* are the boundaries within which I must work, including limitations such as budgetary constraints or regulatory requirements, like 'the project has a limited budget of £100' or 'the design must comply with MHRA regulations for medical devices'. Finally, the *criteria* are the metrics used to assess the success of the design, which might include factors like 'body integration', 'accuracy', or 'sonic fidelity'.

By focusing on design tensions rather than design spaces and setting my own briefs, I can explore enhancement from an expansive and reflective perspective. This approach allows me to engage with the enhancement problem in a way that is open-ended, adaptable, and responsive to the complexities of the subject matter. In this context, (re)framing enhancement technologies around the agent's body becomes a crucial creative process (Paton and Dorst, 2011), enabling the design of both buildable and desirable prototypes while enabling a dialogue between the experiential and the theoretical. Through this reflective practice, design emerges as a tool for innovation, offering a new and distinct lens for approaching technological advancements (Dorst, 2015, pp. 143–144). As I will detail in the next three chapters, these briefs started as a simple question and co-evolved with my practice, as concisely described by MacCormack in conversation with Cross (1999):

> *"I don't think you can design anything just by absorbing information and then hoping to synthesise it into a solution. What you need to know about the problem only becomes apparent as you're trying to solve it".*

The Design Briefs and the PhD

In my PhD, each design brief serves a dual purpose: it functions as a pragmatic tool for invention within the space of enhancement technologies while also deepening my theoretical understanding and addressing my research question. This approach aligns with the conversational and cybernetic structure that underpins design as a practice. Drawing from Schön's (1983, pp. 76–104) "reflective conversation with the situation", design involves a constant back-and-forth process, where ideas are explored and revised by designing itself. This circular process is not just a technical exercise but a fundamentally epistemological one, in which the designer's interaction with their methods, tools, and context shapes the knowledge that emerges.

Glanville's (2007) assertion that "cybernetics is the theory of design and design is the action of cybernetics" reinforces the idea that both disciplines are concerned with constructing the new. In my case studies, I engage in this "forward-looking search" (Pickering, 2011, p. 18), using the design process to generate new enhancement technologies and refining my Guidelines rather than simply replicating existing models. This approach positions my work not just as a series of representations but as a performative exploration of ideas – much like the experimental devices used by early cyberneticians such as Schöffer and Pask, as discussed in section 2.4.

Each case study is an experiment in this sense: practical work that grounds abstract concepts in concrete practice and contributes to the ongoing theoretical conversation about enhancement. The methods I use in my prototyping are not merely representations of pre-formed ideas but are integral to developing those ideas – a way to externalise my internal representations (Dix and Gongora, 2011), as discussed in section 3.2. Therefore, each design brief is not just a practical task but a method of inquiry that advances both the field of enhancement and my understanding of how design can rethink these approaches – a way to understand my main research question better.

3.4 Conclusion

This chapter presents my practice-led research methodology, which combines reading, theorising, making, reflecting, and synthesising to generate transferable design guidelines for practitioners working with enhancement technologies. By developing three experiential prototypes, I demonstrate tangible future interactions with enhancement technologies by designing experiential prototypes that address specific human and human-made navigation challenges.

These case studies, which I will detail in the following three chapters, embody one possible answer to a design brief rather than claiming universality. This reflects the iterative nature of design practice, where solutions are constantly evolving. The underlying concepts, however, aim to be transferable to other contexts relevant to enhancement technologies, demonstrating the potential for generative frameworks to guide practitioners in their own work.

In relying on physical prototypes as research tools, I have drawn upon a design tradition that recognises the importance of tangible representation in externalising thoughts and planning future iterations. This approach has allowed me to reflect on instances of enhancement technology and generate transferable design guidelines that can be moulded and reshaped by others' practices.

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4 Case Study 1: Designing Redundant Actuation Systems for Enhanced Resilience Through Sensory Layering

4.1 Introduction

This thesis has so far presented the theoretical and methodological basis for designing enhancement technologies. This chapter and the two following contextualise the design guidelines in real-world experiential prototypes. This section explains how design guidelines relate to prototyping enhancements for human-made agents. My decision to focus on human-made agents for my first investigation stems from the rationale presented in chapter 2. If agents understand the world by moving and interacting with it, one necessary consequence is that the requirement to describe species-typicality to determine enhancement is eliminated. The body of each agent serves as the frame of reference and, thus, the starting point for enhancement. The primary goal of this chapter is to determine if conventional robotic actuators like brushless motors benefit from the design-led enhancement paradigm proposed in this thesis. Actuators are electric, hydraulic or pneumatic devices that allow a robot to move and apply forces in controlled ways (Lynch and Park, 2017, pp.1–10, 304). For clarity, I use the terms *motor* and *actuator* interchangeably in this chapter, while I refer to the redundant system I designed as the *actuating assembly*.

Designing redundant actuators capable of continuing to perform the required activity when under threat of partial breakdown is an active area of research (Gosselin and Schreiber, 2018; Martín-Barrio et al., 2020; Seetohul and Shafiee, 2022; Xu et al., 2019). In this project, I propose applying sensory layering to develop a resilient actuation system based on K-means clustering[8]. The resulting actuating assembly can predict abnormalities in its motion system caused by irregular motion behaviour using a deep learning[9] fault detection algorithm[10]. Section **Error! Reference source not found.** details the rationale for choosing deep learning, its relevance to this thesis' main argument and its implementation in this use case. The system then activates backup motors autonomously to continue performing its intended purpose. On a conceptual level, the experience prototype reported here exemplifies the guidelines of enhancement technologies by layering the actuator with a sense of proprioception. I define proprioception in this application as the robotic system's ability to continuously assess its actuating system to predict malfunctions in advance and recover owing to a redundancy system. As a result, when installed on a robot, the proposed actuating assembly increases the agent's degrees of freedom (Chiaverini et al., 2016), enhancing the robot's resilience. It is important to note that, whilst the actuating assembly proposed in this study employs deep learning to

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[8] Clustering is a technique for organising data in an unsupervised way, that is, without the use of examples as a basis for learning. Each cluster represents a different class. K-means is one of the most widely used and effective clustering techniques. K-means is based on the centroid, a feature space point that averages the distances between all data in the cluster associated with it.

[9] Deep learning is a subset of machine learning. While the latter aims at creating artificial systems that learn and adapt through data or experience, deep learning is a specific machine learning technique employing artificial neural networks – hierarchical algorithms inspired by the brain's neurons.

[10] Algorithms that enable predictive maintenance rather than addressing errors after they occur, hence decreasing the time and expenses involved with unplanned equipment downtime.

predict future faults at a component level autonomously, it does not offer an adaptation mechanism to the fault beyond switching to its redundant system.

The prototype I developed[11] features a mechanical assembly of two brushless motors coupled to a common axle. One of the pair's motors is engaged during operation, while the other is electromechanically isolated from the rest of the system. A microprocessor communicates with an accelerometer[12] to continuously sample the motor's vibrations. The microcontroller processes the time series data with a K-means clustering deep learning algorithm, anticipating anomalies in the motors' operation pattern. If the motor's vibrations exceed their operational threshold, the actuating assembly's controller autonomously isolates the malfunctioning motor, switching to the backup motor.

Fault prediction algorithms are becoming crucial in automated and autonomous systems to ensure high robot safety and reliability levels. Consequently, the scientific community has made substantial efforts in recent years to develop systematic methods of fault prediction and detection in many types of robotic systems (Abaei and Selamat, 2014; Abbasi et al., 2018). The literature reported emphasised robotic systems operating in hostile or isolated environments where a high level of safety and exceptional self-diagnosis capacities are desired. Furthermore, developing fault prediction systems for industrial robots is vital to ensuring safe human-machine interaction and securing the system's quick and appropriate response to the onset of atypical and potentially dangerous situations (Abid et al., 2018). Redundancy, or the inclusion of additional sensors or actuators in the robot's architecture that can grant backup in the event of malfunctioning, is a fundamental property of robots for withstanding abnormalities (Abid et al., 2021; Abid and Khan, 2017). Artificial Intelligence (AI) fault detection for motors and robotic applications is a developing focus of study with the potential to reduce downtime and boost the efficiency and reliability of robotic systems – a recurring and unmet industrial requirement (Cusido et al., 2011; Shamilyan et al., 2022; Yunusa-Kaltungo et al., 2014).

The actuating assembly described in this chapter has several applications. Redundant actuators have historically been recognised as essential in outdoor or rough terrain applications and safety in human-robot applications (Qiang Huang et al., 1998). More recently, researchers evidenced the potential of dexterous robotic arms equipped with redundant actuators to transform industrial contexts such as infrastructure repair, disaster response, casualty extraction and logistics (Danko and Oh, 2014). Other potential applications are mobile robotic platforms for robot-human interaction in domestic unstructured environments (Carbonari et al., 2021), mobile humanoid robots (H. Wang et al., 2021), automated warehouse systems (F. Zhang et al., 2020) and large-area remote exploration (Gan et al., 2021). The actuating assembly presented in this chapter could be adapted to any of the scenarios described.

This chapter first presents the role of AI in robotic applications, then covers existing research on designing redundant robotic systems based on machine learning algorithms, highlighting the field's existing challenges. Following that is a methodology for developing resilient robots using sensory layering guidelines, followed by implementing a redundant robotic actuating assembly. This chapter concludes with the findings of the design-led inquiry, their significance regarding the literature, and this thesis's central hypothesis.

[11] The GitHub repository for my prototype can be found following this link: https://github.com/fsanzeni/Redundant-Actuation-with-Sensory-Layering
[12] A sensor capable of measuring minute fluctuations in acceleration in three dimensions.

4.1.1 Design Brief

The following table summarises my self-imposed design brief guiding this case study. I include two columns, one about the objectives, requirements, constraints and criteria for this specific case study and the other regarding the overarching thesis. My initial question was: *Can we enhance human-made agents with sensory layering?*

	Case Study	**Research**
Objectives	Establish sensory layering guidelines in a real-world robotics use case.	Explore if and how sensory layering can enable human-made agents to access hidden affordances.
	Enhance the robot's control system awareness via AI.	
	Design a preventative, redundant hardware system with increased degrees of freedom.	
Requirements	The software solution should be implemented on a central processing unit with limited computing resources. It must use commercially available sensors to detect unexpected variations in the actuator's rotation.	Design and document the integration of new sensory layering systems, assessing how this integration influences the robot's ability to perceive hidden affordances.
	The enhancement system must integrate with the centralised controller.	
	Redundancy should be achieved without significantly increasing the cost of the final solution.	
Constraints	The agent's body is electro-mechanical, requiring integration with existing communication channels.	Given my limited robotics experience, the primary goal was to produce a working prototype that demonstrated the core concept rather than optimising its performance.
	The designer should exercise caution when determining the system's position on the body to ensure ease of integration and mechanical compliance and avoid conflicts with pre-existing sensory systems.	
	Third-party access to the enhancement system must be considered, and open-source and widely available hardware and software should be favoured whenever possible.	
Criteria	The enhancement system should leverage existing communication protocols for feedback.	Verify whether sensory layering and the design guidelines apply to human-made agents while being generalisable across different wearable robotic systems.
	The system should be positioned close to the motor and mounted rigidly to maximise sensor accuracy.	
	Off-the-shelf hardware or custom solutions should be freely accessible by third parties.	

Table 4.1 The design brief for my first case study.

4.1.2 Embedding Artificial Intelligence in Robots

Computing power, along with the most recent algorithmic techniques, indicates that AI is now ready for widespread use in real-world applications (Mukhopadhyay et al., 2021). AI applications in industry have flourished in recent years, providing enormous opportunities and challenges for designers and developers. Some applications include decision assistance, customer and employee interaction, automation, new service and product offerings (Borges et al., 2021), confidence, reliability, and data validation for intelligent systems (Mukhopadhyay et al., 2021).

The project discussed here focuses on enhancing the robot's control system awareness via AI. The definition of AI adopted throughout this project follows the European Commission's (2018) working principle, which refers to systems that display intelligent behaviour by analysing their environment and acting – with varying degrees of autonomy – to achieve their goals. The AI system in this chapter is integrated, implying that it comprises AI software embedded in a hardware platform (ibid). An integrated AI system, in general, includes four distinct sub-systems: (i) sensors for environmental perception, (ii) sensor data processing algorithms, (iii) decision algorithms to act on sensor data, and (iv) actuation. Whereas in traditional integrated AI systems, engineers select the robot's sensors and algorithms to boost its performance, in this project, I propose layering sensors to improve the robot's awareness of itself to prevent failures in its locomotive system.

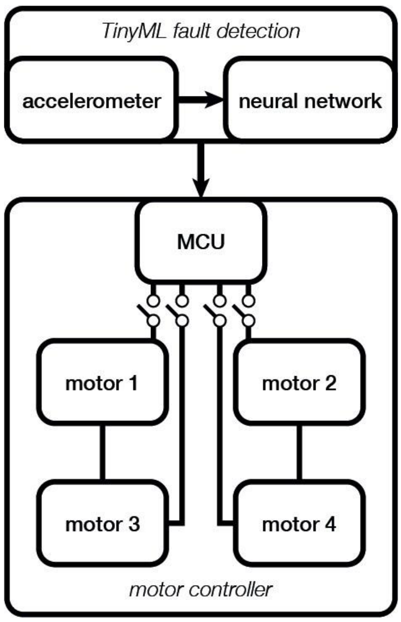
The three core features that define a robot (sensing, processing, and actuation) demonstrate the lively link between AI and robotics. A robot's degree of autonomy is measured by its ability to sense and respond to its environment. In other words, the body of the robot and its sensory and motor abilities are pivotal to its efficacy in executing prescribed tasks. Similarly to what I discussed previously, I consider the robot's body the reference point for designing sensory enhancement technologies.

This project consists of two development stages: (i) a software system that can run on a microcontroller with limited computing resources, and (ii) a redundant hardware system. The solution I implement for the software focuses on Tiny Machine Learning's (TinyML)[13] emerging field. TinyML is a tool for developing deep learning algorithms that execute autonomous learning operations on devices with little processing power, such as microcontrollers and embedded devices. Running machine learning models on embedded devices is advantageous for this project for three reasons. Firstly, it is possible to avoid transmitting sensor data to an external computer for processing and elaboration since the algorithm executes locally on the microcontroller. As a result, a constant internet connection is not required, resulting in fewer costs and bandwidth constraints. Second, TinyML algorithms run on microcontrollers that require extremely little power, on the order of one milliwatt or less, reducing the robot's reliance on battery recharges. Finally, microcontrollers are cheap and readily available, lowering the barrier to entry for designers interested in the field.

This study proposes doubling the number of motors to implement a redundant actuating assembly. My decision to increase the number of motors – and, as a result, the robot's degrees of freedom – is consistent with the existing literature on redundant systems. I developed a coaxial design for the motors in which motor pairs share the same rotating shaft. Figure 4.1 depicts an overview of the

[13] TinyML stands at the intersection of Machine Learning and the Internet of Things (IoT). It can be understood either as "serving Machine Learning to IoT devices" and "processing Machine Learning within IoT devices" (Sanchez-Iborra and Skarmeta, 2020). My case study is aligned with the second definition, which implies that the robot's controlling unit interfaces with sensors and is able to execute predictions on the sensor's data without requiring a connection to a Cloud infrastructure (Dutta and Bharali, 2021).

robot, highlighting the two primary sub-systems. The first sub-system includes the TinyML algorithm on a microcontroller[14] monitoring accelerometer data. This microcontroller samples the motor's vibrations emitted during operation, inferring abnormalities when the motor's operational parameters exceed a defined threshold. When the first sub-system notifies it, the second sub-system switches to the backup motors. The final prototype consists of two redundant actuator assemblies (each consisting of an axle coupled to two motors) mounted onto an aluminium frame.



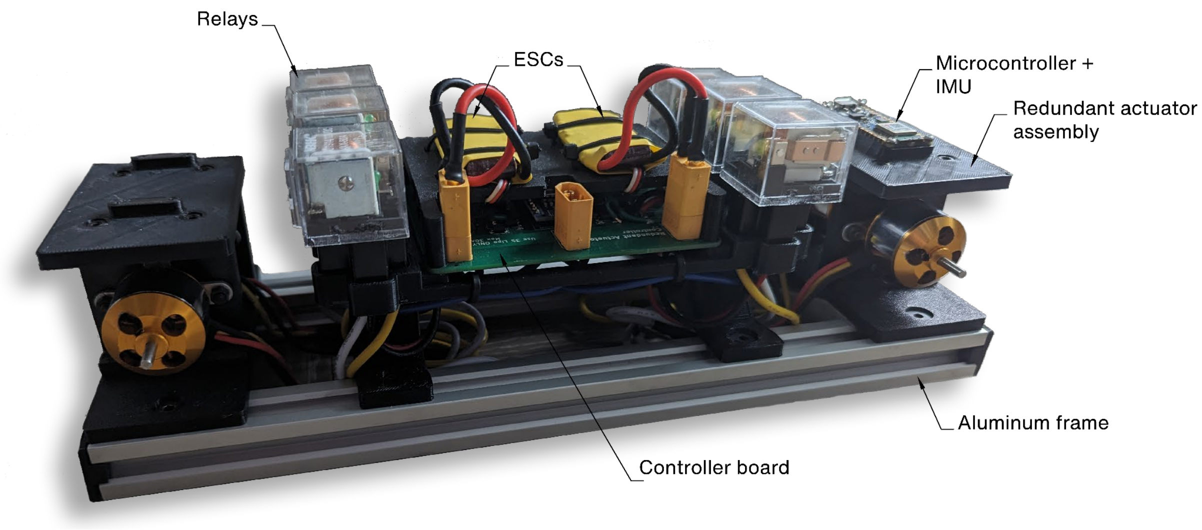


Figure 4.1 Overview of the resilient actuating assembly and experimental setup. A deep learning fault detection system running on the microcontroller determines which motor in the pair should be activated if a fault is detected.

4.1.3 Robots at the Edge: The New Design Paradigm of AI

Designers of 'smart' items, such as Internet of Things (IoT) devices, traditionally follow the established Cloud computing model, where Internet-connected data centres process the data from the smart device. The IoT device is essentially a gateway streaming data elsewhere, either in its raw form

[14] nRF52840, 32-bit ARM architecture, 64MHz clock speed, 256kB RAM.

or after applying some simple filtering or compression techniques (Cavigelli and Benini, 2019; Samie et al., 2019; Yoshimura et al., 2014). However, the number of IoT devices has grown tremendously recently, introducing bottlenecks in Cloud data processing – the IoT 'application explosion' (Cui et al., 2022). As a result, a growing tendency is to build systems with a built-in level of "smartness" so that the device can make decisions without sending data to the Cloud (Yao et al., 2019). This latest trend also answers longstanding reservations about these devices' privacy, reliability, and latency (Andri et al., 2018; Premsankar et al., 2018). The 'edge computing' paradigm refers to migrating processing power and decision-making capabilities to embedded devices closer to sensors (Samie et al., 2019).

Edge computing's approach presents exciting design problems for both industry and academics (Jeon et al., 2018; Yoshimura et al., 2014). Furthermore, edge intelligence is becoming more accessible to designers, thanks partly to the availability of low-cost microcontrollers capable of performing hundreds of calculations while consuming milliwatts of power. Thanks to the efficiency of these computing devices, designers can construct battery-powered electronics that run machine learning models. Despite being only an emerging paradigm, promising examples surface from the literature on edge computing. Researchers successfully employed hardware accelerators (Andri et al., 2018; Cavigelli and Benini, 2019), memory access optimisation (Zheng et al., 2020), near-threshold technology (Andri et al., 2018; Gautschi et al., 2017) and parallel architectures (K. Wang et al., 2021).

Embedding machine learning on edge devices is especially appealing for developing resilient robots. Although not deployed on the robot itself via edge computing devices, fault detection algorithms were previously used to autonomously reconfigure a robot controller in the event of a malfunction (Levine et al., 2016). As the name implies, a resilient robot can recover its designed function in the event of partial system damage (Zhang and Lin, 2010). Fault tolerance is a software engineering term referring to a system's ability to provide a service in the event of failures (Avizienis et al., 2004; Zhang and Lin, 2010). In the context of robotic systems (Zhang et al., 2017), fault tolerance refers to the ability of the system to reconfigure its software or hardware when a component fails. A robot's resilience is determined by how much of its original functioning can be recovered automatically. If the system can perform the same action in a damaged state, it is a strong resilient machine; if it only resumes partial functionality, it is a weak resilient machine (Zhang and van Luttervelt, 2011).

This project aims to create a strong resilient actuating assembly based on sensory layering guidelines. The following section describes the design rationale for sensor selection and placement on the actuating assembly's body and how the feedback loops relate to the layered sensing system and the robot's controller. After that, the design of the machine learning algorithm is detailed, as well as how the data required for fault prediction was gathered.

4.2 Designing Enhanced Robots Through Sensory Layering

Following the design guidelines of sensory layering, I demonstrate their contribution to enhancing resilience in actuating systems in this project. My decision to concentrate on actuators stems from the extensive range of applications they can be used in, including industrial, academic, and healthcare sectors. The system described here was expected to predict whether one of its motors would fail and automatically switch to its redundant system after that. The system was designed using a combination of off-the-shelf sensing components and bespoke hardware – both the actuating assembly's controller board and actuators. The software employs deep learning for system-level fault prediction and a finite-state machine (FSM) for autonomously switching between operation modes. The following paragraphs sets out how my emerging guidelines for sensory layering and enhancement related to my design brief for enhancing human-made agents.

Regarding *selecting which hidden affordance to sense* (design guideline 1), it is clear from the preceding sections that overlaying the sense of proprioception – or, in technical terms, the ability to predict and detect malfunctions in its actuation system – aids in enhancing redundancies in robots. The agent's body is mechanical, with sensors and actuators relaying data to a central processing unit. As a result, the hardware and software solution must integrate with the centralised controller.

When *determining which sense to layer* (design guideline 2), the existing literature assists in deciding which sensors are appropriate for the application. Researchers successfully deployed accelerometers (Mirzaei et al., 2020), gyroscopes (Yu and Qiao, 2020; Zhu and Zhou, 2020) and current sensors (Wang et al., 2020) for fault prediction and detection. In the planned application, the enhancement system must detect unexpected variations in the actuator's rotation. This can be achieved either directly – i.e., with a sensor measuring the axle's rotation speed – or indirectly – i.e., by measuring the motor's vibrations. I used the latter solution for this prototype and employed an accelerometer to detect the actuating system's emitted vibrations. All rotating devices, such as motors, produce vibrations. Throughout a machine's service life, component deformation and damage cause an increase in the magnitude of vibrations in an actuator (Raj et al., 2013).

Accelerometers are usually paired with gyroscopes on the same chip (Filippeschi et al., 2017). Still, the data generated by a three-axis accelerometer without a gyroscope, would be sufficient for producing features the deep learning system requires to execute inference and predict faults. As a result, to reduce extra complexity, a gyroscope was omitted. Encoders could be employed similarly, as they convey positional and rotational speed information about the axle (Li and Liu, 2019). Nevertheless, encoders are highly integrated sensors, often specifically designed for a specific application, such as in Kau & Bowers (2021) and significantly increase the motor's structure complexity, system cost and maintenance difficulty (Y. Li et al., 2021; Shinnaka and Takeuchi, 2007). Moreover, vibration analysis is the most common and reliable analysis for fault prediction in motors (S. Zhang et al., 2020). My goal was to design the new sense to be transferable to as many kinds of motors as possible. Hence, I employed an accelerometer. This technique is established and reflected in the recent literature (e.g., Dionisio et al., 2021; Mones, 2021; Rocha et al., 2021; Watson and Reichard, 2021).

Given the agent's mechanical body, *establishing the sensory feedback loop* (design guideline 3) is relatively straightforward, as the new sense should leverage the robot's existing 'communication channels'. In other words, the new sense should leverage similar communication protocols as the robot's pre-existing sensory systems. Usually, robot central processing units are microcontrollers, relatively simple programmable electronic processors that execute instructions sequentially. One of the microcontroller's roles is communicating with the outside world via sensors and actuators using established "languages" or protocols. The three existing protocols are Universal Asynchronous Reception and Transmission (UART), Serial Peripheral Interface (SPI), and Inter-integrated-circuit (I2C). While UART is easy to use, it has slow transfer speeds (Glória et al., 2017) and is mainly used for device-to-device communication rather than sensor-to-device communication (Peňa, 2020). SPI, on the other hand, is faster and can transmit and receive data simultaneously, however, it requires sophisticated routing with four transmission lines (Motorola, Inc., 2004). Finally, I2C communicates with devices using two bidirectional connections without necessitating additional circuitry (Irazabal and Blozis, 2003) – for comparison, SPI relies on four connections and UART on two. Fast data transmission and a limited number of connections between devices were desired in this project to manage its complexity; hence, the choice fell on the I2C protocol.

In *determining the system's position on the body* (design guideline 4) in the context of a human-made agent, while the designer clearly should exercise some caution, less is at stake than when working with human agents, as I discuss in chapters 5 and 6. The areas to focus on are mechanical compliance, ease of integration with the existing robotic system, and avoiding conflicts with pre-existing sensory systems. The redundant actuating assembly was designed to be self-contained to minimise interference with pre-existing sensory systems, such as cameras, ranging sensors or wheel encoders. Integration with current hardware was addressed by carefully assessing the communication protocol. On the other hand, the mechanical compliance and positioning of the new sensor on the robot's body were of immediate importance to maximise the quality and reliability of the dataset used to train the deep learning algorithm and monitor the system's performance. For example, the accelerometer needs to be rigidly fixed as close to the potentially faulty actuators as possible. Furthermore, the sensor needs to be self-contained within the agent's body, ruling out systems that rely on transmitting data to an external computing unit – such as the Cloud – to process the data to detect faults.

Finally, whether designed for a human or human-made agent, the *ease of access by the community* (design guideline 5) is, I argue, an essential aspect of enhancement system design. Whenever possible, the designer should favour open-source and widely available hardware and software for prototyping the system. There are two points to approaching enhancement technologies from an open-source perspective. The first is socio-political: open-source challenges traditional notions of ownership, control, and profit based on competition and exclusivity. Instead, it promotes collaboration, sharing, and transparency, and it seeks to create a more equitable and democratic society (von Hippel, 2005, pp.121–131). The second point is pragmatic and twofold. First, open-source approaches can promote transparency and accountability. Because open-source hardware and software are publicly available and can be examined by anyone, they can be more transparent and accountable than proprietary technologies. This can help ensure that the technology is being used ethically and responsibly, reducing the potential for abuse or misuse. Second, because open-source technologies are freely available, they can be used and improved upon by anyone. This can encourage competition among individuals and organisations, which can drive innovation and lead to the development of better and more advanced technologies. These points are important for enabling problem-solving for enhancement technologies: by enabling accessibility from a large community, the problem can be approached by collective intelligence, generating collaborative, inclusive and participatory solutions (Bonvoisin et al., 2017; Paulini et al., 2011).

This final design guideline reflects recent research on the importance of open-source hardware and software for economic growth – quantified by the European Union as a cost-benefit ratio of 1:4 (Blind et al., 2021, p.16) – and for enabling localised production, circular economies and citizen science (Ezoji et al., 2021) by reducing entry costs for enabling technologies up to 90% (Heikkinen et al., 2020). My project was primarily developed with off-the-shelf sensors and motors to ensure reproducibility from a larger community. However, the controller board and coaxial motor mechanism were uniquely designed for this prototype. To comply with the fifth design guideline, the schematics, fabrication specifications, and source code were released as open-source and are freely accessible on GitHub.

In conclusion, employing the five design guidelines for enhancement technologies establishes a clear foundation for developing redundant actuating assemblies. The envisioned system:

1. Should sense and monitor its actuators to predict faults,
2. Achieves proprioception by employing accelerometers,
3. Feeds back on the occurrence of a predicted fault through the I2C protocol,
4. Should be positioned as close to the motor as feasible and mounted rigidly to increase vibration transmission to the sensor,
5. Should employ off-the-shelf hardware, or the custom solutions should be freely accessible by third parties.

The guidelines led me to choose brushless motors for the redundant actuating assembly due to their high power-to-weight ratio and low maintenance requirements. Further, my design includes a single Electronic Speed Controller (ESC) that uses relays to switch between the two brushless motors. This module allows for efficient control of the motor's speed and direction. Finally, software implementation is essential for predicting motor malfunction and switching to a backup motor. My prototype used AI-based fault prediction and central control systems to achieve this goal. Please refer to This page *was intentionally left blank.*

Appendix A for more information on the mechanical design and software architecture – including the AI system and the FSM I implemented to switch to the backup system.

4.3 Discussion and Conclusion

Recent robotics research indicates that redundancy is a rich area of inquiry. The developing edge computing paradigm allows researchers to design self-contained redundant actuating assemblies that do not require a connection to the cloud to predict failure patterns. The robot's fault prediction subsystem can be approached from various perspectives, depending on the sensors available or implementable on the robot's body.

The project presented in this chapter introduces a novel actuation mechanism for enhancing redundancy in actuators. The system was designed using the sensory layering design framework discussed previously. The overarching goal of this project was to test the design framework described in chapter 0 in the context of a human-made agent. To that aim, the research focused on designing a redundant actuator by including a sense of proprioception in the robot's controller and a novel redundant actuating assembly based on two brushless motors coupled to the same axle. The presented method incorporates deep learning to forecast actuator failures and an FSM-based controller to automate motor switching. In the case of an anticipated fault, the robotic platform described here can switch to backup motors autonomously, allowing it to continue performing its intended task without interruption. The system presented in this study constitutes an enhancement because it adds an intelligent system to a previously limitedly self-aware robot. This point was the critical driver for employing deep learning techniques.

4.3.1 Reflecting on the Design Guidelines of Sensory Layering

In this first case study, I investigated whether conventional robotic actuators, such as brushless motors, can be enhanced by integrating sensory layering. I approached the research question guiding my first case study – how can design offer a new perspective on enhancement technologies – by exploring how an agent's body could serve as the primary frame of reference for determining enhancement rather than relying on species-typicality, especially because such thing does not exist for human-made agents.

This case study confirmed some of my prior assumptions regarding the benefits of applying a design-led approach to technological enhancement. For instance, the introduction of sensory layering via proprioception in a robotic actuator revealed how enhancement could be achieved by focusing on the agent's specific capacities, leading to a more targeted and transferable form of resilience. This point reinforces the argument that enhancement should be grounded in the agent's embodied form and interaction with the environment rather than predefined functionality standards. However, the study also raised significant questions about how such enhancements can be generalised across different systems while maintaining flexibility and adaptability. These questions directly inform the following stages of this research, where the focus will shift to wearable systems for human enhancement.

Designing and prototyping allowed for insights that would have been difficult to acquire through theoretical analysis or purely technical methodologies. The iterative process of making and reflective practice revealed emergent properties of the system – such as the relationship between sensor placement and data fidelity – that traditional methods might have overlooked. Further, design practice's speculative inclinations discussed in chapter 3.1 allowed me to explore ideas that push conventional thinking. This case study was not just about incremental improvements in fault detection; it was about envisioning a system where sensory layering could redefine the boundaries of what a robot could perceive and act on. I argue that this approach is vital when the goal is to rethink established paradigms rather than merely optimising within them – as reflected in my research question.

This case study directly engages with cybernetics, affordance, and embodiment theories. From a cybernetic perspective, the study illustrates how feedback loops and increased sensory variety can be harnessed to create more resilient agents. In terms of affordance theory, the layering of proprioceptive sensors enabled the actuating assembly to perceive and respond to hidden affordances that were previously inaccessible. Finally, embodiment was central to this investigation: I treated the actuator's mechanical assembly, sensory systems, and interaction with the environment as the starting point for exploring enhancement.

The design guidelines outlined in chapter 3 served as a solid foundation for navigating the unfamiliar field of robotic actuators. In choosing which hidden affordance to target (Guideline 1), I took inspiration from the theories of embodiment. If the agent's body is the starting point for enhancement, then how the human-made agent 'perceives' itself would be a rich design space to explore. Therefore, I decided to explore proprioception, as explained in the introduction to this chapter.

From this initial decision, I needed to determine which sense to layer (Guideline 2). This guideline is tricky in human-made agents, especially in my case, where I am not adding to an existing robot but focusing solely on an actuating assembly. I wanted to retain a somewhat modular solution that could be easily translated to other actuating assemblies, even ones already part of a functional robot. This point guided my choice of using TinyML and a FSM, even though this solution is technically not the most efficient in terms of costs, as it requires another microcontroller with custom code. On the other hand, though, my implementation presents the controlling system (in cybernetic terms) with a binary value: the actuator is working well or will fail soon. This new sense can be layered on any system that can interface with the external world via a digital input.

Establishing the sensory feedback loop (Guideline 3) was the most far-reaching aspect of this project. Sensory layering's distinguishing aspect is using the agent's pre-existing morphology as an avenue of enhancement. Further, the use of industry-standard protocols assured the project's transferability. The redundant actuating assembly can communicate with any processing unit with an I2C interface, a worldwide standard supported by over 1000 integrated circuits (NXP Semiconductors, 2021). Although not universal, the actuating assembly suggested in this chapter can be implemented into a wide range of robotic systems requiring a higher redundancy level.

Determining the new sense's position on the body (Guideline 4) was not a primary concern for this project. The sensibilities for selecting the sensor's placement on an actuating assembly differ from those required for enhancing a living agent. By contrast, designing for ease of access from the community (Guideline 5) was a challenge. Finding an open-source deep-learning pipeline with an appropriate licence, in particular, proved challenging. Other unanticipated obstacles were discovered while designing the robot's bespoke actuating assembly and control board. I needed CAD software, but the majority of such systems are closed-source and require the purchase of a license. Similarly, software packages for designing custom printed circuit boards share the same limitations. I ultimately chose Autodesk Fusion 360[15] for 3D modelling and KiCAD for printed circuit board design because they are both freely available, with KiCAD also being open-source.

Further, in an attempt to address the issue of unequal access to enhancement technologies, the final prototype is expressly designed for access from a large community. From a design standpoint, this project demonstrates how sensory layering guidelines allow the designer to traverse the technological challenges, ultimately leading to prototyping a fully functional actuating assembly. Finally, this chapter is particularly pertinent to one of the thesis' core claims since it successfully demonstrates how enhancement technology design ideas can be applied to human-made agents. This point is crucial, as it reinforces the detachment from the idea of augmentation beyond 'normal' as a metric for enhancement, as argued in section 2.2.2.

Researchers wanting to expand from the implementation of the guidelines of sensory layering presented in this chapter could quantitatively characterise the best sensor positioning on a robot's actuator to maximise the sensor's signal intensity. Further, it would be particularly interesting to develop a redundant robotic system, such as a mobile robotic platform for deployment on rough terrain, as mentioned in this chapter's introduction, employing concepts of sensory layering. Whereas traditional resilient robots might perform a new behaviour, change their configuration or change the state of their components (Zhang et al., 2017) in the event of a fault, a robot platform employing sensory layering might perform a combination of these actions. Taking the redundant actuating system presented before as an example, deep learning allows for learning new behaviour, and the electro-mechanical relays simultaneously allow reconfiguring the system on the fly. This study presents a single actuating assembly designed as a plug-and-play solution for existing robots rather than a bespoke robotic platform. Further research on sensory layered robots could explore how to tightly integrate the whole robot's body with its senses. Finally, it would be particularly relevant to the field of enhancement technologies to expand the system presented here to include a lifetime learning system that would grant the robot the ability to adapt to different environments. For example, evolutionary algorithms – algorithms that take inspiration from nature and animal behaviour to solve problems – could be added to the actuating assembly controller to determine if the robot is on rough terrain and needs more torque on its wheels, consequently activating all the motors.

As a final note, I chose to explore enhancement for human-made agents in this chapter to see whether the design guidelines would be useful for agents other than humans. Reflecting on this case study, the guidelines of sensory layering were invaluable in navigating my practice and its technical challenges. Further, equally treating human-made and human agents highlights their commonalities: both types of agents rely on sensory information to interact with their environments, and both can benefit from enhancements that expand their perceptual capabilities. This approach indicates that the challenges and solutions in enhancing mechanical systems can provide valuable insights into enhancing human systems and vice versa. For instance, the strategies used to integrate sensors and feedback mechanisms in robotic actuators can inform similar approaches in wearable technologies for humans, as I will explore in the following two chapters.

My approach explicitly challenges the traditional boundaries between biological and mechanical systems, suggesting that enhancement technologies should be designed with a consistent framework

[15] When I started developing this use case, Autodesk Fusion 360 was fully free software – albeit, not open-source. As of October 2021, Autodesk changed its policy, restricting some features to subscription-only users (Autodesk, 2021). The software's basic capabilities included in the free for personal use tier are sufficient for recreating the redundant actuating assembly detailed in this chapter.

regardless of the agent's nature. My approach emphasises that design is not limited to solving problems within isolated contexts but can address fundamental challenges shared by various types of agents.

4.3.2 Limitations

The prototype has a few drawbacks. The deep learning system was trained on a dataset of the motors spinning in place without any load. In fully-featured robots, motors seldom directly drive the actuators, relying instead on gearboxes to slow the motor's rotation and increase their torque. Furthermore, the actuation system described here was not trained using data from different terrain types. The accelerometer could be expected to produce unique vibration patterns depending on the terrain traversed by, for instance, a mobile robot platform. Although outside the scope of this prototype, the shortcomings of this project can be addressed by future research using the same methodology outlined in this chapter. Transferability is built into my approach: I chose deep learning during the design phase because it offers a design framework dependent on the dataset used to train it. As a result, researchers or individuals who want to use the redundant actuating assembly described here can re-train the deep learning model with a suitable dataset.

This chapter demonstrates how practitioners could use sensory layering design guidelines in the context of human-made agents to approach prototyping redundant actuators. The guidelines were effective for systematically addressing the subject matter, considering both the technologies involved and the overall design brief for the project. While this chapter concentrates on human-made agents, the following chapter will show how the same guidelines can be applied to human agents.

5 Case Study 2: Design for a Body-Moulded Haptic Compass

5.1 Introduction

Following the last chapter, which addressed the implementation of design guidelines for enhancement technologies for non-humans, this chapter focuses on applying the five guidelines to human agents. Human bodies evolved with several senses for interpreting and interacting with the world. However, humans lack organs that can detect magnetic fields. In this project, I use sensory layering techniques to prototype a wearable system that interacts with magnetic fields' hidden affordance. The resulting wearable is tightly coupled with the wearer's body because modern modelling and manufacturing techniques allow for significant customisation in the final prototype. By layering a new sensory system on the wearer's body – magnetoreception – the prototype described here embodies the design guidelines of enhancement technologies. The resulting experiential prototype detects magnetic North and conveys its direction to the wearer through haptic feedback. As a result, the ability of the human agent to navigate an environment is enhanced.

The prototype discussed here[16] comprises a body-moulded casing with three sensors: an accelerometer, a gyroscope, and a magnetometer. The sensor data is integrated to build an Attitude and Heading Reference System (AHRS), providing pitch and roll angles relative to Earth's gravity and heading angle relative to magnetic North (Geiger et al., 2008). An AHRS system allows the wearable to be oriented in 3D space, giving a drift-free, high-accuracy approach for detecting magnetic North. The electronics are stored in a 3D-printed casing moulded to fit the wearer's body. To maximise bodily compliance, I used photogrammetry – the process of converting a physical shape into a digital model using images – to create an accurate reference model of the agent's body first. The shape of the wearable is then modelled using the scanned body mode as a reference. The resulting wearable 3D model is an accurate surface representing the user's body shape that can be turned into a physical prototype using a filament deposition 3D printer.

The value of this project is twofold. Firstly, exposing the wearer's absolute direction is an effective enhancement for navigating the environment. Magnetoreception has been proven an effective tool for human navigation, both in academia (Schumann and O'Regan, 2017; Witzel et al., 2021) and the military (Canciani and Raquet, 2016). Based on the design guidelines presented in this thesis, I argue that research on seamlessly integrating wearable enhancement technology is still in its infancy. Although several researchers are addressing the subject of on-skin devices for sensing, especially in the case of soft and flexible electronic materials (J. C. Yang et al., 2019; Yin et al., 2021), the applications of these technologies for enhancement are just emerging (Tu and Gao, 2021). Therefore, the second contribution of this project to the thesis' core proposition was to shed light on the importance of designing a wearable system that can persist on the agent's body – which in turn led to the more nuanced formulation of Guidelines 3 and 4.

[16] The GitHub repository for my prototype can be found following this link: https://github.com/fsanzeni/Body-Moulded-Haptic-Compass

Unlike the more mechanical focus of the previous case study, working with human wearables and reviewing relevant literature, such as that from Zeagler (2017), highlighted the importance of how and where wearables are positioned on the body. This new understanding prompted an expansion and refinement of Guidelines 3 and 4. The process of customising the wearable to fit the agent's body revealed that positioning and bodily integration are critical to the effectiveness of the new sensory system, not just the technological capability of the sensors.

Furthermore, design practice facilitated a shift in my thinking from simply adding a new sensor to the body to creating a seamless, distraction-free enhancement. Initially, I considered using visual feedback, such as screens. However, this approach felt somewhat simple, leading me to explore the differences between tools and prosthetics, as discussed in chapter 2.3.1. Whereas a screen felt more like a tool – something to look at – I wanted to design a prosthesis: an addition to the body that would blur the boundary between the body and the environment. This reflective act of weaving reading and making made me realise that the true value of a new sense lies in its ability to be perceived as a natural extension of the body, rather than a separate component. This insight was instrumental in shaping the design and implementation of the wearable, ensuring that the new sense would be as intuitive and integrated as possible.

The following section examines current advancements in wearable technology for improving navigation performance in human agents, emphasising the rationale for my approach of layering magnetoreception on the human body. This chapter discusses current efforts in body-centric design for wearables and the field's gaps. I will describe the prototype's construction and integration, focusing on body scanning technologies and sensor fusion approaches. Finally, this chapter analyses the significance of the experience prototype offered to the literature and the primary hypothesis of this thesis.

5.1.1 Design Brief

The following table outlines the design brief I developed for this case study. It presents the objectives, requirements, constraints, and criteria for this specific project and their alignment with the overarching goals of the thesis. My initial question was: *Can we layer a magnetic compass on a human agent?*

	Case Study	**Research**
Objectives	Design a wearable system that layers the sense of magnetoreception onto a human agent.	Explore how integrating a new sense into the human body challenges and extends current understandings of sensory enhancement.
	Enhance the ability of human agents to navigate an environment by detecting magnetic North.	
	Design a transferrable pipeline for generating body-moulded wearables.	
Requirements	The wearable should be a self-contained unit able to sense magnetic North.	Document the design and implementation of self-contained wearable systems, examining how it can be systematised and adapted across different contexts.
	Provide feedback when the wearer is facing North through a wearer-adjustable haptic pattern.	
	Use off-the-shelf hardware and software whenever possible and make custom solutions freely available to the public.	
Constraints	The wearable system should be tightly coupled with the wearer's body.	The wearable's position should be considered carefully to (i) detect the hidden affordance, (ii) not impede the agent's movements and (iii) provide suitable feedback.
	The wearable system must be self-contained and not rely on external hardware or software.	
	The design must prioritise bodily compliance to ensure ease of integration and mechanical compatibility with pre-existing sensory systems.	
Criteria	The ability of the human agent to navigate an environment should be enhanced through the detection of magnetic North and haptic feedback.	Examine how body-moulded designs facilitate sensory layering, informing future approaches to wearable sensory enhancements.
	The wearable system is moulded to the wearer's body to maximise bodily compliance.	
	The design integrates off-the-shelf hardware and software whenever possible.	

Table 5.1 The design brief for my second case study.

5.1.2 Wearable Overview

Haptic wearable systems interact with the skin directly or through clothes. It is well understood that the human skin can be regarded as a receptor for information transmission (Geldard, 1957). Skin sensations like pressure, vibrations, and elasticity can sense and transmit tactile messages to the brain via afferent nerves. Haptic sensations involve the sense of touch and include pressure and vibration, temperature, itch, pain, and pleasure sensations (McGlone et al., 2014; McGlone and Reilly, 2010).

According to current literature (for an in-depth discussion, see Shull and Damian, 2015), haptic wearables are a viable method for transmitting data to (and from) individuals who have lost some of their sensory abilities. It is widely agreed that transmitting information through the sense of touch for navigation purposes is helpful where using visual or auditory feedback would be inconvenient or distracting (Paneels and Roberts, 2010; Pielot et al., 2010). Using haptics instead of visual or aural cues is especially relevant since it allows the wearer to navigate hazardous or unfamiliar areas with personal and effective cues (Pacchierotti et al., 2017, p.594).

Following this thesis' argument for pursuing enhancement by overlaying novel sensory systems on the agent's pre-existing competence, the prototype shown here leverages haptic feedback and, more precisely, vibrotactile feedback to convey spatial information to the wearer. Furthermore, when combined with an accelerometer and a gyroscope, it gives a consistent and dependable method of determining magnetic North. Because of the tight coupling with the wearer's body, I suggest that the wearable proposed here is an enhancing system rather than a tool. Because it was built utilising 3D scanning of a human body, the prototype can be perceived as providing a new sense, giving a level of integration with the agent that surpasses using a dedicated analogue compass or a smartphone to detect North. This reasoning is consistent with the thesis' premise that the novel sensory system should be persistently coupled to the body to effectively enhance an agent, transitioning from a tool to a new sense, as argued in section 2.3.1.

The project discussed here is broken into two sections. First, I established a photogrammetry-based design approach for body-moulded wearables. The prototype in this chapter was tailored for my own body, with 3D scans of my torso and neck as the starting point for designing the wearable shape. This section develops a transparent and transferrable pipeline for obtaining comparable findings to overcome the bias on my own body.

The second stage of this project involves creating a hardware and software system that indicates to the wearer whether they are facing North. The hardware consists of a custom solution based on a microprocessor interfacing with an Inertial Measurement Unit (IMU) to calculate the wearer's direction and a specialised haptic controller and motor to provide feedback. The IMU comprises an accelerometer, a gyroscope, and a magnetometer integrated into the same chip. This project's software implementation depends on sensor fusion techniques to produce an Attitude and Heading Reference System (AHRS). The AHRS constantly monitors the wearer's facing direction, and when they face North, the haptic motor is activated. As previously stated, I use a specialised integrated circuit to actuate the motor, allowing the wearer to choose their preferred vibrotactile pattern from the several possible waveforms. Figure 5.1 depicts the architecture of the wearable.

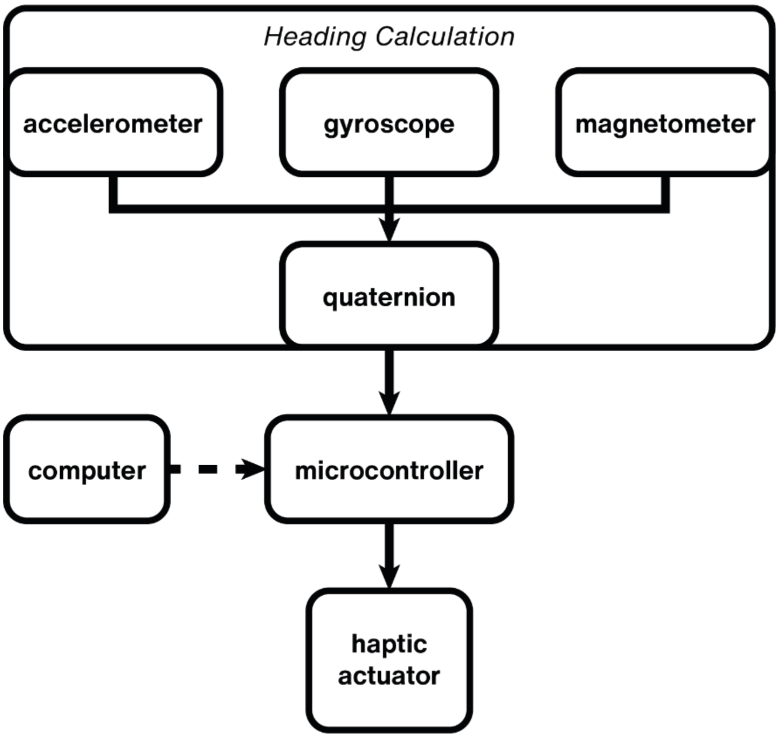


Figure 5.1 Overview of the body-moulded wearable haptic compass. An IMU acquires environmental data in real-time using three sensors: an accelerometer, a gyroscope, and a magnetometer. The data is combined in a quaternion, a four-element vector expressing rotation in a three-dimensional coordinate system widely used to estimate heading and direction (Renaudin et al., 2014). When the wearer faces North, the microcontroller analyses the vector and triggers the haptic actuator. Wearers can use a simple script on a computer to choose their preferred haptic pattern for feedback.

5.1.3 Body-centric Design

It is necessary to survey the existing literature on how humans perceive space before detailing the body's role in designing interactions. Neuropsychology has thoroughly investigated the subject, creating a taxonomy of how one experiences space in relation to one's own physical body. Holmes and Spence (2004) evaluated the modern neurological theory of space, building on Hall's (1968) pioneering work on proxemics – or the study of body-related space. They classified space into three types: percutaneous, peripersonal, and extrapersonal. Percutaneous space is the area immediately outside the body, whereas peripersonal space is the area reachable by the hands. Finally, extrapersonal space includes the space beyond the reach of one's arm.

In the context of sensory layering, the distinction between the three levels of space perception is essential. If enhancement is reframed as the act of manifesting hidden environmental affordances, as outlined in section 2.6, its role in the context of body-centric design is to translate signals from extrapersonal to percutaneous space. As argued there, an enhancement should translate magnetic cues embedded in the environment into sensory feedback that takes advantage of pre-existing senses. I chose to develop a haptic device rather than leveraging other senses, such as vision or sound, because I wanted to manifest a hidden affordance on the wearer's skin. I wanted to reach out and materialise hidden information to understand it better, much like we pick up objects to use and understand them. The fundamental role of touch has been extensively documented, from its importance in facilitating positive development in infants (Ardiel and Rankin, 2010) to enhancing the feeling of presence in VR environments (J. Li et al., 2021).

Recent studies in the literature have shown several implementations of wearable haptic devices for the wearer to aid navigation. Haptics is a feasible method of delivering information to the wearer, from hand-based devices (Chernyshov et al., 2018; Maeda et al., 2017), to neck-worn (Matsuda et al., 2020; Schaack et al., 2019), to head-worn (Berning et al., 2015; Kaul and Rohs, 2017), to waist-worn (Cosgun et al., 2014) to full-body systems (Furukawa et al., 2019; Konishi et al., 2016). However, as Peiris et al. (2019) pointed out, wearable technologies that integrate seamlessly with the body are only now surfacing in the literature. Zeagler (2017), building on Gemperle et al. (1998) seminal work, thoroughly reviewed where wearable devices for environmental navigation should be located on the body to communicate spatial awareness and directionality, determining that the trapezius and dorsal muscles will be best suited for this application.

Wearable haptic compasses were developed both in academia and the industry. In the former, projects such as the hearSpace app and wearable system (Schumann and O'Regan, 2017) or the ActiveBelt tactile display (Tsukada and Yasumura, 2004) facilitate navigation in unfamiliar settings, providing cues through the wearable system. In the latter, commercial systems such as the wearable anklet North Paw (SenseBridge, 2009) and The North Sense (CyborgNest, 2016), a transdermal device, were released to gauge market demand for this type of technology. My approach differs from the existing solutions in that it focuses on implementing a body-compliant wearable that conforms to the wearer's body shape and minimally impacts their movements. This research pertains to contemporary advancements in human enhancement, which have seen cognition and perceptual augmentation technology move closer to the body (Schmidt, 2017).

The project detailed in this chapter aims to create a wearable, body-moulded haptic compass for improved navigation. The project addresses the literature gap about the need to design devices that closely follow the wearer's body. This device exhibits the sensory layering guideline for human wearing systems. The wearable demonstrates how the body schema can expand into extrapersonal space by introducing a new sensory ability. The following sub-chapter covers how the guidelines of sensory layering were implemented in this context, followed by a description of the wearable's hardware and software implementation.

5.2 Designing Haptic Wearables to Enhance Humans

This prototype was designed using a combination of widely available open-source electronics and a custom printed circuit board to create a standalone, battery-powered wearable. I began prototyping by experimenting with technologies that would customise the wearable to fit my body. My goal with this project was to seamlessly integrate the prototype with the body, allowing it to be worn for extended periods – thereby transforming a tool into a new sense by allowing it to persist on the body, as argued in section 2.3.1. The choice of sensors and algorithms was secondary to the primary design goal.

I used a bio-inspired approach to *establish the hidden affordance* (design guideline 1) within navigation. Bio-inspiration seeks to understand, reproduce and improve the mechanics of chosen aspects of biological beings. Materials, architectures, systems, and functions of considerable scientific and technological interest can be found in all species, from the most primitive to the most complex. Living beings, such as animals (Johnsen and Lohmann, 2005) and plants (Galland and Pazur, 2005) can detect magnetic fields to orient themselves or explore unfamiliar environments (Johnsen et al., 2020).

Additionally, the biohacking community has already examined magnetoreception as a technique of human enhancement, most notably through the work of Lepht Anonym (Clark, 2012). They were the first to use neodymium magnets implanted in the fingertips to detect weak magnetic fields associated with electrical equipment. My research is positioned as an alternative to invasive surgical intervention. This stance is based on research (Bergmann et al., 2012) emphasising that enhancements should be wearable rather than implanted to achieve a larger community's acceptance. As a result, I sought to *enhance humans by layering magnetoreception* (design guideline 2), allowing them to detect magnetic North.

I examined my body's sensory abilities and opted to layer my sense of touch to *establish the feedback loop* (design guideline 3). As previously said, I chose to layer this sense since it signifies the hidden affordance by physically stimulating the wearer's skin rather than relying on visual or auditory cues. The feedback loop is completed when the wearer adjusts their movements based on the haptic information received. Following this rationale, I chose vibrotactile stimulation to indicate the wearer's direction. Second, to maximise the use of haptic feedback, wearers should be able to customise the vibration pattern and intensity. To this end, I employed miniature vibration motors embedded in the body of the wearable and a specialised controller capable of producing a range of vibration patterns.

The sensibility necessary for the *wearable's placement on the body* (design guideline 4) differs from that expressed in chapter 4. The wearable here should be unobtrusive, compact, and inconspicuous. Moreover, the wearable's placement on the body must not impede the wearer's movements. As a result, the wearable should be body-moulded to adapt to the wearer's morphology as if it were a second skin. Furthermore, to avoid interference, the sensor should be as far away from potential sources of interference, such as magnetic fields emitted by other electronics, such as mobile phones, as possible. Zeagler (2017) argues that the neck is optimal for wearables to provide spatial information while minimising its on-body footprint and interference.

Finally, particular consideration should be given to *developing a wearable enhancement readily available to a larger audience* (design guideline 5). The wearable should employ readily available hardware and software. In this project, I chose an off-the-shelf microcontroller development board, the Arduino Nano 33 Ble, which includes an Inertial Measurement Unit (IMU). Rather than designing a proprietary sensor board, this solution allows others to easily replicate the same wearable device without the need to design and test sophisticated sensor modules. The microcontroller is part of a system I designed that charges a battery and powers the haptic motor. The custom printed circuit board, the CAD models, and the software are available to the public in a repository hosted on GitHub.

The five enhancement technology guidelines provide a robust framework for creating a wearable enhancement that layers the sense of magnetoreception. In a nutshell, the wearable system demonstrated here follows my working guidelines in the following ways:

1. Should be a self-contained unit able to sense magnetic North,
2. Use an IMU to establish magnetoreception,
3. Feedback when the wearer is facing North through a wearer-adjustable haptic pattern,
4. Should be worn around the neck and integrated with the wearer in a seamless and body-moulded manner,
5. The design should use off-the-shelf hardware and software whenever possible. If a custom solution is required for the wearable, it should be made freely available to the public in a publicly accessible repository.

The following section in this chapter outlines how I designed a body-moulded wearable system employing photogrammetry. The need for a methodology that incorporates the user's needs of functionality, practicality, aesthetics and fashion using highly personalised solutions is reflected in recent literature (Amft et al., 2019; Tansaz et al., 2019). After that, I will provide an overview of the electronics and software implementation.

5.2.1 Body Scanning

The introduction of 3D scanning technology has provided new opportunities in a range of industries, including healthcare (Heymsfield et al., 2018), industrial (Javaid et al., 2021), fitness (Casadei and Kiel, 2021), fashion (Moog, 2021), and entertainment (Bartol et al., 2021). Body scanners are designed primarily to capture human bodies in three dimensions quickly and precisely, obtaining data on their shape, proportions, and measurements faster and easier than earlier manual methods. Most 3D body scanners digitally capture the entire human body or specific sections like the arms, legs, ears, or head by capturing thousands of photographs and stitching them into a point cloud to create a 3D model. Figure 5.2 depicts three types of body scanning equipment: full-body scanners, handheld scanners, and smartphone-based scanners. While full-body and handheld scanners produce more accurate 3D models than mobile devices (Strunevich et al., 2020), their accessibility can be limited due to their high cost, constraining practitioners' access to them (Daanen and Psikuta, 2018). Aside from the medical sector, handheld scanning capabilities such as smartphones and photo cameras are adequate for most applications (Bartol et al., 2021) since they consistently feature an accuracy ranging from a tenth of a millimetre to less than 1mm (Grazioso et al., 2018; Straub and Kerlin, 2015). Consequently, designers interested in implementing body scanning into their processes should focus on low-cost, widely available cameras.

Figure 5.2 The three standard body scanning systems. Figure 5.2a shows a full-body scanner (Dassault Systems Solidworks Corp, 2019), Figure 5.2b a handheld scanner (Creaform, 2019) and Figure 5.2c a mobile device equipped with a Time-of-Flight sensor commonly used to unlock the device (Standard Cyborg, 2021). This specialised sensor can capture depth data, besides colour, and can be used by third-party software to scan the mobile phone user, e.g., creating a virtual avatar.

Along with the hardware required for body scanning, there is also 3D processing software that analyses raw data and derives measurement data. Photogrammetry is the method of constructing three-dimensional models from two-dimensional data, such as photographs. It is formally defined as the process of recording, measuring, and analysing the shape of an object based on at least two photographs of the same subject taken from two different perspectives (American Society for Photogrammetry and Remote Sensing, 2019). Although this method was developed for architectural surveying, it is now primarily utilised for topographic terrain surveys, mainly aerial photogrammetry (Mancini and Pirotti, 2021).

Photogrammetry for body scanning is a relatively recent subject of inquiry in the Humanities (Boe and Carter, 2020). Current implementations of this method rely on fixed equipment outfitted with many cameras synced to snap pictures simultaneously. Commercial stationary setups with over a hundred cameras are typical, such as the T170 Capture Stage, which contains 170 cameras (Ten24, 2016, p.24). Similarly, efforts to develop low-cost alternatives continue to rely on dozens of cameras, both for partial body scans (Yang et al., 2021) and full-body scans (Boe and Carter, 2020; Zeraatkar and Khalili, 2020). Further, each camera in the array must undergo a time-consuming calibration procedure to identify its position in space, focal length, and lens distortion (Galantucci et al., 2014). I aim to provide the lowest possible entry point into this technology for design practitioners, effectively excluding multi-camera or stationary installations.

Thanks to the Structure From Motion technique, it is possible to scan a body accurately with a single, uncalibrated camera (Snavely, 2011; Snavely et al., 2008). Structure from Motion is an image processing method that allows the geometry of entities to be reconstructed by automatically aligning and extracting points from a series of pictures. The algorithm identifies significant points from individual images, deduces photographic properties, and then crosses the recognised points across multiple shots to get the points' locations in space. This first stage of image alignment allows for automatic image orientation in space and extracting critical points necessary in point cloud and mesh processing. The algorithm then generates a point cloud model triangulated into a solid mesh and editable in conventional 3D modelling software. Figure 5.3 depicts the phases of converting 2D photographs into a 3D body scan. Figure 5.3a shows the 63 images of my upper torso that the software used to construct the 3D point cloud shown in Figure 5.3b. Figure 5.3c depicts the finished 3D model of my upper torso, which was exported and rendered in modelling software.

Figure 5.3 The design pipeline for scanning bodies using Structure of Motion. I employed a standard DSLR camera (Sony NEX 5n) with a fixed 25mm lens to capture 63 snapshots of the body from different angles, as seen in 3a. The software (Agisoft Metashape Pro) autonomously infers the 3D point cloud, as shown in 3b. Finally, the 3D mesh is exported for further elaboration in other software (3c).

When Structure of Motion is applied to a body, a high-definition mesh is generated, which is the foundation for building the wearable device. Despite the availability of numerous open-source techniques (Schönberger et al., 2016; Schönberger and Frahm, 2016) and software (Rupnik et al., 2017), they struggle to orient the pictures to construct accurate 3D models (Stathopoulou et al., 2019, p.335). As a result, the closed-source photogrammetric processing tool Agisoft Metashape Professional Edition Version 1.7.3 was chosen for this project. Metashape was preferred because it is industry-standard software (Over et al., 2021) that allows practitioners to execute the entire Structure from Motion workflow, from raw images to completed 3D models (Turner et al., 2014).

After creating a 3D model of the body's torso, it was used to design a body-moulded wearable device. The following steps were taken using Blender, open-source 3D modelling software:

1. A bézier curve[17] was sketched around the virtual neck,
2. The curve was aligned to the torso scan using the shrink-wrap modifier (Blender, 2021), which aligns the bézier's vertices to its closest surface,
3. The bézier was extruded and manipulated to achieve the final shape.

The housing for the electronics was then modelled on the back of the wearable, including mounting holes for the printed circuit board (Figure 5.4). The final model was manufactured on a Prusa Mini 3D printer with Polylactic Acid plastic at 0.3mm layer height (Figure 5.5). After removing the 3D print from its support material, the uneven areas were filled with putty, then covered with automotive primer and sanded to a smooth finish before receiving its final coat of paint (Figure 5.6). The resulting wearable fits the body closely without impeding the wearer's motions (Figure 5.7).

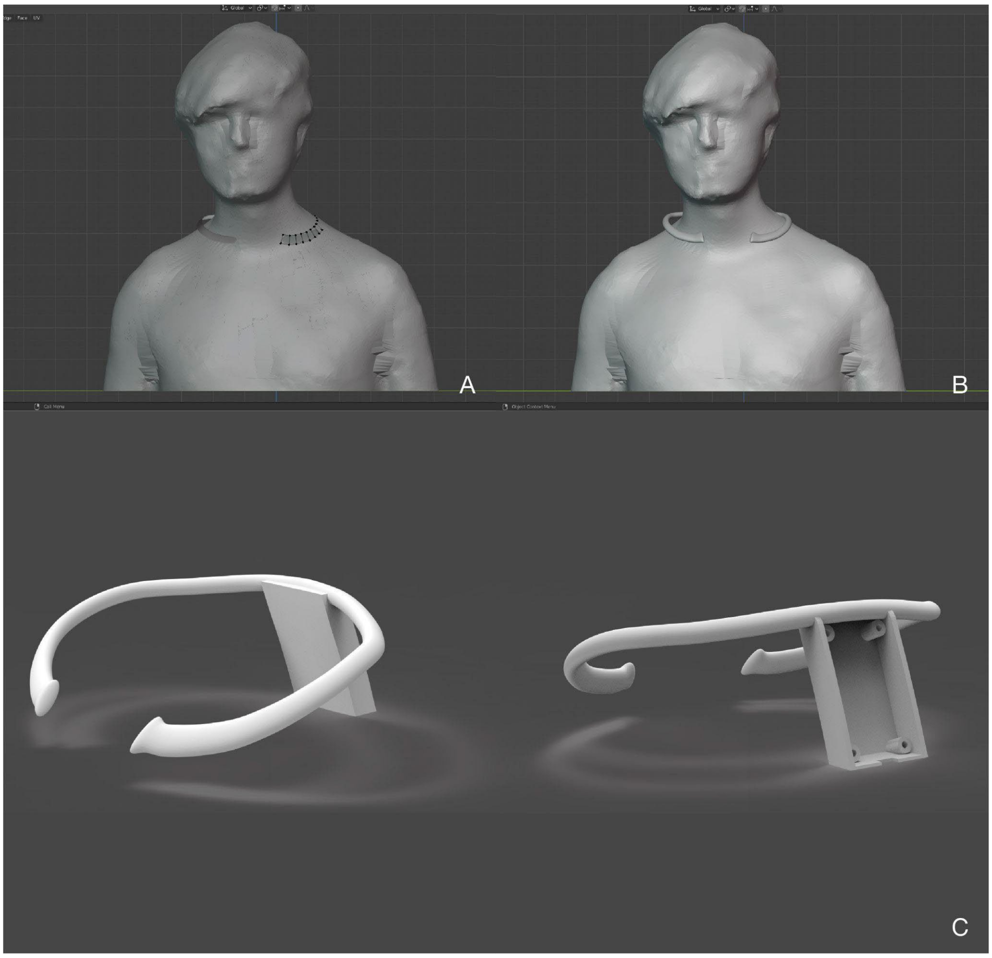


Figure 5.4 Blender's modelling process. 5.4a depicts the bézier curve shrink-wrapped around the neck of the reference model. 5.4b represents the final shape of the wearable. 5.4c shows the model before it is printed.

[17] Bézier curves are used to draw curves from a set of points in space. They are defined by a polygon, the vertices of which serve as control points for the final curve. The (number of vertices -1) of the control polygon determines the degree of the curve.

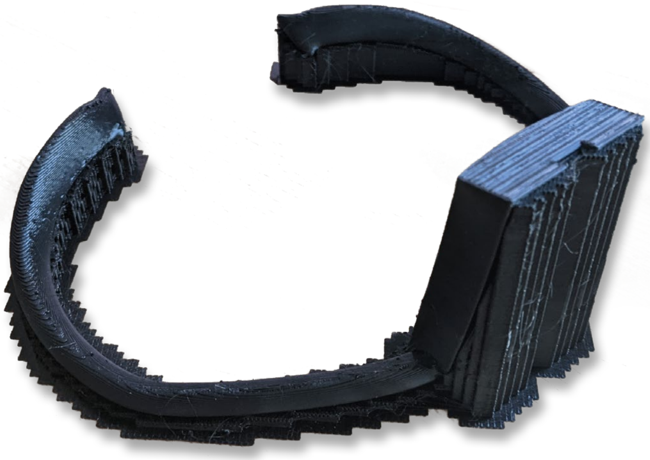


Figure 5.5 The model was 3D printed on a Prusa Mini with a 0.4mm nozzle and a layer height of 0.3mm. Because of its unusual and organic shape, the model took 4.6 hours to print despite its comparatively high layer height. Because of its organic design, it required the placement of multiple support structures to print accurately. Due to the manufacturing method, the 3D printed object has a staircase appearance. This flaw was remedied using bi-component putty and automotive spray primer, as seen in the following figure.

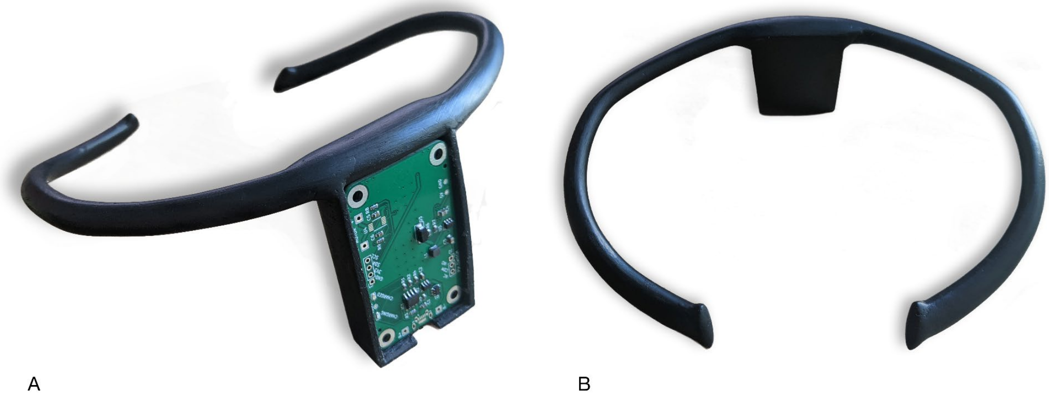


Figure 5.6 The model after it has been post-processed. I used self-hardening epoxy putty (Milliput) to address the imperfections in the 3D printed model. I used automotive spray filler (SP-037) to smooth the model further. The wearable was then sanded and painted black. A shows the wearable with the electronics installed. These are discussed in the next section. B shows the front of the wearable

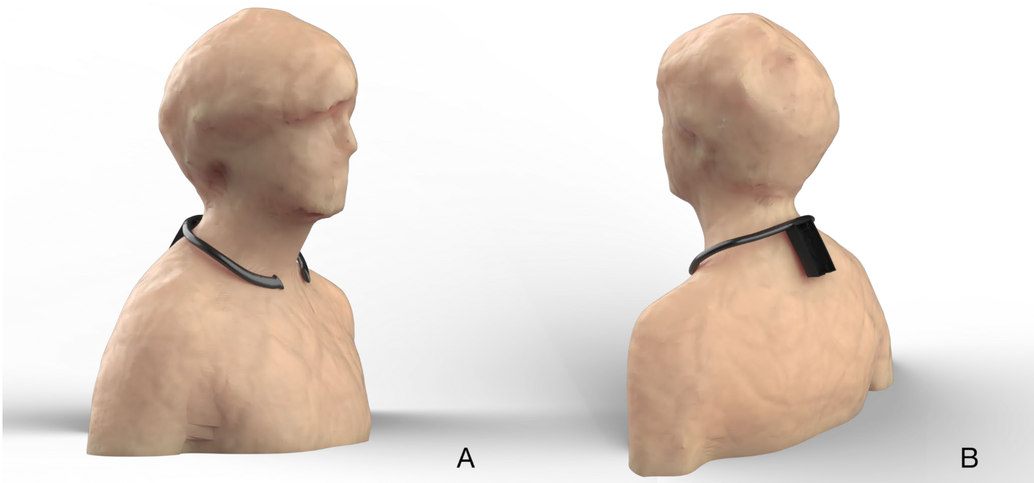


Figure 5.7 The wearable's fit on the body: front (A) and back (B).

5.2.2 Electronics and Software Implementation

As I continued developing my wearable device, I concentrated on refining its electronics, opting for Lithium-Polymer batteries as the power source. To address issues like over-current, over-discharge, and short circuits, I designed a safe charging system that ensures constant-current and constant-voltage charging, along with current sensing, reverse discharge protection, programmable charge current, thermal regulation, and cell balancing. I implemented a boost regulator to regulate the battery voltage to a stable 5V for the microcontroller.

As a microcontroller, I selected an ultra-low power model suitable for safety-critical applications, such as the case of electronics in contact with the body. I used the Arduino Nano 33 BLE platform for programming convenience and to mitigate the ongoing IC shortage. The onboard Inertial Measurement Unit (IMU), including an accelerometer, gyroscope, and magnetometer, communicated with the microcontroller via the I2C protocol, facilitating the prototyping process. To achieve accurate heading and orientation detection, I implemented the Madgwick filter, which uses quaternions for 3D orientation representation, providing a balance of accuracy and computational efficiency. After calibrating and testing the IMU's raw sensor data, I achieved the necessary ±2 degrees accuracy for my application, confirming the wearable's precision and reliability. For more in-depth information, refer to Appendix B.

5.3 Discussion and Conclusion

Recent research into wearable robotics clearly shows that one area that needs further development is adaptability to the body. The literature further points towards consolidating manufacturing technologies, such as 3D printing, as tools that would allow researchers and practitioners to design higher customisation and integration between wearable and wearer. Although haptic wearables have been developed to aid in navigating the environment, they focus on exemplifying proof of concepts with insufficient regard to body integration.

The research presented in this chapter adopts photogrammetry, a method from architectural surveys, and, more specifically, Structure from Motion, to establish a cost-effective and adequately accurate method for scanning the wearer's body, positioning it as the starting point for the design of wearables. The digital body scan provides the scaffolding for practitioners to design body-moulded wearables. The system presented in this chapter layers the wearer with magnetoreception, enabling them to perceive the direction of magnetic North via haptic feedback. The wearable uses a custom integration of off-the-shelf microelectronics with bespoke powering and actuating circuitry. The system uses sensory fusion to determine whether the wearer is facing North.

I decided to design a wearable compass, rather than a 'regular' one, to exemplify the difference between a tool and a prosthesis. As covered in section 2.3.1, sensory enhancements are prostheses that enable persistent access to information, while tools are media through which agents interact with the environment. Following this definition, whereas a traditional compass is a tool, a wearable compass becomes a sensory enhancing prosthesis as it persists on the body. Wearable compasses allow wearers to access their functionality anytime and in any location.

5.3.1 Reflecting on the Design Guidelines of Sensory Layering

Unlike the work outlined in chapter 4, this project focussed on enhancing human agents, emphasising the sensibilities required for approaching their bodies. To that aim, the experiential prototype focused less on the technologies' novelty and more on establishing a practice-led methodology for designing body-moulded wearable enhancements. The methodology, therefore, focuses on the agent's body. Its morphology is digitised through low-cost scanning techniques and establishes the starting point for tightly coupling the new sense with the body.

When I began this case study, I knew I wanted to access the hidden affordance of direction (Guideline 1) to explore spatial orientation, as I was inspired by work by other researchers, such as ActiveBelt (Tsukada and Yasumura, 2004), and because I need help navigating the environment without using the GPS on my phone. Although it might sound trivial, this point highlights the positive side of pursuing a self-funded PhD: I could reflect on my experiences and enhance small aspects of them.

Determining the new sense's position on the body (Guideline 2) was my first concern once I decided to explore magnetoreception. The literature on wearable positioning on the body indicates that the wearer's neck maximises comfort and freedom of movement. At the same time, establishing the feedback loop between the wearer and wearable (Guideline 3) offered a range of possibilities. In this prototype, I chose to rely on vibrotactile feedback rather than, for example, visual feedback or other forms of haptic feedback such as heat because it is an established method with several instances of its use documented in the literature. Further, vibrotactile feedback is a mature technology with several specialised integrated circuits available on the market, offering a high degree of customisability in the vibration patterns and ease of purchase for designers. Besides the technical aspects, my reflective practice surfaced the relevance of body integration: if the 'new' sense is uncomfortable to wear or distracting, it will not be genuinely a prosthesis. This realisation led me to research more about human-wearable interaction, which in turn led to adding nuance and context about microinteractions to Guideline 3.

This dialogue between theory and practice allowed me to surface the relevant literature – introduced before – on placing wearables on the body (Guideline 4). Zeagler (2017) was instrumental in reinforcing my initial decision not to use head-mounted visual feedback systems and directed me to choose the neck for its particular suitability to convey spatial information.

Similarly to the question discussed in chapter 4, designing the wearable for ease of access from the community (Guideline 5) proved challenging. Although the prototype primarily leverages open-source software, the Structure from Motion process employed to digitise my morphology is closed-source and requires purchasing. Although its use was unavoidable for this research, other practitioners interested in replicating the process outlined in this chapter may wish to avoid the photogrammetric process and rely on generalised human body proportions instead. Chapter 6 shows how a generalised body 3D mesh can be used similarly to design head-worn enhancement systems.

Finally, a filament deposition modelling 3D printer was used to materialise the 3D model. The choice of this technology, rather than using higher fidelity additive manufacturing processes, such as stereolithography or selective laser sintering printers, was again influenced by the fifth guideline of enhancement technologies. Plastic filament 3D printers are easily accessible as their cost has steadily decreased in recent years and are preferred by researchers and nonacademics alike (Kermavnar et al., 2021). The same process described in this chapter can be replicated with stereolithography or selective laser sintering processes, with the added benefit of requiring significantly less post-processing.

To close the loop with theory, this case study reinforced the importance of embodiment in enhancement. Customising the wearable to fit the wearer's body stressed the role of physical alignment and personalisation for effective enhancement. This case study supported the notion that the effectiveness of enhancement technologies is deeply tied to how well they integrate with the body, adding nuance to the formulation of my framework.

The wearable acts as an extension of the human body's regulatory system, allowing it to manage and interact with a broader range of environmental variables – specifically, magnetic fields. From a cybernetic perspective, this additional variety enables more robust and adaptive control, aligning with Ashby's principle that an effective system must have enough internal variety to match the complexity of its external environment. In practical terms, this enhancement helps close the gap between environmental complexity (e.g., the directional information in magnetic fields) and the agent's ability to perceive and act upon it.

Moreover, the case study also suggests a nuanced view of how affordances are layered. The wearable does not simply add a new affordance; it minimally intrusively integrates it into the user's senses. This integration is key to making the new affordance actionable in everyday scenarios: without careful design, the affordance could become a distraction rather than an enhancement. As the user becomes more accustomed to the new sensory input, the affordance itself may shift from being something consciously engaged with (a tool) to something that becomes second nature (a prosthesis), as discussed in chapter 2.3.1. This transition reflects that affordances are not static but develop as the relationship between agent and environment deepens over time.

In synthesis, the contribution of the process outlined in this chapter to the core argument of this thesis is twofold. First, the project documents how the conversations between my practice and the theory led to refining the guidelines. At the same time, the design guidelines offered a pragmatic foundation for navigating the knowledge domains needed for prototyping enhancements. Secondly, this project evidences one of the current issues in designing enhancement technologies: the need for a viable, fully open design pipeline. Although this chapter demonstrates a feasible approach for enhancement technologies from a design perspective, its transferability and replicability from a wider community can be hindered by the relatively high cost of software licensing required. A single licence for Agisoft Metashape Professional Edition is priced at 3499 USD, with an educational licence option retailing for 549 USD[18].

5.3.2 Limitations

The prototype described in this chapter has two main drawbacks besides the previously mentioned cost of a licence for the photogrammetry software. From a technical perspective, it requires access to 3D printers and rapid prototyping facilities overseas. Although the cost of these technologies has vastly declined in the last few years, the time required to manufacture the PCBs is significant – around one month from submitting the files to production to receiving the boards. From a usability perspective, the wearable system only points the wearer towards magnetic North. In its current state, the software cannot give more directed cues (e.g., "turn left in 200m") – although it technically could

[18] Pricing as of September 2023.

be made to do so. Using the Arduino BLE development board allows, in fact, pairing the device with a smartphone and acting as an external output to it. Although outside the scope of this prototype, others can easily implement this additional functionality.

This case study complements the previous chapter's focus on redundant actuators by showing how I can apply the guidelines of sensory layering to both mechanical and biological agents. While the first case study addressed mechanical resilience, this case explored human sensory enhancement, revealing the versatility of design guidelines across different agent types.

This contrast between the two cases also emphasises different aspects of integration. For mechanical systems, integration focuses on technical resilience and redundancy, whereas for human systems, it centres on seamless integration and personalisation. This contrast reveals that while enhancing human-made agents requires robustness and mechanical compliance, enhancing human agents requires different sensibilities, focusing on the balance between functionality and bodily integration.

In chapter 4, I realised that sensors' position and integration with an agent's body are critical. The project revealed how connected sensory enhancement is with the physical and perceptual constraints of the agent itself. This insight reinforced the importance of tailoring enhancement technologies integrated with the user's sensory architecture, whether mechanical or biological. The shift from thinking of enhancements as mere add-ons to seeing them as deeply embodied systems led to refining the original design guidelines, particularly Guideline 2.

In this chapter, my practice highlighted how essential it is to balance new sensory inputs with existing senses. The decision to opt for haptic feedback over visual stimuli stemmed from reflecting on the distinction between a tool and a prosthetic – an insight that crystallised during the design process. This distinction also raised the importance of persistence: a new sense must be continuously accessible and distraction-free to be fully incorporated into the wearer's perceptual framework. This finding expanded my understanding of sensory layering, revealing that the success of an enhancement depends not just on the new capability it offers but on how well it integrates with existing sensory modalities without disrupting them. This point led me to re-interfacing with the theory, allowing me to then add nuance to Guideline 3 around the types of microinteractions in feedback loops and the heuristics for placing wearables on the body of Guideline 4.

These insights prompted new intellectual questions and challenges. For example, what other senses would be good candidates for sensory layering? Can I truly claim reproducibility from a wide community if I use prohibitively expensive software in the design process? These questions influenced my next exploration of audio feedback via bone and soft tissue conduction technology, which avoids interfering with existing senses and further supports the thesis's focus on creating non-disruptive enhancements – as explored in the next chapter.

6 Case Study 3: Layering Digital Affordances: Designing Mixed Reality Wearable Enhancements

6.1 Introduction

"But what is reality? [...] A movie that gives one sight and sound. Suppose now I add taste, smell, even touch, if your interest is taken by the story. Suppose I make it so that you are in the story, you speak to the shadows, and the shadows reply." (Weinbaum, 1949).

The preceding two chapters demonstrated how sensory layering design guidelines seek to provide a robust framework for practitioners approaching enhancement technologies. Despite encompassing both human and non-human agents, the experiential prototypes covered so far have only concentrated on signifying physical affordances in the environment. The prototype in this chapter studies how agents – in this case, human agents – might be enhanced by enabling seamless access to digital affordances embedded in the built environment. The quote at the beginning of this chapter introduces this project's scope: merging physical reality with synthetic signifiers, allowing for seamless interaction with digital worlds.

This chapter outlines the design of a new wearable aural enhancement system that combines bone and soft tissue conduction to communicate audio information to the wearer without occluding their ear canal. The wearable is accompanied by a second system that tracks the wearer's movements and delivers targeted audio cues based on their location. This indoor tracking system uses Ultra-Wideband technology to track precise movement, Internet of Things (IoT) communication protocols to broadcast location data, and Unity3D, a video game engine platform, to model the virtual world. This experiential prototype aims to explore sensory layering inside the framework provided by audio-based hybrid reality, allowing the user to interact with "digital shadows" (Becker et al., 2021).

The prototype investigated in this chapter[19] seeks to explore how the sensory layering guidelines mentioned in section 3.3 benefit the design of hybrid reality experiences. Although this chapter focuses on designing an entertaining experience, different practitioners can use the same methodology to generate a variety of aural virtual/analogue experiences. The methods given here would be appropriate whenever the context demands the wearer to maintain contextual awareness – when headsets should not interfere with the wearer's pre-existing senses. The solution presented in this chapter benefits the user by providing access to hidden digital affordances, focusing on the guidelines discussed in the previous two chapters: seamless integration with pre-existing sensory contingencies and body compliance. As a result, the contribution of this chapter is dual. Firstly, the hybrid bone and soft tissue conduction wearable presented in the beginning section of the chapter has a more comprehensive dynamic range and acoustic fidelity than current alternatives.

[19] The GitHub repository for my prototype can be found following this link: https://github.com/fsanzeni/Hybrid-Hearable-and-Indoor-UWB

Second, combining indoor localisation with audio-based spatial cues represents a use case for human agent enhancement, where the feedback loop signifies hidden digital affordances to wearers. Integrating Ultra-Wideband technology and IoT protocols to track the wearer's movements and provide context-aware audio cues adds a new layer of technological complexity to enhancement systems.

In a nutshell, this project showcases the layering of a new sense while preserving existing sensory capabilities. The use of bone conduction and soft tissue conduction in this project does more than preserve an agent's interaction with their surroundings – it also demonstrates the potential for a nuanced integration of new sensory information. This idea further underlines the importance of designing enhancements not to compete but to complement existing senses, which aligns with cybernetic notions of Requisite Variety. Figure 6.1 depicts a high-level overview of the prototype's two components and how they interact to deliver an audio-based mixed reality experience.

These two focus areas partition this final prototype chapter into two sections. First, this chapter provides an overview of the relevance of auditory cues for indoor spatial navigation. The following part looks into designing a hybrid bone and soft tissue conduction wearable device. Following that, I briefly contextualise the wearable within audio-based hybrid reality. More information on how I tested the wearable's sonic fidelity and how I developed the hybrid reality experience is reported in Appendices 0 and E. This section describes the methods to convert the wearer's physical movements into digital translations within a 3D game engine and how contextual auditory cues are returned. Before going further into the rationale and implementation of the experiential prototype, it is helpful to review the history of mixed reality and its significance to enhancement technologies.

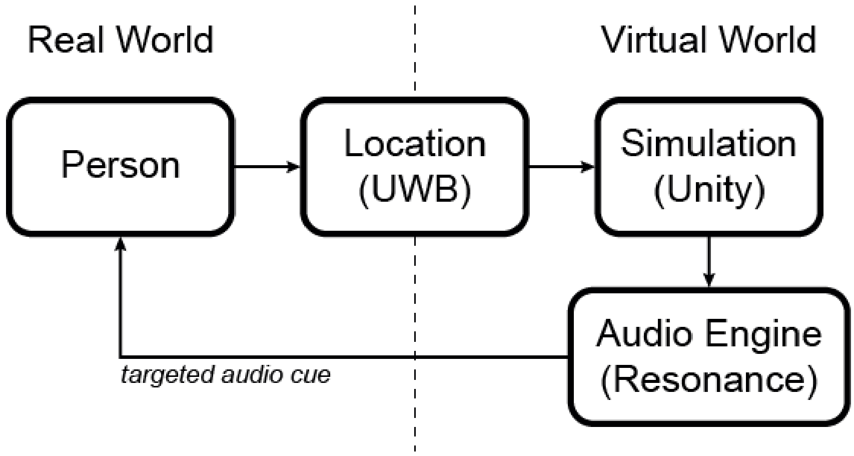


Figure 6.1 Project overview: the movements of human agents in a physical environment are translated into a simulation in Unity 3D via Ultra-Wideband sensor nodes. Virtual agents move in the simulated world, generating sounds as they move. These spatialised audio cues are then conveyed to the human agents in the real world based on their position respective to the virtual agents.

6.1.1 Design Brief

The table below summarises the design brief that framed this case study. It outlines the objectives, requirements, constraints, and criteria particular to this project while also considering the broader context of the thesis. My initial question was: *Can we have embodied access to digital affordances?*

	Case Study	**Research**
Objectives	Design an experiential prototype that explores sensory layering within hybrid reality.	Investigate if and how the guidelines of sensory layering generalise to hybrid reality environments.
	Demonstrate how sensory layering guidelines benefit audio-based hybrid reality experiences.	
	Provide access to hidden digital affordances while maintaining contextual awareness.	
Requirements	The wearable system should combine bone and soft tissue conduction to communicate audio information without occluding the ear canal.	Examine the balance between enhancing sensory capabilities and preserving the agent's existing awareness.
	The indoor tracking system should use open-source technologies to track precise movement and deliver targeted audio cues based on location.	
	The prototype should allow seamless integration with pre-existing senses and focus on body compliance.	
Constraints	The wearable system should not interfere with the wearer's pre-existing senses (e.g., hearing).	Building on the previous chapter, this case study should only use open-source software and hardware.
	The design should prioritise contextual awareness, allowing the wearer to maintain awareness of their surroundings while interacting with digital affordances.	
Criteria	The prototype should provide a comprehensive dynamic range and acoustic fidelity.	Evaluate how sensory layering can reveal hidden digital affordances, contributing to the broader discussion on how these technologies can enhance the sensory capabilities of agents in hybrid reality environments.
	The combination of indoor localisation and audio-based spatial cues should represent a use case for human agent enhancement, where feedback loops signify hidden digital affordances to wearers.	

Table 6.1 The design brief for my third case study.

6.1.2 Virtual, Augmented, Extended: The Role of Hybrid Realities for Enhancement

Mixed Reality originates from Milgram and Kishino's (1994) pioneering work, where they first defined the notion of a virtual-real continuum. The writers describe virtuality as a spectrum, with the physical and virtual worlds as opposites. Figure 6.2 illustrates the authors' use of Mixed Reality to indicate the spectrum between those two opposites. In other words, mixed reality refers to any situation in which actual and virtual elements coexist in any proportion. It is vital to stress that mixed realities are not the exclusive domain of one sense or the other; instead, they collectively apply to all human senses. According to Milgram's diagram, in Augmented Reality, the agent moves in a physical environment enhanced with virtual information; however, the physical world still plays a dominant role over digital information. In Augmented Virtuality, on the other hand, the agent is part of a digital environment and interacts with physical affordances. Virtual data are hierarchically more relevant in this situation, whereas the system can access physical information if necessary. Whereas augmented reality complements physical reality with digital information, virtual reality replaces the physical world with a simulated one. Nevertheless, in the case of mixed reality, agents move in an environment where the real and the digital coexist.

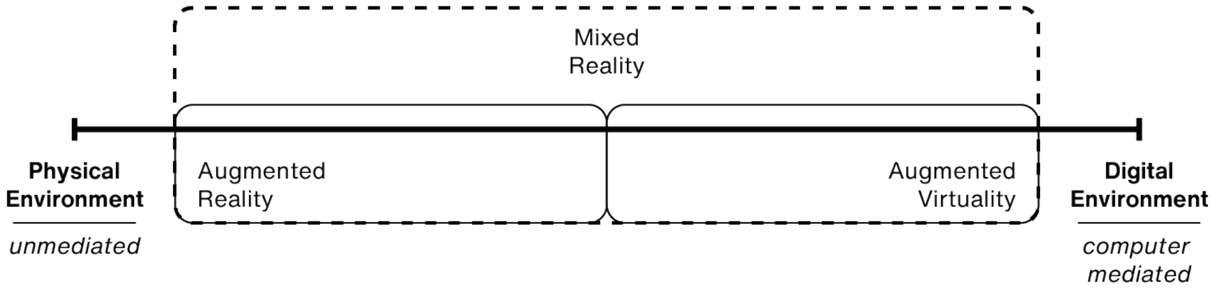


Figure 6.2 Re-elaboration of Milgram's (Milgram 1994) diagram of the virtual-real continuum. The physical environment, unmediated by digital technology, is at the far left end of the spectrum. We can find anything perceived and engaged solely by the human senses in this space. On the far right is virtual reality, a world of intangible objects produced by models and simulations and observable only through electronic devices. Mixed reality, which refers to hybridising physical settings or objects with virtual ones, exists between the two extremes.

However, returning to the central argument of this thesis, enhancement refers to the act of signifying to an agent a previously hidden environmental affordance. Most sensory-specific affordances would be lost if a digital world replaced the one the agent's body moves and interacts within. This viewpoint is consistent with the premise that enhancement should be body-centred and contextual. Thus, it becomes evident that only systems located on the left-hand side of Milgram's spectrum can be regarded as enhancements, as defined in section 2.6. As a result, recognising virtual reality as an enhancement would be antithetical to the thesis's fundamental claim. As a result, the prototype shown in this chapter focuses exclusively on hybridising reality rather than replacing it entirely with a virtual environment.

Milgram's (1994) description of mixed reality is rather broad and does not provide a firm foundation for designing in domains other than visual displays (Skarbez et al., 2021). Azuma's (Azuma, 1997, p.356) framework for mixed reality is more fitting, with three rules underpinning mixed reality: (i) the hybridity arises from synthesising virtual objects with the physical environment; (ii) the experience must be interactive and in real-time; and (iii) the experience of mixed realities must be registered in three dimensions. Milgram and Azuma's descriptions of mixed reality have withstood the test of time and remain the starting point for building mixed realities, as Rokhsaritalemi et al. (2020) stated.

However, Azuma's definition should be expanded to add a fourth point: (iv) the digital entities are coherently arranged into the physical environment (e.g. a virtual chair is rendered as resting on the physical ground). This observation is consistent with other researchers' extension of Milgram and Azuma (Collins et al., 2017; Kim et al., 2021, 2017), highlighting the necessity of retaining a logical continuum between virtual and physical environments.

In other words, mixed realities enhance agents by allowing them to experience affordances from two distinct domains: digital and physical. The agent effectively performs as a bridge between two worlds. The digital environment offers unique affordances tailored to enhance the agent in different sectors, such as training, collaborative engineering, or recreational activities (Olmedo, 2013). Rekimoto and Nagao (1995) proposed that mixed realities enhance world interactions. Figure 6.3 depicts a digital system that overlays the physical environment with additional, contextual, and interactable information. This final definition of mixed realities fully positions itself within the realm of enhancement technologies, as discussed in this thesis. To summarise, when properly integrated with the physical environment, the digital world effectively enhances the agent by allowing access to hidden affordances.

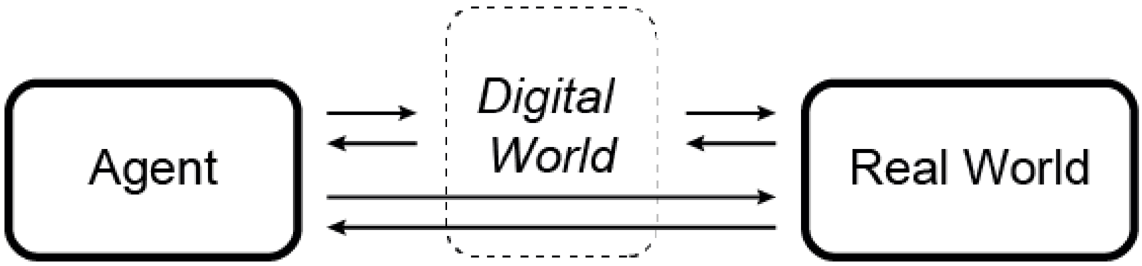


Figure 6.3 Hybrid reality as enhancement, elaborated from Rekimoto & Nagano's (1995) definition of augmented reality as a style of human-computer interaction. In this paradigm, digital information supports and enhances an agent's interaction with the physical environment. Similarly to sensory layering, digital information overlays reality without hindering it.

There are some challenges with designing mixed realities. Firstly, robust agent tracking methods are essential to preserving coherence between the physical and the virtual (Costanza et al., 2009; Ghazwani and Smith, 2020). Furthermore, hybridisation is frequently accomplished by see-through head-mounted displays (Rokhsaritalemi et al., 2020), posing the difficulty of matching adequate visual resolution with comfort and battery life. The experiential prototype reported in this chapter addresses these two problematic areas of mixed reality by (i) building a robust, scalable and centimetre-level accurate tracking system that works indoors and outdoors and (ii) leveraging spatialised audio rather than visual feedback to enhance navigation. The following section briefly outlines the rationale for employing aural cues for navigation and the gap in the research this chapter addresses.

6.1.3 Sonifying Navigation: Exploring the World Via Sound

The world of technology-mediated navigation has grown in recent decades due to the availability of devices that aid in navigating through non-visual input, primarily audio or tactile (Kuriakose et al., 2020). These technologies convert affordances in the environment into a format that the agent's senses can interpret. This process is analogous to my reinterpretation of augmenting technologies as transducers that remap hidden affordances into a form compatible with the agent's body. While researchers have been investigating haptic feedback for navigation (Swaminathan et al., 2021), existing solutions either do not provide hands-free navigation or are perceived as invasive (Presti et al., 2021). Previous studies included haptic gloves (Aqeel et al., 2017; Tu et al., 2020), haptic vests (Prasad et al., 2014), belts (Heuten et al., 2008; Pielot and Boll, 2010; van Erp et al., 2017), or even whiskers (Moriyama and Kajimoto, 2021). Similarly, both verbal cues (Constantinescu et al., 2019; Sato et al., 2019) and spatial audio (Fauzul and Salleh, 2021; Wilson et al., 2007) were shown to be equally effective as haptic feedback for navigation (Koslover et al., 2012). Remarkably, all the research presented here was intended for visually impaired people, with only Wilson et al. (2007) implying that nonverbal audio-based navigation cues might be transferable to the area of enhancement, such as for firefighters or military personnel.

Sonification, or transforming non-audio information into sound to improve communication or interpretation, is used in audio-based navigation interfaces (Kramer et al., 2010, p.4). Sonification entails matching a sound's emission with a unique event's occurrence. Sonification is exemplified by the Geiger counter, which converts the hidden affordance of radiation into an audible chirp. When the information to be presented is too complex to portray visually or when immediate action is necessary, choosing sound over other feedback systems becomes clear (Walker and Nees, 2011, p.10). For example, in real-world situations, the perceiver may be visually impaired, either physically or due to environmental influences such as smoke or an obstructed line of sight. Finally, sonification is a well-developed field of study with formally codified auditory dimensions. Dubus and Bresin's (2013) seminal work identifies 30 physical dimensions that sound can easily encode, such as acceleration, orientation, colour, time elapsed and more.

Despite their equivalent efficacy as feedback methods (Hoggan et al., 2009), I chose to focus on audio rather than haptic feedback because of its advantages in mixed realities. When compared to haptic feedback, it enables greater immersion (Broderick et al., 2018) and engagement (Bermejo and Hui, 2021) while maintaining low levels of obtrusiveness for the wearer and higher levels of social acceptance compared to traditional head-mounted displays (J. Yang et al., 2019). Finally, Raisamo et al. (2019, p.137) suggest that audio-based feedback is vital to wearable enhancement technology as it provides a seamless means to bridge the physical and digital worlds, enabling immersive mixed realities.

Choosing audio over tactile feedback itself has consequences. Specifically, headphones usually deliver spatialised audio[20] that blocks ambient sounds and impairs spatial awareness (Wilson et al., 2007). Bone conduction is an alternative to headphones (Asakura, 2021; Voong and Oehler, 2019). This technology still has two significant drawbacks: (i) the transducer must be firmly pressed to the skin surrounding the ear, causing discomfort in the wearer; and (ii) the transmission of acoustic information is poor due to multiple tissues between the transducer and the inner ear, limiting the perceivable frequencies (Beros et al., 2021; Håkansson et al., 1984). Furthermore, wearable bone conduction systems are 10 to 25 decibels quieter than implanted systems (Beros et al., 2021; Harder et al., 1983). Finally, bone conduction systems are limited to reproducing frequencies between 250Hz and 4kHz (Stenfelt, 2011), compared with the full range of human hearing of 20 Hz to 20 kHz.

Soft tissue conduction could solve the disadvantages of bone conduction technology. This research branch investigates auditory stimuli induced by vibrating the skin and soft tissues other than the skull

[20] Spatialised audio, or binaural spatial sound, is an umbrella term for denoting digital technologies developed to present listeners with the impression that a sound emanates from a point in three-dimensional space by using standard headphones (Cuevas-Rodríguez et al., 2019).

bones, such as the cheeks, neck, and thorax (Sohmer, 2017). Soft tissue conduction has also been referred to as non-osseous bone conduction (Adelman et al., 2012; Ito et al., 2011) and body conduction in the literature (Berger et al., 2003). Current research has proposed soft tissue conduction to cause several low-level auditory phenomena, such as hearing the soft scratching of fingers on the cheek and perceiving sound underwater or in noisy environments, despite heavy hearing protection (Sohmer, 2017). The benefits of soft tissue conduction include a reduced sound intensity threshold required to elicit a reaction (Berger et al., 2003) and avoiding the transducer's direct contact with the skin or bone (Sohmer, 2017).

In conclusion, enhancing an agent's understanding of digital affordances in a physical environment via spatialised audio feedback is a compelling and rich area to test the design guidelines of sensory layering. Two central problems, though, emerge from this context. As discussed in chapter 2.6, enhancement technology should signify hidden affordances without hindering the agent's pre-existing senses. Second, a motion-tracking system is needed to accurately blend physical and digital environments. Previous literature addresses the first issue by employing bone conduction headphones but with all the abovementioned difficulties. In this project, I address the shortcomings of bone conduction technology by designing a new headset that integrates bone with soft tissue conduction, as explained in section **Error! Reference source not found.**. Sections **Error! Reference source not found.** and 6.2.1 introduce the experimental setup and the trials I conducted with the prototype. Section 6.2.2 covers the problem of movement tracking, outlining how Ultra-Wideband enables us to track agents with centimetre-level accuracy. Finally, 6.2.3 outlines the design of a mixed reality environment using Unity3D, a video game engine, that combines the hybrid bone and soft tissue conduction headset with the motion tracking system in an experiential prototype.

6.2 Designing Wearable Mixed Reality Enhancements

As noted above, designing wearable enhancements for signifying digital affordances is a complex problem that necessitates traversing the domains of sonification, physiology, tracking technology, and hybrid reality. The concepts of sensory layering can provide a solid foundation for approaching it. The agent can navigate a physical world by *following digital cues contextual to their position in space* (design guideline 1). As discussed, two possible senses are accessible for layering additional cues (design guideline 2): *touch and hearing*. For the reasons already discussed, I chose to focus on spatialised audio in this prototype.

The wearer should perceive the sound (design guideline 3) through *a system that does not impede their pre-existing senses.* This requirement excludes standard headphones as they physically obstruct the wearer's ear. While bone conduction meets the requirement of unobtrusiveness, it is insufficient on its own. These disadvantages could be mitigated by combining bone with soft tissue conduction, as discussed in section 6.1.3.

This wearable system's positioning (design guideline 4) *is deceptively nuanced*. Because sounds supplied by bone and soft tissue conduction are considerably attenuated the further away the transducers are positioned from the inner ear (Röösli et al., 2021), they should be placed as close to the ear canal as feasible without impeding it. While modern bone conduction headsets are typically positioned on the temporal bone or the mandibular condyle (Joubaud et al., 2020), as shown in Figure 6.4, soft tissue conduction systems can be placed on the head not directly above skull bones, eyes, neck, chest or back (Sohmer, 2020). During the prototyping phase, the designer can experiment with positioning the soft tissue conduction transducers in any of these positions.

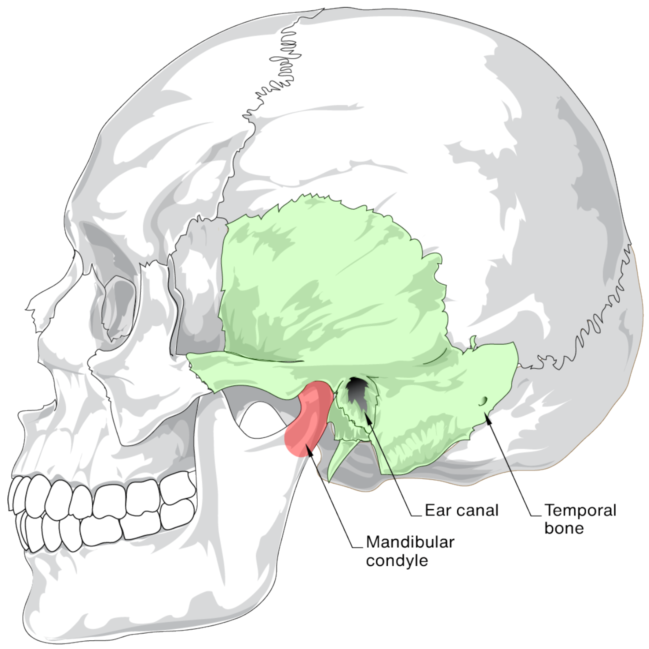


Figure 6.4 The mandibular condyle is the mandible's closest point to the ear canal. The temporal bone is the skull plate surrounding the ear canal. These are the two ideal locations for bone conducting systems (Eeg-Olofsson et al., 2011) as they are the closest to the ear canal.

In relation to Guideline 5, *design for accessibility and* distribution, the unique hybrid bone and soft tissue conduction headset presented in this chapter was designed using readily available hardware and modelled in Fusion 360, CAD software that offers a free tier for non-commercial use. Third parties should also be able to reproduce the test method. Similarly, Unity 3D is a cross-platform software that supports all major operating systems and mobile phones, enabling the creation of mobile mixed realities. Further, Unity 3D is free for personal and academic use and is an effective tool for researchers (Nakano et al., 2016, p.95). Finally, Unity 3D offers extensive flexibility thanks to its scripting environment, allowing developers to extend the game engine's core functionality by writing C# code.

Particularising the Guidelines for this Case Study, one can say:

1. The system should signify to the wearer digital affordances embedded in the physical environment,
2. It should use audio feedback to convey the hidden digital affordances. The wearable audio system should be unobtrusive without blocking the agent's ears,
3. As a consequence of point 2, the system should employ a combination of bone and soft tissue conduction to deliver sound to the wearer,
4. Because of the technology it depends on, the wearable should be placed around the wearer's ear canal without occluding it,
5. The experiential prototype should be open-source. Third parties should be able to easily build the wearable and customise it to their needs. The simulation, spatialised sound engine, and movement tracking method should also be readily accessible.

The remainder of this chapter will first detail the hybrid bone and soft tissue conduction headset's design and testing findings compared to off-the-shelf bone conduction headphones and traditional air conduction headphones. This chapter examines how human movements may be tracked indoors and how that information provides contextual audio cues.

6.2.1 Hybrid Bone and Soft Tissue Conduction Headset

To address bone conduction's drawbacks outlined in the previous section, the headphones outlined in this chapter integrate bone conduction with soft tissue conduction. By using two transducers loosely pressed on the skin[21] – a piezoelectric disk positioned on the zygomatic process and a high excursion moving coil exciter positioned on the cheek – the mechanism can convey a broader range of frequencies than off-the-shelf bone conduction headsets (e.g. Aftershockz Trekz Air Wireless, USA). The hybrid mechanism operates as follows: a sound input is applied to a stereo amplifier to which two transducers are connected in parallel. The piezoelectric disk reproduces the high frequencies, while the surface transducer the low frequencies. Figure 6.5 illustrates the proposed mechanism's signal pathway from the audio input to the inner ear. The hybrid bone and soft tissue conduction headset was fabricated through custom integration of piezoelectric and electrodynamic transducers, comprising a piezoelectric transducer with a diameter of 10mm, a DAEX-9-4SM moving coil exciter by Dayton Audio and a custom enclosure 3D printed using Polylactic Acid (PLA) plastic. The headphones were tested with an external 20W amplifier (Lepy LP-2024A+).

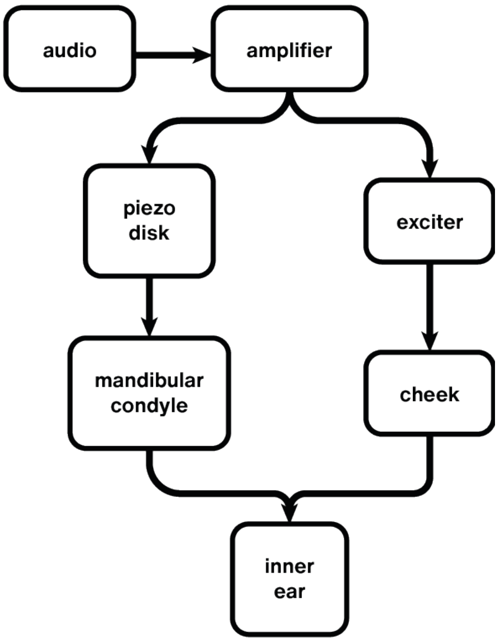


Figure 6.5 The audio signal is amplified using a headphone stereo amplifier. This signal is then sent to a piezoelectric transducer on the mandibular condyle (the region of the mandible closest to the ear canal) and a moving coil exciter on the cheek. The audio then travels to the inner ear via bone and soft tissue conduction.

Building onto chapter 5, which focussed on the fundamental importance of body-moulded wearable systems, the headphones were designed from a body-centric perspective. Dissimilarly to chapter 5, I did not employ a 3D scan of my head for this project, as I wanted to explore other prototyping methodologies that did not require additional materials, such as digital cameras. Instead, I used an anatomically precise, gender-neutral model (Brown, 2019) as the starting point for digitally "moulding" the wearable. Figure 6.6 shows that the headset has two sections linked by a metal stiffener. The ear hook conforms to the area around the wearer's ear. It houses the 10mm piezoelectric disk for bone conduction, positioning it on the wearer's mandibular condyle, as shown in Figure 6.7. This positioning was selected as the condyle is reported to be the most receptive location, as it

[21] 1N, measured with a membrane force sensor, model MF01-N-221-A01.

requires the lowest threshold level to elicit responses compared to the mastoid or other positions on the skull (McBride et al., 2008; Qin et al., 2020).

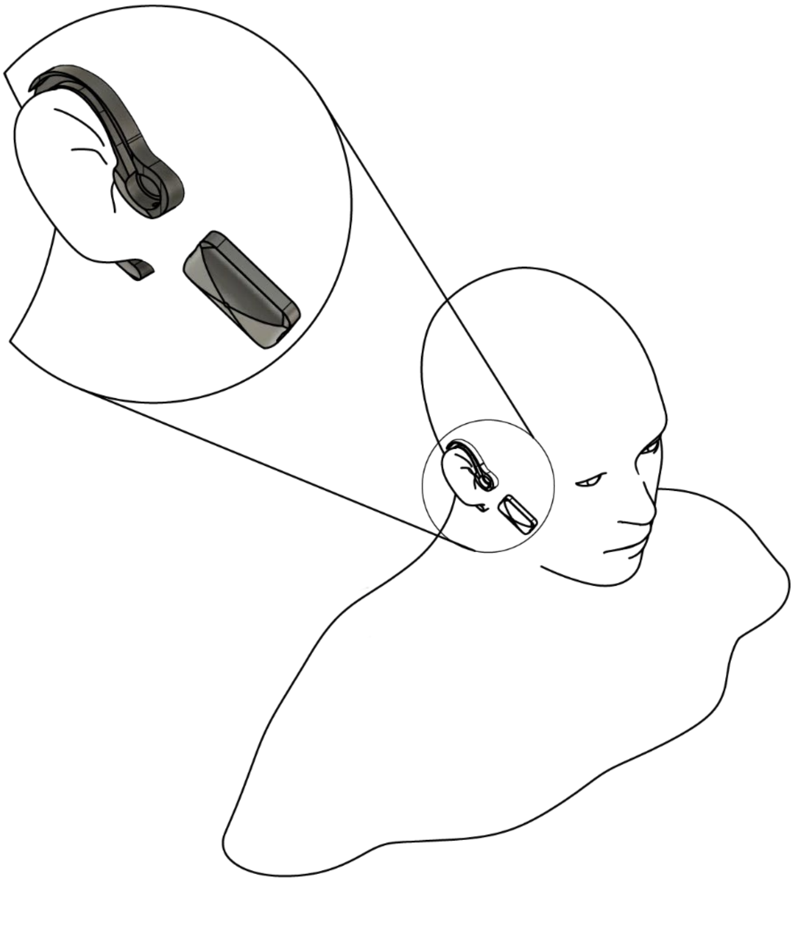


Figure 6.6 The hybrid bone and soft tissue conduction's positioning onto a wearer.

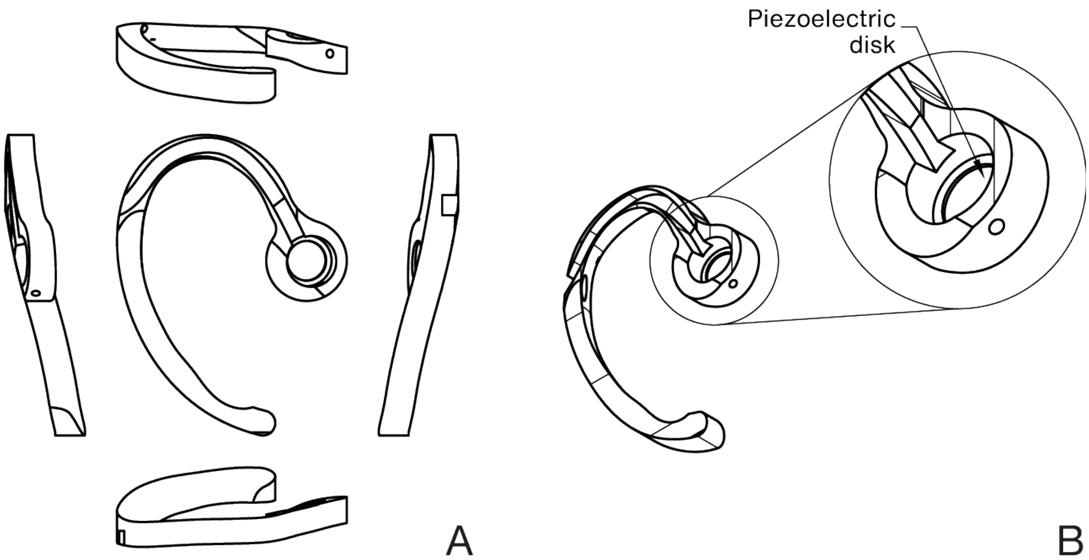


Figure 6.7 Figure 6.7A depicts the orthographic projections of the ear hook design. The contour of the ear hook was moulded onto a gender-neutral anatomical reference model (Brown, 2019). Figure 6.7B illustrates a detail of the ear hook, a cavity for a 10mm piezoelectric disc. This disc is placed loosely on the wearer's skin above the mandibular condyle. A channel can be seen going from the piezoelectric disc location to the opposite end of the ear hook in both Figure 6.7 A and B. This channel routes the signal wires leading to the piezoelectric disc and the moving coil exciter.

The moving coil exciter was positioned on the wearer's cheek. Although the literature identified several possible locations for soft tissue conduction, I chose to locate the exciter close to the ear hook sound signal. The exciter selected for this application, the DAEX-9-4SM, is a compact device, measuring 24x11x5mm, with 4 Ohm impedance, appropriate for small, battery-powered audio listening devices due to its minimal power use (Dayton Audio, 2021). The manufacturer designed this exciter specifically for haptic feedback for mixed reality applications and it came pre-installed with self-adhesive tape suitable for applying on the skin, as it resists oils, water, and ultraviolet light (3M, 2018). Figure 6.8 shows the exciter enclosed in a 3D printed housing. For more details on how I tested this wearable, see This page *was intentionally left blank.*

Appendix C.

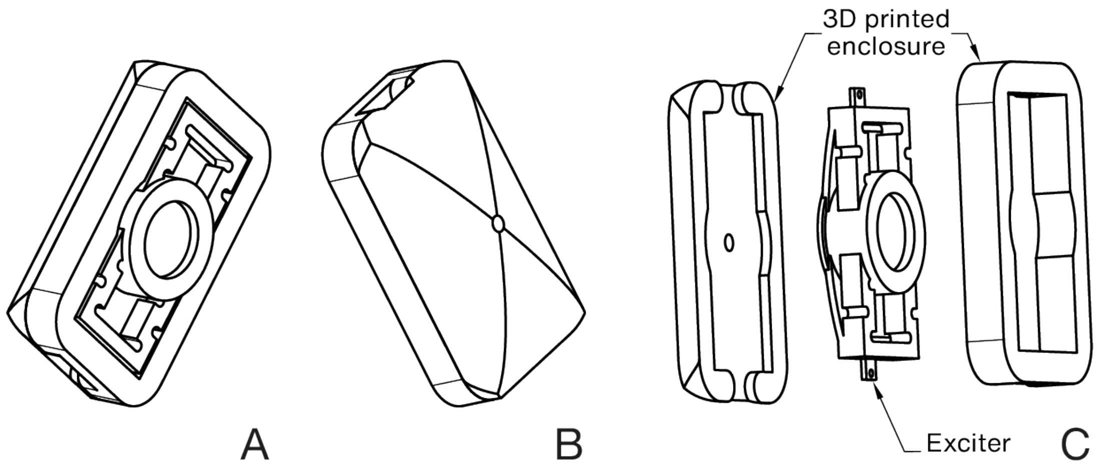


Figure 6.8 The assembly housing the moving coil exciter to be positioned on the wearer's cheek. A and B show, respectively, the front and back views of the assembly. C shows an exploded view of the assembly, with the exciter firmly secured between the 3D printed parts.

6.2.2 Real-Time Location Services

I paired the wearable described above with an indoor localisation system and a Unity simulation to create targeted audio cues for human agents navigating a space. I implemented a Real-Time Locating System (RTLS) using Ultra-Wideband (UWB) technology to track users and objects within an indoor environment. I selected UWB after comparing several localisation options like Bluetooth, Wi-Fi, and RFID, for its high accuracy and resistance to interference, making it particularly suitable for hybrid reality – especially when indoors. Although UWB requires dedicated hardware, it offers centimetre-level precision, making it suitable for ensuring smooth and real-time overlap between physical and digital environments.

UWB works by measuring the time of arrival (ToA) of pulsed radio waves from fixed nodes to the mobile tag, allowing the mobile tag's position to be tracked in real-time. I selected the Decawave MDEK1001 system for this project due to its open-source nature, cost-effectiveness, and built-in support for several tags simultaneously – in response to Guideline 5. The system publishes location data to a Raspberry Pi, which in turn forwards the location information over a Wi-Fi network. Any device connected to this network can 'subscribe' to the data. As discussed in the next section, I used Unity to process this spatial data. For more detailed technical information, including configuration and setup processes, refer to Appendix 0.

6.2.3 Unity for Audio-based Mixed Reality

As the introduction mentions, Unity is a graphics engine for developing cross-platform applications. A project developed with Unity can be deployed on Windows, macOS, Linux, Nintendo Switch, PlayStation, Xbox, Android, iOS, Google Stadia, virtual and augmented reality devices. Unity can be installed on a computer with a Windows or macOS operating system, has a user-friendly interface and presents all the typical features of 3D graphics software, from the construction of three-dimensional scenes to the setup of lights and materials, up to the scripting of additional properties, via its support for custom software written in C#. Unity is particularly suited to build mixed realities that stream location data via MQTT, as it supports integration with the .NET framework (Patierno, 2019).

I set up an immersive audio-based hybrid reality experience using Unity in my apartment. I modelled the virtual environment to mirror the apartment's layout, incorporating the walls, floors, and materials like brick, wood, and glass to simulate their acoustic properties accurately. I then combined UWB location tracking and smartphone gyroscope data to capture both the wearer's position and facing direction to ensure precise spatialised audio.

I also programmed two virtual agents generating footsteps as they moved through the space. The overall setup allowed the human agent to navigate the space while receiving contextual sound cues aligned with their movements and orientation, as shown in Figure 6.9. For further technical details, including screenshots, system architecture, and code implementation, refer to Appendix E.

Figure 6.9 Conceptual visualisation of how the hybrid bone and soft-tissue conduction headset, RTLS and Unity came together in a cohesive experience for the wearer.

6.3 Discussion and Conclusion

While research about mixed reality settings abounds, it focuses on hybridising digital and physical worlds via visual methods, such as head-mounted displays. Concurrently, sonification positions itself as a valid alternative to visual-based mixed realities, as it maintains low levels of obtrusiveness and even offers higher degrees of immersion. Bridging physical and virtual environments with a mixed reality experience is particularly relevant to this thesis, as it exemplifies its core argument. Wearable technologies that enable the bridging of the two domains constitute an enhancement, as it allows for the interaction of hidden digital affordances. Digital affordances, such as audio cues, offer a rich testbed for the guidelines of sensory layering. These affordances are signified to the wearer via an unobtrusive headset to avoid hindering the agent's pre-existing senses.

The research presented in this chapter approaches the design brief of human enhancement by layering audio data in two ways. From a body-centric perspective and building onto the procedures outlined in chapter 5, this chapter explores bone and soft tissue conduction to convey spatialised audio to the wearer. This body-moulded wearable headset can deliver a broader frequency spectrum than modern, off-the-shelf bone conduction headphones. Secondly, this chapter outlines the technologies available for tracking people's location indoors, focusing on Ultra-Wideband sensors and MQTT. Combining these sensors and transmission protocol allows precise, affordable and open-source indoor tracking in a format easily interpretable by other software packages. I specifically employ Unity and the Resonance API to feedback spatialised and contextual audio to wearers exploring the mixed reality environment.

The wearable presented in this chapter could be applied in several cases. For example, such a device could be used in training or educational scenarios, where the user can practice interacting with virtual characters in various situations. This use case could improve the wearer's communication, social, or other skills. Additionally, a wearable that allows a user to interact with virtual agents could also be used for entertainment or recreational purposes, providing an immersive and interactive experience for the user.

6.3.1 Reflecting on the Design Guidelines of Sensory Layering

Trying both approaches – using a body-specific scan in chapter 5 and opting for a gender-neutral, generalised model in this project – has sharpened my understanding of the trade-offs between individual fit and broader applicability in wearable design. The body-scanning approach excels in comfort and integration, aligning with the sensory layering guidelines where the wearable becomes a natural body extension. However, using a generalised model has revealed the benefit of wider adaptability; while the fit is less precise, it accommodates a broader range of agents, making the design more versatile.

Although I present this case study last in this thesis, it was the first one I conceived, even before applying to the PhD. I collaborated as a service designer at the time with the Royal Opera House, developing new service concepts to use in the space when plays were not being shown. I thought that it would be fascinating to record the performances and play them back in off-hours, with the added immersive element of being able to walk around the venue.

Although this concept was not successful with the Royal Opera House, it came back to me when I wondered whether *agents could access hidden digital affordances* (Guideline 1). I specifically chose digital affordances because I was aware of immersive theatre production companies, such as Punchdrunk[22], and I was keen to *explore non-visual feedback mechanisms* (Guideline 2).

The first option for *establishing the feedback between physical and digital agents* (Guideline 3) was headphones. However, that approach would not align with sensory layering; instead, it falls into the sensory substitution (Bach-y-Rita and Kercel, 2003) domain. I then purchased a set of bone

[22] Punchdrunk is a pioneering immersive British theatre production company. Their plays do not take place on a stage but in a space, with actors moving throughout it. Spectators wear masks and capes and are free to follow any actor or stay in a room.

conducting headphones so the agent would not have their senses occluded. However, I quickly realised that the trade-off between sonic fidelity and sensory layering was not suitable for my application. Hybrid Reality (Azuma, 1997; Milgram and Kishino, 1994), as discussed in this chapter's introduction, requires high degrees of immersion and three-dimensionality – elements that were lacking in off-the-shelf bone conducting headphones.

This point spurred my practice to *find more suitable feedback mechanisms* (Guideline 4), eventually leading me to the emerging field of soft tissue conduction and my final design of the hybrid bone and soft tissue conduction headset. This reflective approach of theory (sensory layering) → practice (bone conduction) → theory (soft tissue conduction) → practice (wearable headset) highlights once again how fruitful and suitable reflective practice is to create new meanings for enhancement theories.

Finally, this final case study directly shaped my decision to explicitly state in my guidelines the need for *designing for accessibility and distribution* (Guideline 5). As I anticipated in chapter 3.3, I was given the opportunity to patent my hybrid headset, given its novel approach to delivering sound to the wearer. Although tempting, I ultimately decided not to pursue a patent, because I could only design the headset – not to mention the redundant actuating assembly and the wearable compass – by relying on open-source technologies. I solidified this final reflection by adding the fifth guideline to my framework.

Going back to the foundational theories driving my research, from an Embodiment perspective, I realised that a personalised, body-moulded design enhances the sense of ownership and makes the enhancement feel more blended into the agent's perceptual and motor routines. In contrast, while less tailored, the more generic design raises interesting questions about how quickly agents can adapt to such devices. This tension between personalisation and versatility is notable in deciding the focus of wearable technologies – whether they should prioritise a close fit or broader adaptability. This case study pushes me to think about how future designs can balance individual customisation and transferability, especially when scaling up for different users is a key objective – albeit it was beyond the scope of this case study.

Ultimately, this experiment has made it clear that Guideline 4 encompasses a spectrum of solutions, each of merit. In my case, I opted for established design paradigms for wearable audio – an ear hook – but several other approaches could have been equally valid depending on the specific goals of the enhancement. For instance, more experimental placements like neckbands or collarbone-attached designs could offer different affordances, particularly in balancing audio fidelity with spatial awareness. Exploring these alternatives would involve trade-offs in body compliance and comfort, which ties back to the tension between personalised fit and generalised usability.

This experiment has highlighted that the positioning of wearable audio components is not a one-size-fits-all decision but a strategic choice influenced by the intended interaction between the new sensory input and the pre-existing sensory contingencies of the user. By selecting a familiar ear hook design, I prioritised ease of use and adaptation, aligning with the sensory layering guidelines. However, this decision also revealed limitations, especially in maintaining contextual awareness and immersion across environments without compromising audio clarity, hence my integration of bone with soft tissue conduction.

Using bone and soft tissue in conjunction evidenced the possibility of improving audio conduction headphones by integrating a second transducer on soft tissue close to the ear canal. Additional research can optimise the positioning of the moving coil transducer to maximise its sound output.

According to the literature, possible locations would be the mastoid process, the neck or the frontal bone. Finally, the experimental results above can enhance audio playback on bone conduction devices by suggesting which frequencies should be dampened or boosted during post-processing and equalisation.

Unlike chapter 5, I successfully prototyped the experience using only open-source and free software. On the hardware side, though, I rely on a proprietary sensor commercialised by Decawave. Although open-source and easily accessible, Decawave's solution might pose a barrier to entry, as a basic setup requires four nodes and a tag for around 20 British Pounds per unit. On the other hand, these sensors offer centimetre-level accuracy and an extensive scripting API for integration into other software.

6.3.2 Limitations

The prototype presented in this chapter has several limitations. Although relatively easy to reproduce with an FDM 3D printer, the wearable system requires 10mm piezoelectric discs, which are not readily available to purchase and often are supplied without a datasheet. Further, the assembly requires soldering additional wires to the piezoelectric disks. This operation is hard to perform without a soldering iron with thermal mass sufficient to overcome that of the piezoelectric disk. Further, although the wearable's ear hooks are small, they do not contain a battery, requiring an external voltage source. Further research can address this issue by implementing miniaturised and wireless power delivery systems similar to commercial wireless earbuds. Finally, the transducer on the cheek is currently attached to the wearer's skin with the provided adhesive tape. This is not a reusable solution that can be addressed with other biomimetic approaches to anchoring and skin-safe adhesives, such as gecko-inspired dry adhesives (e.g., Cho et al., 2012; Hu et al., 2012).

The immersive mixed reality system's main limitation is its scale, as it was deployed in my flat instead of a public or larger space. The system was designed to be scalable to address this shortcoming. The choice of the sensor allows for scaling the implementation to large indoor locations: the DW1000 has a range of up to 290m if line of sight is available and 45m if it is not (Decawave, 2014).

This final case study underscored the nuances embedded in the sensory layering guidelines. Guideline 4 emerged as particularly critical when designing a wearable audio system. The exploration of bone and soft tissue conduction highlighted how positioning and sensory modality interact and influence each other. The necessity to balance audio fidelity with maintaining the wearer's spatial awareness led me to deeper reflections on how sensory layering must adapt to the changing environments in which agents operate and the physical diversity of agents themselves. Through this, I refined my understanding of how sensory enhancement technologies can be both body-compliant and versatile enough for general use – critical insights that refined the design guidelines.

Crucially, this case also contributed to answering the broader research question by exemplifying how design methodologies and reflective practice can uncover hidden affordances. Integrating the physical and digital domains through a body-centric interface aligned with and expanded upon current affordance theory by demonstrating how mixed realities can extend sensory perception in contextually embedded ways. This provides a fresh lens through which we can understand the relationship between human agents and their environment – an increasingly relevant lens as we move toward hybrid realities.

In relation to Embodiment Theory, the project illustrated that merging new sensory channels with existing ones is not merely a technical exercise but a profoundly embodied negotiation. The feedback loops between digital and physical domains rely on synergies between the agent's sensory capacities and the technology's capabilities. This project offers insights for theorists and practitioners alike: the challenge of enhancement for mixed reality lies in creating immersive experiences via new senses.

7 Conclusion: reframing Enhancement through Design Practice

The assumptions of enhancement have always been problematic, perhaps even more so because of the implicit associations with the word ‘human’. Despite recent rapid technological progress and the historical shadow of eugenics, the enhancement problem is very much not solved. This is partly because the current debate is often theoretical, making it challenging to articulate clear examples of what enhancement means.

Is it a pill for increasing attention spans? Is it a bionic leg that gives you a little ‘boost’ when climbing stairs? Is it the prospect of never dying, frozen in liquid nitrogen until we have the technology to wake you up? Why is ‘enhancement’ usually discussed in tandem with ‘human’? What even is a human? Where do we draw the line between enhancement and augmentation? Is enhancement primarily about sensory experience or action? Why is ‘normal’ the baseline for enhancement, and what does ‘normal’ actually mean?

I believe the enhancement field requires a fundamental shift from problem-solving to problem-finding, as discussed in chapters 3.3.2 and 3.3.3. As designers, traditionally, we identify a clear need or want and then propose solutions. However, these new technologies introduce complexities that require us to rethink what it means to be human, what constitutes “normal”, and how often unspoken norms shape these concepts.

In this thesis, I set out to reframe enhancement technologies through a design lens, as reflected by my research question: *How can design re-think the approach to enhancement technologies?* My objectives were twofold: first, to challenge dominant paradigms by grounding enhancement in embodiment theory, design cybernetics and affordance theory, and second, to locate the distinctive contributions that design can offer. I achieved these goals by combining theory and practice, using each to inform and improve the other through reflective practice, as I will discuss in this chapter.

To address the first sub-question – *How can a pragmatic design framework for enhancement technologies be developed from an embodied approach?* – I developed guidelines centring the body as the only necessary reference point. In practice, this took shape through iterative making and reflecting on my case studies (Glanville and Pak, 2010; Polanyi, 1966; Schön, 1983), as discussed in chapters 4 to 6.

In answering the second sub-question – *What are the critical points that practitioners should consider when designing enhancement technologies?* – my practice-led research revealed three key priorities: seamless sensory integration, body compliance, and retaining context-awareness. These three priorities respectively emerged from the three case studies. Each case study contributed in shaping and re-shaping the focus points: sensory integration via layering existing sensory modalities (e.g., Bach-y-Rita and Kercel, 2003; NXP Semiconductors, 2021) body compliance (Gemperle et al., 1998; Zeagler, 2017) and context awareness (Rekimoto and Nagao, 1995).

To answer the third sub-question – *How can a design framework for wearable enhancements be transferred to other practitioners?* – I created a framework composed of five guidelines that capture ways of working and questions that, when asked by different practitioners, would lead to enhancement systems different from those detailed in this thesis. The adaptability of the framework is vital: rather than prescribing a fixed solution, it encourages different outcomes – an innate characteristic of frameworks (Jabareen, 2009; Levering, 2002) and guidelines (Greer et al., 2008; Matthews et al., 1998). The cross-fertilisation between theory and practice was vital here. Insights gained from prototyping – like designing a self-contained new sense for human-made agents in Case Study 1 or the challenges and attention in body scanning in Case Study 3 – directly informed how I developed and refined these guidelines.

Further, I intentionally used the term 'guidelines' rather than 'principles' or 'heuristics', as discussed in 2.6.1. Unlike principles, which are broad and universal, or heuristics, which depend on rules of thumb, guidelines provide a flexible approach that is inherently context-driven and encourages refinement. I chose this term to ensure that the framework remains relevant across contexts, guiding practitioners in ways best suited to their objectives while leaving room for creative freedom and contextual situatedness.

The final sub-question – *How can a framework be developed that guides practitioners without prescribing a checklist?* – was parallel to the previous question. I deliberately avoided rigid, step-by-step instructions in favour of dynamic guidelines that evolve through iterative design and reflection. I can only report my reflections on the framework, but I found it extremely helpful in navigating unknown bodies of knowledge to pick out the information I needed to start my practice. I did not have to know everything about actuators, AI or robot architectures to design Case Study 1. I did not have to become an expert in ergonomics for Case Studies 2 and 3. Instead, my guidelines provided a structured approach that allowed me to integrate technical knowledge effectively without being a specialist in every domain. Sometimes, as detailed in the last two Case Studies, I found the framework lacking in specificity, which led me to go back to theory – microinteractions (Aleksy et al., 2016; Saffer, 2013) and research about wearable placement on the body (Zeagler, 2017) – to add nuance to Guidelines 3 and 4.

7.1 Theoretical Contribution

Contradictions and tensions mark the debate surrounding enhancement technologies that I must acknowledge and explore. One fundamental concern is the dichotomy between the desire for enhancement (Al-Rodhan, 2011; Boström, 2005a) and the fear of losing humanity's essence (Agar, 2013; Fukuyama, 2002, p.101; Pugh et al., 2016). This tension is mirrored in the literature, where some scholars advocate for rapid advancement and adoption of enhancement technologies as a means to solve pressing problems such as disease, death, and suffering (Boström, 2005b; More, 2003; Pearce, 1995, p.14), while others propose a more cautious approach to ensure responsible development and deployment (Cabrera, 2017; Ida, 2010).

These tensions are not mutually exclusive but rather intersect and overlap. For instance, the desire for enhancement can sometimes be at odds with the fear of losing one's essence, while the push towards progress may be driven by a wish to preserve existing social structures.

Rather than caving to binary thinking that pits progress against preservation, my research argues for a more nuanced approach by integrating the perspectives of embodiment, cybernetics, and affordance theory into design practice. My core theoretical contribution lies in how these fields when woven together through practice, provide a more pragmatic and context-sensitive understanding of enhancement – one that avoids the need for rigid definitions of "human" or "enhancement". Instead, I propose reframing enhancement as empowering agents – whether human or human-made – to perceive and interact with hidden affordances in their environments.

By shifting focus from 'human' to 'agents', I address a key issue in the enhancement debate: the unspoken assumptions underlying what it means to be 'enhanced' (Parens, 1998; Sanzeni et al., 2022). Traditional discussions often hinge on defining and preserving an idealised version of humanity, which can lead to both philosophical dead-ends and ethical conundrums. My approach circumvents these pitfalls by treating the agent's body and situated experience as the primary benchmark for enhancement.

My research challenges Cartesian dualism of the mind as separate from the body, grounding experience in embodiment: agents make sense of the world by interacting with it (Foglia and Wilson, 2013; Garbarini and Adenzato, 2004; Seth and Bayne, 2022). I found that by designing enhancement technologies around the body's senses (or lack thereof), rather than imposing ideals of enhancement, I can translate theoretical insights into experiential prototypes and vice versa.

This understanding was informed by my concept of *sensory layering* – a term I introduced to denote the design practice of integrating new sensory information without impeding existing senses. Sensory layering moves enhancement theories forward by offering concrete footing for designing enhancements, for moving from the lab and seminar to the street – to paraphrase Buchanan (1992, p. 6).

Besides embodiment theory, my research extensively draws on first- and second-order cybernetics. First-order cybernetics offers epistemological grounding for understanding how systems interact with their environments through feedback loops (Rosenblueth et al., 1943), while second-order cybernetics introduces the observer as an inseparable part of the system (von Foerster, 2003a).

Notably, second-order cybernetics and design share many commonalities, as designers do not design only 'in their head' but externalise their thoughts through practice (Glanville, 2009, 2007; Sweeting, 2016, 2015). In other words, I (the designer conducting this research) am part of the system and will inevitably bring my bias and past experiences into the outputs. This point reinforces two insights: (i) a design approach to enhancement cannot be universal, instead, it should recognise its situatedness, and (ii) enhancement is about feedback loops between the controller and the environment. This second point is particularly important in my research: as discussed in chapter 2.4, first- and second-cybernetic theories apply to both "Animal and Machine" (Wiener, 1948), hence, I opted to shift my wording from 'human enhancement' to 'agent enhancement'.

My reflective-design cybernetic approach echoes the work of Glanville (2009), who positioned reflective practice as inherently cybernetic. Glanville's view aligns with the idea that conversation is central to design processes, where dialogue – whether between individuals or within the self, as in the case of my research – facilitates iterative learning and exploration. Glanville mirrors Schön's (1983, p. 76) description of design as a "conversation with the situation".

The relevance of cybernetics extends to my practice, particularly through Ashby's (1957, p. 207) Law of Requisite Variety. Through a Requisite Variety lens – that is, an agent's sensory complexity must match its environment – I reframed enhancement as increasing the sensory variety available to an agent via sensory layering, thereby expanding the range of sensory cues they can perceive. My reframing aims to bridge the gap between the theoretical and practical, offering a pragmatic approach to designing technologies that expand an agent's sensory reach.

I further refined this initial definition by relating it to Affordance Theory. Whereas 'traditional' affordance theory focuses on *real* and *perceived* affordances (Norman, 2013), my research extends this taxonomy by positing that enhancement can enable agents to sense *hidden affordances* – a term I introduce to denote opportunities for interaction that remain inaccessible due to the limitations of an agent's senses.

In my braiding – refined through practice – of embodiment, design cybernetics and affordance theory, I argue that enhancement technologies should be understood as systems designed to reveal hidden affordances in the environment, enabling new forms of agent-environment interaction, as shown in Figure 7.1. I posit:

> *Enhancement is the practice of layering new senses onto agents, allowing them to access hidden affordances.*

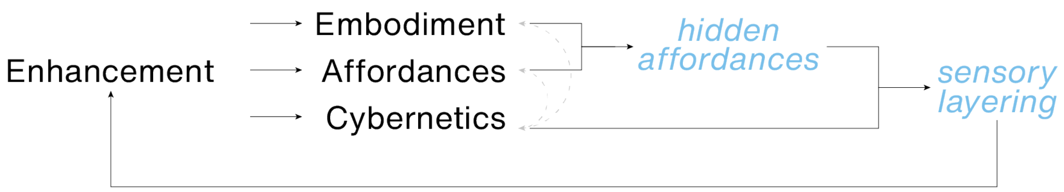


Figure 7.1 The interplay between the theories of embodiment, affordances and cybernetics. I re-theorise enhancement through the lenses of hidden affordances and sensory layering.

My theoretical position offers a more context-sensitive understanding of enhancement than the idealised and, sometimes, implicit models discussed in the literature. By focusing on the real-time interplay between an agent's body, its sensory extensions, and the environment, sensory layering provides a pragmatic methodology for designing theoretically robust and practically effective enhancements. My position does not prescribe a fixed methodology for enhancement. Instead, this position allows for a diverse approach to enhancement that is contextual to the targeted affordance and the agent's body.

My re-theorisation of enhancement shifts the debate from 'human' enhancement to an actionable framework that prioritises the agent's embodied experience. Further, it broadens the theoretical landscape by incorporating hidden affordances as a legitimate focus for design practice. Finally, it advances our understanding of enhancement by presenting sensory layering as a flexible design approach that can be applied across different contexts and technologies.

7.2 Methodological Contribution

Design researchers (e.g., Archer, 1979; Pickering, 2002; Sweeting, 2015) have long recognised that the design process can lead to a redefinition of the questions and objectives initially posed. In my case, however, reflective practice has not only prompted a reconsideration of the original questions but has also led me to reframe the epistemological basis of design in this area. To this point, my methodology bridges a gap in enhancement research, where theory often remains speculative and disconnected from practice, and practice frequently lacks a guiding theoretical framework.

My methodological contribution lies in how I translated my theoretical framework into practice using design guidelines. Further, my reflective practice allowed me to work through, rather than think through my framework – closing the loop between theory and practice. My guidelines surface key concerns for designing enhancement technologies – specifically, how to consider the agent's body, environment, and the interactions between the two. The guidelines operate at the intersection of theory and practice, offering an adaptable framework while still being deeply informed by the underlying theories.

Reflective practice (Ravanal Moreno et al., 2021; Rodgers, 2002; Schön, 1983) shaped my methodology, enabling me to develop and refine both theoretical insights and design outputs iteratively. The solitary nature of my reflective investigation was not a limitation but a strength, allowing me to deeply engage with the cyclical process of reading, thinking, making, and reflecting. The research itself, together with my account of it, provide new evidence of the value of reflective practice as a method with distinct advantages over the increasingly conventional approach of iteration based on user-testing.

Though not sequential and incremental in a traditional way, the three case studies I presented in this thesis acted as probes exploring different aspects of enhancement technologies. This methodological decision was intentional. Rather than focusing on incremental developments within a single domain, I chose to explore a range of contexts, each linked by its relationship to my overarching research question.

For example, the first case study demonstrated how embodiment can guide sensory layering for human-made agents, while the second focused on designing body-moulded feedback loops. The third case highlighted the challenges and opportunities of designing enhancements that remain both body-compliant and generalisable. By taking this approach, I developed a robust methodology across varied contexts rather than being confined to single instances. Also, each case study contributed to refining the guidelines themselves: the first one validated the guideline's relevance to human-made agents, the second case study prompted an exploration of microinteractions (added to Guideline 3) and on-body placement for wearables (added to Guideline 4), whereas the third case study made me reflect on the tensions between body-compliance and transferability, which led me to add Guideline 5. Moreover, I added this last guideline to stress the open-source community's contributions and address concerns about the unequal distribution of enhancement technologies (Opinium Research, 2020).

My methodological contribution lies in the five design guidelines that emerged from my reflective practice. Each guideline embodies both a theoretical principle and its practical application. Positioned at the intersection of my theoretical and practical contributions, my guidelines are a conduit for integrating conceptual understanding into real-world design processes. Together, they offer a structured approach for navigating the knowledge domains involved in designing enhancement technologies. They are:

1. Establish the hidden affordance,
2. Determine which sense to layer,
3. Establish sensory feedback loops,
4. Determine the enhancement's placement on the body,
5. Design for accessibility and distribution.

My guidelines purposefully avoid human-centred language, echoing cybernetics' agnosticism regarding systems. The first three guidelines stress the underlying approach of the framework by encouraging practitioners to assess the environment's hidden affordances first, then the agent's pre-existing senses, and finally, how these senses can be used to convey the chosen hidden affordance. These first three guidelines imply that the focus on enhancement technology shifts from the domain of philosophy to a pragmatic, practice-led domain. These guidelines are intended to be the starting point for the practice, resulting in experiential prototypes. The fourth guideline prompts practitioners to carefully address the agent's body and its pre-existing senses, or lack thereof. This guideline stems from my argument against seeking a standardised baseline to establish an enhancement system, as discussed in chapter 2.6. Instead, the agent's body constitutes the baseline with its peculiar sensorimotor contingencies. The final guideline captures the importance of considering how a new enhancement system will be distributed or accessed, directly addressing the literature highlighting the concerns of unequal distribution of these technologies. Figure 7.2 shows how my guidelines and case study came together through reflection to become my Sensory Layering Framework.

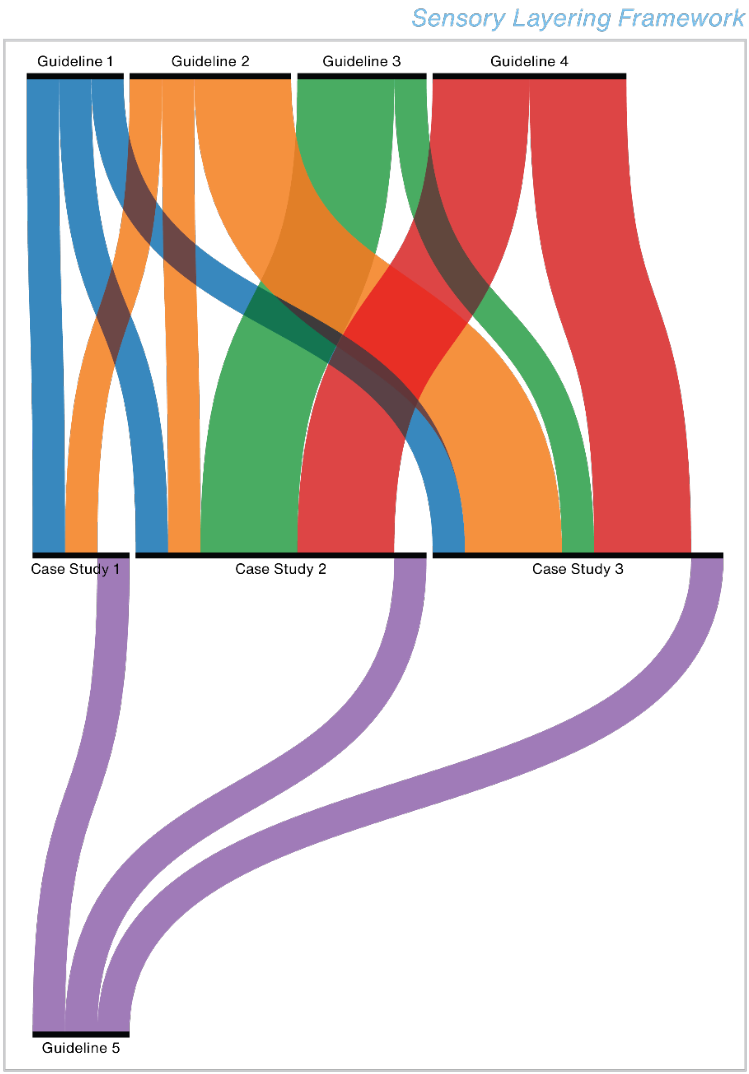


Figure 7.2 I initially postulated four guidelines. Through my case studies, I refined and added nuance to some of them, as shown by the thicker connections. At the end of my research I chose to add the fifth guideline, as discussed previously. These five guidelines constitute my Sensory Layering Framework – my methodological claim to new knowledge.

I position my methodology as a pragmatic extension of Critical Design. While my work shares Critical Design's aim of provoking dialogue through objects (e.g., Bleecker, 2009; Dunne and Raby, 2013; Thackara, 1988), it diverges by embedding these objects in experiential contexts rather than exhibiting them in galleries or museums. Focusing on prototypes meant to be worn and interacted with in everyday settings, I push Critical Design beyond provocation and into actionable practice.

My shift toward embodied experience offers a new way for design research to engage with the subtleties of enhancement technologies, where their implications are not merely talked about but experienced. Instead of showing and telling about enhancement technology, I demonstrate the case for embedding it in everyday interactions.

This experiential approach connects directly to my decision to prioritise reflective practice over user testing. User testing, while valuable in refining designs based on direct feedback and identifying usability issues, is fundamentally an evaluative method. It is suited to refining existing products rather than creating frameworks that challenge or reimagine the understanding of a field. Reflective practice offered richer insights for my research, which is fundamentally concerned with proposing new meanings of enhancement.

In this context, my reflective practice framework, though initially developed primarily for my own work, is particularly valuable for designers balancing theoretical rigour with pragmatism. The framework offers a structured approach that is agnostic about technologies and types of agents. The experiential prototypes in this thesis contribute to my research by exemplifying how the design guidelines for enhancement technologies support practitioners in reframing the matter, consequently producing innovative solutions (Dorst, 2015, pp.144–145; Paton and Dorst, 2011).

This point is in line with the literature on reflective practice and externalisation, where the designer clarifies a problem through the act of making and evaluating, coupled with bespoke terminology and a route to action that affords several possible actions, generating an "epistemology of practice" (Schön, 1983, pp.132–133). Consequently, the design guidelines in this thesis allow practitioners to generate either completely new solutions or, to borrow Tonkinwise's words (2011), the "not-so-new-as-to-be-unimplementable". The contextual and situated practice of (re)framing enhancement technologies based on the agent's body is a critical, creative process (Paton and Dorst, 2011) that allows us both to design buildable and desirable prototypes and create a dialogue between the experiential prototype and its theoretical grounding. In this way, design practice becomes a tool for innovation, leading to a significantly different lens for doing so (Dorst, 2015, pp. 143–144).

Ultimately, the methodology I developed serves as a compass for navigating the tension space of enhancement technology design. It is not just about creating functional prototypes; it is about creating systems attuned to the embodied experience of agents, integrating theory and practice in adaptable and actionable ways. This approach aligns with design-driven innovation, where the focus shifts from refining existing solutions to envisioning new meanings and languages (Norman and Verganti, 2014; Verganti, 2008) – precisely the stance I advocate in addressing enhancement technologies.

7.3 Practical Contribution

As I mentioned in chapter 3.1, one of my objectives was to move the conversation about enhancement "beyond the library or the laboratory" (Buchanan, 1992, p. 6) into embodied artefacts. By exploring new ways to integrate existing senses, wearable technologies, and access to hidden affordances, my research provides actionable and transferrable insights for other practitioners. My contributions are not just theoretical; they offer concrete tools and approaches that can be applied to future research, helping others push the boundaries of what enhancement is and can be.

In the first case study, I used the guidelines to determine the design brief for exploring how sensory layering could enhance the motor redundancies in a robot. I determined that the robot's controller should predict faults in its actuators using a continuous stream of acceleration data interpreted by a machine learning algorithm. This premise allowed me, a designer without formal training in robotics, to individuate the tools and technologies necessary to develop a functional prototype. I specifically focussed on unsupervised machine learning with K-clustering algorithms, motor coupling and Edge Computing. This project resulted in a novel redundant actuator and sensing system that can be used when the application requires high resilience and an Internet connection is unavailable.

The new knowledge produced from this case study includes the application of sensory layering to enhance robotic fault prediction, the integration of machine learning for autonomous diagnostics, and using Edge Computing for decentralised operations. Practitioners can apply these insights to design more resilient robots in scenarios with limited data connectivity. Further, practitioners can transfer my approach of using unsupervised learning for adaptive fault detection in their domain-specific applications.

The second and third case study focused on human agents. Consequently, the attention and sensibility to positioning the system on their body were more significant than in the first case study. This element of care led to designing a Structure from Motion-based design pipeline for body-moulded wearables. The outcome of this project was an experiential prototype that signifies to the wearer the hidden affordance of North via haptic feedback. The novelty of the wearable did not lie in the technologies used, as they were an integration of off-the-shelf solutions. Instead, this prototype's contribution lies in charting an approach to developing wearable systems that are moulded onto the specific agent's body. As detailed in section 5.2, this approach allows for highly customised and body-compliant solutions and is transferable to other researchers' practices by employing Structure from Motion techniques.

The new knowledge produced in this case study includes the development of a design pipeline for body-moulded wearables, demonstrating the significance of precise wearable positioning based on the nature of the hidden affordances the agents want to access. Practitioners can adopt this pipeline to create bespoke, body-compliant wearable technologies applying Structure from Motion.

Case Study 3 also resulted in two contributions. First, a novel hybrid bone and soft tissue conduction headset delivers an enhanced frequency range compared to products currently available on the market, resulting in improved sonic fidelity for the wearer. Second, its implementation within an audio-based mixed reality experience advances the field's ability to immerse the wearer in the digital domain beyond traditional, vision-based solutions. Although using Ultra-Wideband technology to track people's movements within Unity is not new (Russell et al., 2016), using sensory layering via a novel headset within the frame of enhancement technologies demonstrates a novel application of the technology. In this project, I used a generalised, genderless body to mould the wearable rather than a 3D scan of my own body. I proceeded in this manner to gauge how generalisable the body-moulding pipeline could be.

The new knowledge produced in this case study includes the development of a hybrid headset that expands the audio spectrum for wearers, contributing to product innovation and experience design. Additionally, integrating sensory layering in a hybrid reality setting hints at how audio-based systems can deepen agent immersion. Practitioners can apply these insights to enhance audio fidelity in wearable technologies and extend sensory immersion beyond visual methods, particularly in gaming, and where agents must interface with digital affordances while maintaining contextual awareness.

My research interwove – in a non-linear way – reading, theorising, making, reflecting, and synthesising working guidelines. The practice-led research I presented in this thesis aimed to generate transferable design guidelines to guide practitioners in approaching enhancement technologies. Following this point, the three case studies were designed as experiential prototypes – critical pieces designed to each reflect on an instance of enhancement technology. These prototypes successfully demonstrated how the five design guidelines outlined could be reformulated and applied in new contexts and projects. It is also important to note that the outcomes of the case studies each embody one of the possible answers to a design brief rather than claiming universality. This point again reflects the role of design guidelines: to act as a generative framework for practitioners rather than a fixed set of rules. Table 7.1 summarises my research's contributions to knowledge.

	Field	**Contribution**
Overall Thesis	Design Practice	Practice-led framework for designing wearable enhancements, where embodiment, cybernetics and affordance theories coalesce via reflective practice
	Enhancement	Theoretical framework going beyond considering solely human agents, introducing the concepts of hidden affordances and sensory layering
Prototype 1	Robotics	Novel redundant actuator employing Edge Machine Learning. This Case Study also shows the applicability of my framework to human-made agents
Prototype 2	Human-Computer Interaction	Body-centric design pipeline for wearable systems. This Case Study prompted the revision of my guidelines, refining Guidelines 3 and 4
Prototype 3 – Headset	Wearable Robotics	Novel hybrid bone and soft-tissue conduction wearable headset. This first part of Case Study 3 made me reflect on the tensions between tailoring a wearable to an agent versus transferability
Prototype 3 – Experience	Human-Computer Interaction	Indoor tracking coupled with audio-based mixed reality system. This second part of Case Study 3 explored the applicability of sensory layering to Hybrid Reality

Table 7.1 Overview of the research's contributions.

7.4 Research Limitations

As my research implies, many enhancement aspects still need to be better understood or explored further: as I have indicated, it was always my intention that the designs produced should be stepping stones to further work and thought. The case studies I present have some compromises that reflect the practical challenges faced during the project. For instance, the wearable haptic compass relies on an off-the-shelf microcontroller board instead of a fully customised solution. Similarly, I initially designed the indoor tracking system for use in public (much larger) spaces, and I instead had to test it in my apartment, which limited its scalability.

Moreover, while my methodology prioritises iterative development and theoretical integration through reflective practice, it also means that I did not address certain practical aspects, such as long-term durability. The case studies were not subjected to user testing, reflecting my decision to focus on the broader conceptual and experiential goals rather than bringing a product to market. Consequently, while my case studies demonstrate the application of the design guidelines, they remain exploratory rather than definitive solutions.

Despite these limitations, my approach demonstrates the ethos of the design guidelines: they exemplify potential enhancement technology implementations rather than claiming universality and completeness. Other practitioners would likely have arrived at different solutions based on the same five design guidelines, which is the strength of my approach. Rather than prescribing a map of actions, other practitioners are given a compass for navigating between disciplines surrounding the subject matter.

7.5 Future Work

Reflecting (once more) on the framework I developed, I can imagine exploring its applications beyond sensory enhancements. One promising area is enhancing agent actions through re-mapping activities within local, remote or virtual environments. This approach presents design challenges, particularly when viewed through Milgram and Kishino's (1994) virtual-real continuum.

Further, exploring sensory enhancements via subdermal or transdermal devices offers another fascinating area of inquiry. Historically, this line of research has been explored in projects such as CyborgNest (2016) and SenseBridge (2009). However, I opted not to pursue this path due to the limitations discussed in chapter 2.6. Nevertheless, approaching sensory enhancement through devices embedded within the agent's body would result in a higher degree of body coupling, potentially leading to smaller wearable devices.

The earlier case studies focus on distinct contexts for enhancing human or human-made abilities. However, the resulting wearables can be applied to scenarios beyond those initially considered. For instance, the redundant actuating assembly described in chapter 4 can be integrated into a mobile robotic platform and deployed in settings where minimising downtime is crucial, such as industrial automation, agriculture, and search and rescue operations.

Similarly, the body-moulded wearable introduced in chapter 5 can be employed when hands-free navigation enhancements are desirable, including in construction, engineering, emergency services, and aviation. The headset and tracking system detailed in chapter 6 can be used when situational awareness is necessary, such as in sports, retail, customer service, and medical settings.

I believe a further, promising direction for future research is expanding sensory engagement in hybrid realities beyond visual feedback. The headset I developed in chapter 6 hints at a new perspective on how agents can interact with these environments. By focusing on 3D sound instead of the usual visual hints, my case study shifts attention to creating rich experiences that engage with multiple senses and feel more like real-world interactions. Future studies could look into how adding sound, touch, smells, and other non-visual stimuli might make people feel more immersed in hybrid environments.

Additionally, my third case study rethinks the role of physical space in hybrid reality design. This study showed how things like walls, floors, and objects in the real world could be woven into the virtual experience. The project hints that paying attention to how sound works in physical spaces could be crucial to creating richer, more context-aware mixed realities. These findings align with Milgram's continuum, hinting that future research should look into how sound and space features could move users along this range – from fully real to fully virtual environments – by blurring the lines between them.

While this research has successfully answered my research questions, it has also – as I intended – raised further questions that point to new research directions. For instance, how can these guidelines be adapted for agents with radically different sensory systems or environments that require entirely new forms of embodied interaction? Moreover, as enhancement technologies continue to blur the boundaries between digital and physical affordances, how can designers ensure that these technologies remain ethically and culturally aligned with diverse user needs?

These questions emphasise the continuous relevance of my research and suggest areas for future exploration to build upon and test the findings presented here. As enhancement technologies continue to evolve, the frameworks and insights developed in this thesis provide an established starting point rooted in practice-driven research.

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A. Appendix A

Hardware Configuration

Motors are commonly used to generate rotary motion in robotics. Stepper, brushed, and brushless motors are the most widespread types of DC motors (Derammelaere et al., 2016). Stepper motors excel in precision applications (Marino et al., 1995). On the other hand, brushed motors are chosen when high torque is required rather than precise positioning (Hameyer and Belmans, 1996). Finally, brushless motors are used when high power in proportion to weight is required and when less maintenance is desired due to fewer moving parts prone to degradation due to friction (Rezazadeh and Hurst, 2014). For these reasons, I designed the redundant actuating assembly with brushless motors. Figure A.1**Error! Reference source not found.** depicts a typical brushless motor's mechanical architecture and functioning guideline while Figure A.2 shows the mechanical assembly for the redundant actuating assembly. Two identical brushless motors power the proposed actuating assembly with a shared machined steel axle for strength and longevity.

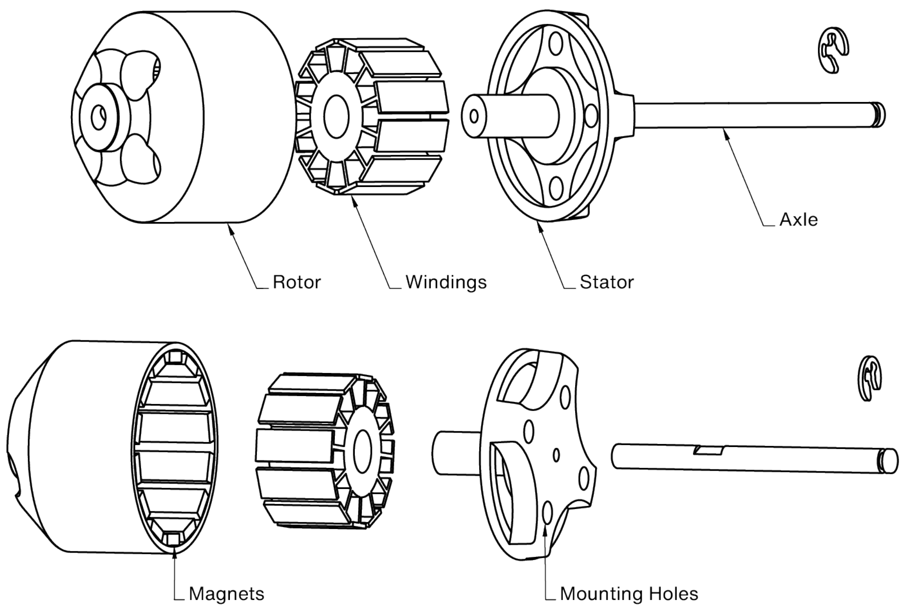

Figure A.1 A typical brushless motor comprises a rotor with permanent magnets and a stator with multiple phases. Each winding will have a distinct magnetic field if the stator phases are fed with three alternating currents 90 degrees out of phase. The sum of the three fields will form a spinning magnetic field with an angular velocity proportional to the number of magnetic pole pairs in the motor (Hemati and Leu, 1992). This figure shows an exploded view of the mechanical assembly for the brushless motors utilised in the redundant actuating assembly.

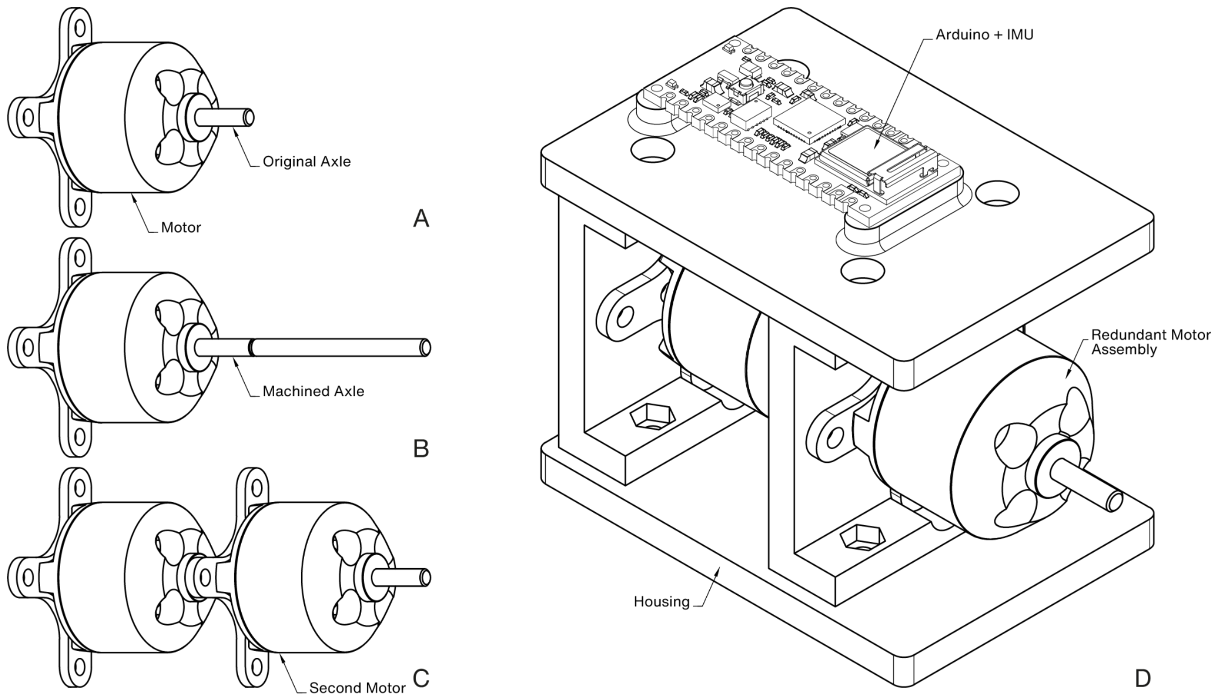

Figure A.2 The mechanical assembly for the brushless redundant actuating assembly. In 3a the motor with its standard axle is shown. The custom machined steel axle is added in 3b, and in 3c the second motor is coupled to the shared axle. Finally, 3d shows the actuating assembly from a perspective view. The two motors are mechanically engaged with the axle at all times but only one of the two motors is powered at any given time, as detailed in the next paragraph.

To correctly actuate and control the speed of a brushless motor, as its actuation requires three out-of-phase control signals, an additional device is required: the Electronic Speed Controller (ESC). An ESC receives signals from a control unit and converts them into a frequency-controlled, three-phase impulse. Typically, an ESC controls a single brushless motor, indicating that two ESCs should control the actuating assembly presented here. However, because only one of the motors will be run at any given time, the inactive motor will produce a voltage at its input, interfering with or harming the ESC to which it is connected. Therefore, the design presented here includes a single ESC that is electrically coupled to only one of the motors at any one time to overcome this issue. In addition, the ESC uses relays to switch between motors. Figure A.3 and Figure A.4 depict the mechanical design, including the actuating assembly, signal switching relays, and controller board.

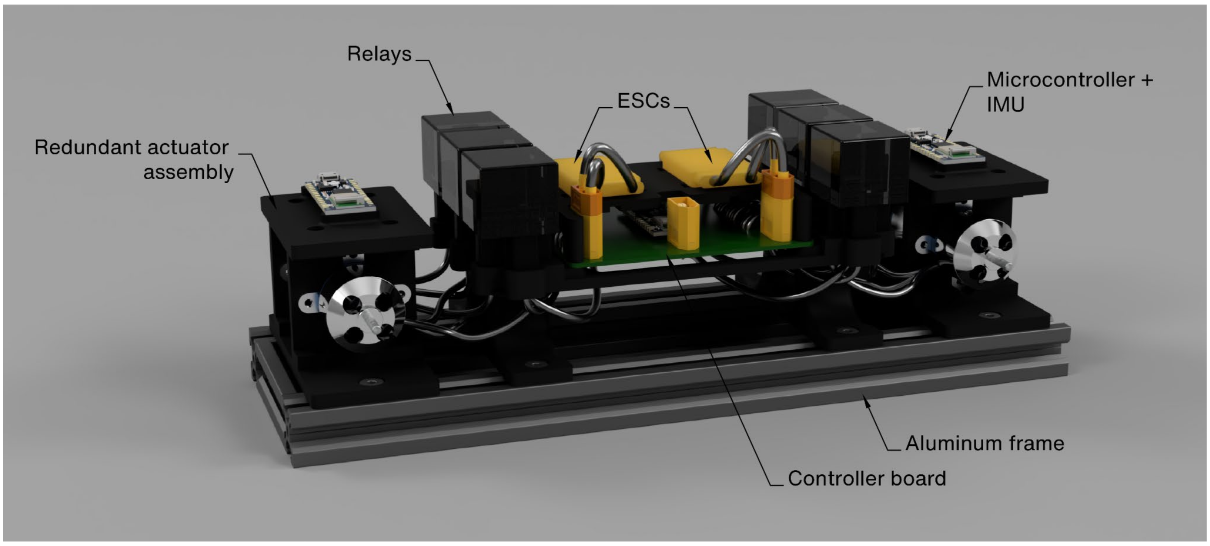

Figure A.3 The robot's mechanical design. The platform is mirrored in its design, with identical redundant actuating assemblies on both sides. Each assembly consists of the two coaxial brushless motors described before, braced between 3D printed supports. The controller board with six relays, three per redundant assembly, features in the centre of the assembly. The three sub-systems attach to a support structure built from aluminium profiles.

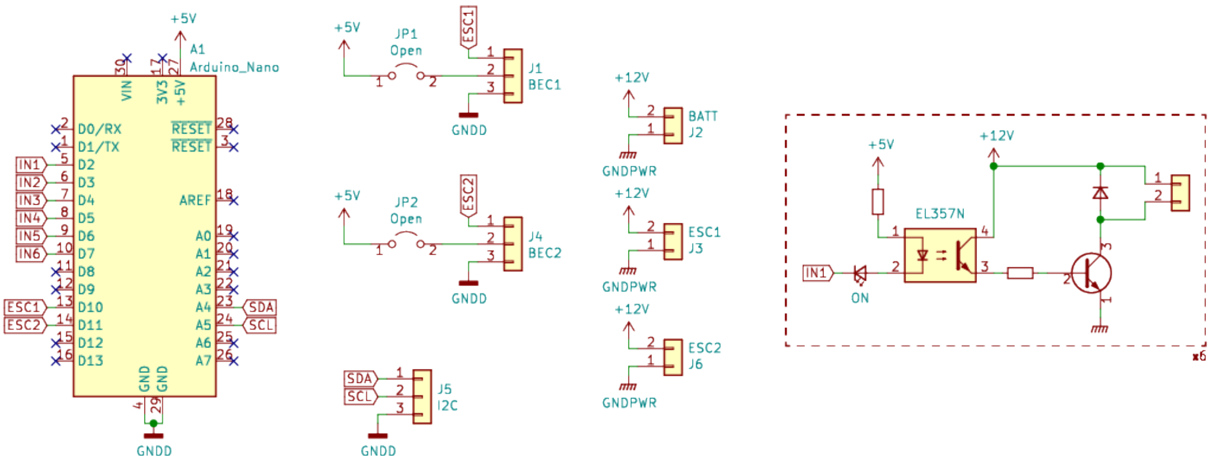

Figure A.4 The redundant actuating assembly's controller board. An Arduino Nano – a common microcontroller development board – is shown on the far left, receiving sensor data via I2C from the connector at the bottom of the board (J5, labelled I2C). Next to the I2C connector, on both of its sides, there are interface ports to connect to the two ESCs (J1 and J4, labelled as BEC1 and BEC2. BEC stands for battery elimination circuit – a subsystem in the ESC that generates the 5V needed for operation by the microcontroller). The additional circuitry on the board consists of power distribution, where a battery connects to deliver the required voltage to the brushless motors and six optoisolators, with their schematic shown on the far right. These optoisolators provide extra protection to prevent voltage spikes induced by relay switching from reaching and damaging the microcontroller.

Software Implementation

Without proper software architecture, the mechanical system would perform poorly in the real world. Installing a sensor to pick up the vibrations of a motor might be an interesting exercise, but it does not enhance the actuator itself. In other words, some 'smart' software system is needed to translate the raw information reported by the sensor to anticipate its malfunctioning. A spinning motor produces small vibrations that are easily detectable. But *predicting* when a motor will fail is not trivial, as we do not know how the motor could be damaged or worn out. One option would be to record the vibration patterns of several broken motors. In this way, we could compare the vibration patterns of our working motor to the ones of the broken ones, and when they coincide, we switch to the backup.

Instead of following this destructive and costly approach we could, as explained in the next few paragraphs, collect recordings of vibration patterns of a normally functioning motor. The data generated would be quite uniform, approximating a cyclic waveform of an amplitude dependent on the motor's speed. We can then create a software system that checks whether the motor's vibrations deviate from the pre-recorded dataset. Finally, by adding a variation 'tolerance', we can precisely set a threshold where we know the motor is not working as intended, but it is not broken yet – and use that threshold to trigger the backup motor.

In technical terms, the software requirements for this actuating assembly can be broadly divided into an AI-based system for fault prediction and a central control system that interfaces with it and handles switching between motors in the case of a predicted malfunction. In this prototype, I relied on Edge Impulse, a company developing Software Development Kits (or SDKs, collections of code that simplify writing complex codebases), for developing the AI system while employing a finite state machine (FSM) as the mathematical computation model for the controller board. I will first discuss the AI architecture, followed by an overview of the controller's FSM.

Before I detail how I implemented AI in this prototype, I should clarify why I chose this technology over others. Returning to the guidelines of sensory layering, it was evident that designing this prototype required a modular approach, with the controller and the new sensor as self-contained as feasible. This approach would allow the insights gained while designing this prototype to be more easily transferred. AI and, specifically, deep learning techniques cater to my choice because if this method of layering senses on robots is successful, the same guidelines (or even identical mechanical assemblies and codebases) might be used in other projects. These technologies enable the design of an architecture for interpreting previously acquired data. As a result, designers and engineers planning to use the same concepts in various robot platforms can employ the same architecture, only training the machine learning model on the dataset they select. Figure A.5 depicts the standard approach to deep learning, emphasising how the majority of the process is fixed while still adapting to new hardware based on how the data was collected.

Figure A.5 A high-level overview of the deep learning process elaborated from (Raschka, 2020, pp.8–9). Data from the newly layered sense must be collected as a crucial initial step. In the instance of this prototype, an accelerometer generates vibration data. Any sensor that generates sample-based data, that is, data with discrete samples in the time domain, can be used to achieve the same result. The collected dataset must be randomly divided into training, validation, and testing. The training set is used to train the machine learning model, which is then compared to the validation set to check if the model correctly interprets previously unseen data. At this point, the designer can fine-tune the model's hyperparameters to improve its accuracy. Finally, the optimised model is compared to the test set to evaluate the model's performance.

Because developing a unique deep learning pipeline was outside the scope of my project, I relied on an existing solution – Edge Impulse. Its open-source SDKs enable designers to conduct the processes outlined in Figure A.5 and export the final TinyML algorithm for integration with custom solutions. Edge Impulse's software, including the SDK, client, and written code, is licenced under an Apache 2.0 (2004) licence, allowing designers to change, distribute, and sublicense any code, fulfilling the last design guideline – designing with technical accessibility in mind.

Data Collection and Classification

Deep learning models for fault prediction follow three separate phases: data gathering, digital signal processing (DSP)[23], and K-means anomaly detection. Figure A.6a depicts how Edge Impulse obtains data: the abscissa axis represents the passage of time – in this case, a ten-second time window. The ordinate axis represents shifts in signal intensity[24] detected from a sensor – in this case, an accelerometer. The motor's activity is observable: while running, the motor emits periodic oscillations on all axes. Figure A.6a depicts a machine learning *feature*: a distinct, quantifiable quality or attribute of an observed phenomenon. It is significant to mention that the acquired data samples are time-series, a collection of discrete values that vary over time. In effect, a 10-second raw data recording at 104Hz (or 104 data points per second, per axis) yields 10*104*3 = 3120 distinct features. While this may not appear to be a significant amount in the context of modern computers, when multiplied by the total number of samples recorded (in this prototype's instance, resulting in approximately 260.000 individual features), it would be far too much for a microcontroller to analyse in real-time.

It is apparent that we must conduct feature extraction after the data collection phase. This approach reduces high-dimensional data[25] to a more manageable dataset while retaining all of the key features from the original dataset. The feature extraction stage is essential in TinyML because it significantly reduces the processing power required to train the dataset and conduct inference after the machine learning model is implemented on the microcontroller. The most effective process to reduce data complexity is to use Fast Fourier Transforms (FFTs) to convert the training dataset from the time domain to the frequency domain[26]. Edge Impulse supports FFTs through its Spectral Analysis routine, which generates three different features per axis, significantly reducing the features by nearly two orders of magnitude. For a comprehensive overview of how I implemented spectral analysis in this prototype, see Figure A.7. In summary, the following steps were followed to adapt and implement the framework offered by Edge Impulse to predict anomalies in redundant brushless actuators:

1. 860 seconds of accelerometer data were sampled (85-15% train/test split) corresponding to three motor operation modes: idle, half speed and full speed,

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[23] Digital signal processing represents analogue signals in the real world, such as those deriving from an accelerometer, with a discrete sequence of numbers and processes those numbers to extract information.
[24] Signal intensity is defined here as acceleration measured in m*g* (milli g-force) in the X, Y and Z directions.
[25] High-dimensional data is characterised by a high number of attributes. Because machine learning requires vast datasets for training purposes, patterns in high-dimensional data can be hard to find. When fed with high-dimensional data, the algorithm takes more time and requires more memory for inference. Dimensionality reduction in the context of this prototype reduces the volume of data to analyse, whilst retaining the information necessary for predicting faults in the actuating assembly. This process is called *feature extraction*.
[26] Representing a signal in the frequency domain rather than the time domain allows for observing characteristics that are not evident in the latter. Relevantly for the prototype brought forward in this chapter, it is easier to analyse cyclical signals, such as motor oscillations, in the frequency domain.

2. The time-series data in the training dataset was sliced (window size: 2000ms, window increase: 80ms),
3. The slices were converted to the frequency domain to identify the spectral power[27] (FFT length: 128, number of peaks: 3, peaks threshold: 0.1) and root mean square,
4. The generated features are the input for a neural network trained to identify the three motor operation modes (for an overview of the neural network, see Figure 3.8),
5. The K-means algorithm provides an anomaly score to identify whether the motor's behaviour exceeds the expected parameters.

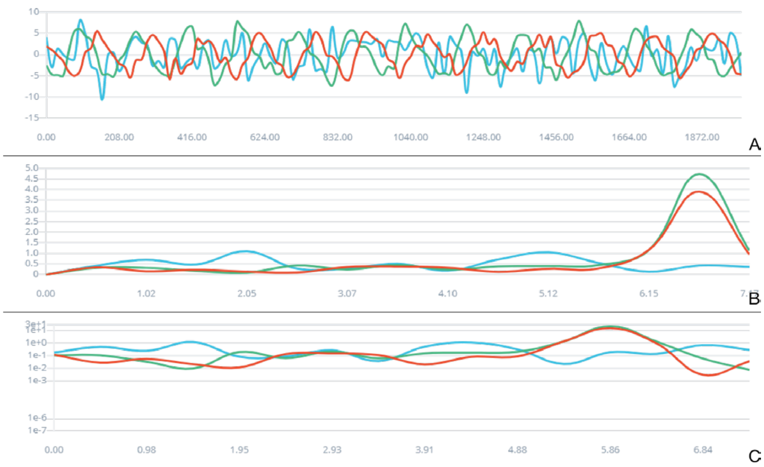

Figure A.6 Detailed overview of the process of extracting features from a raw dataset. Figure 0.6a shows the raw data sample without any filtering. Figure 0.6b shows the processed data transformed into the frequency domain through an FFT. Figure 0.6c shows the spectral power peaks extracted from the FFT. These spectral power peaks are fundamental in determining the typical frequency and amplitude of the motor's vibrations. Using this DSP protocol reduces the number of features from 3120 per 10-second raw data recording to only 33.

The actuating assembly introduced in this chapter is novel in three ways. From a mechanical standpoint, it introduces a new degree of freedom to off-the-shelf BLDC motors by employing a machined axle coupling. From a software standpoint, it combines deep learning and Edge computing techniques to predict motor failure. Finally, the actuating assembly shows how the guidelines of sensory layering led to novel systems when applied to human-made agents.

[27] The spectral power represents the signal's bandwidth and its mean frequencies.

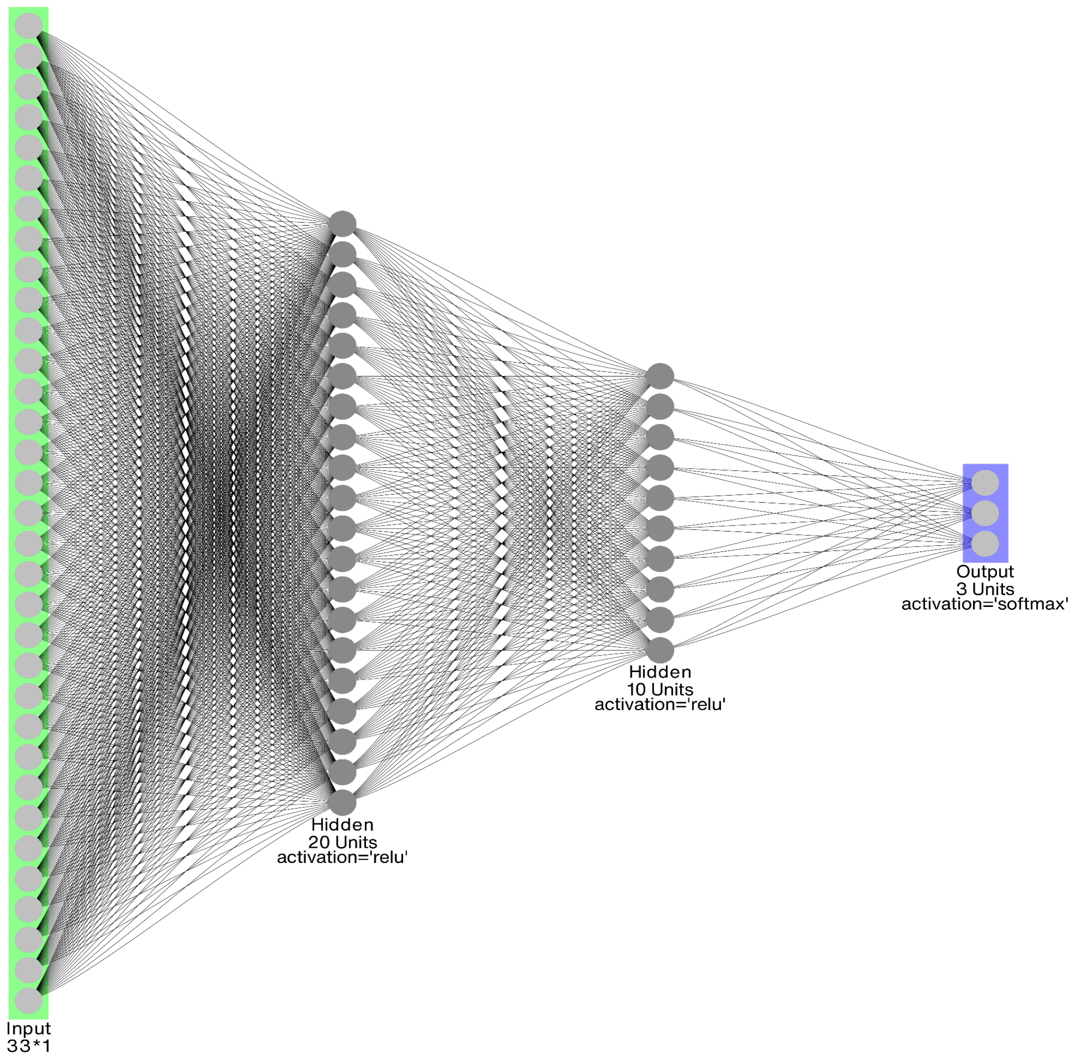

*Figure A.7 Detailed overview of the neural network trained to classify motor behaviour. The neural network features 33*1 inputs followed by two dense hidden layers with a rectified linear activation (relu) function (Nair and Hinton, 2010). The neural network presents three possible outputs: OFF, HALF_SPEED and FULL_SPEED.*

The K-means algorithm is the final stage in the deep learning architecture. This unsupervised machine learning algorithm derives inferences on a dataset using only input vectors and does not require manual data labelling. Its basic principle is grouping similar data points to detect recurring patterns. The algorithm searches the dataset for a fixed number (k) of clusters, hence its name. *Clusters* are groups of data points with specific characteristics – in this case, similar spectral features. The clusters identified by the K-means algorithm serve as the benchmark for predicting anomalies. The sensor continuously provides new, previously unseen data to the algorithm, which compares it to the available clusters. No abnormality will be detected if the latest data is similar to the training dataset. However, an error will be raised if the new sensor data differs from the clusters, indicating a system anomaly. The system's anomaly is expressed as a number between 0 and 1, where 0 indicates that the system performs precisely within bounds and 1 indicates a system malfunction. Having a single number allows the designer to specify an anomaly threshold, a value that, if surpassed, causes the backup motors to switch on. This threshold value is the only data point streamed from the new sense to the robot's central processor. After comparing it with the testing set, the deep learning model developed for this application resulted in a mean accuracy of 99.85% using 1.7kB of RAM and 19kB of flash memory. In addition, the model presents 1 millisecond of delay when sampling the motor's vibrations, resulting in a virtually real-time fault detection system.

As anticipated, this prototype's actuating assembly's central processor is based on a finite state machine (FSM) architecture. FSM is a computational model that describes a machine exhibiting one or more states. Only one of its states can be active at any time, and the machine can switch between them depending on external inputs. The simplest example of an FSM is a lamp. A lamp typically has two states – light on or light off – and an agent can switch between them by interfacing with a switch. The FSM implemented in the actuating assembly presents several states. By default, the rear brushless motors are active and provide the rotation necessary to spin the axle. The redundant motor assemblies stream the anomaly value to the processing unit via I2C. If the value exceeds 0.5, the potentially faulty motor is electromechanically disconnected through relays, triggering its backup. Figure A.8 depicts the whole FSM for this prototype, including all transition phases.

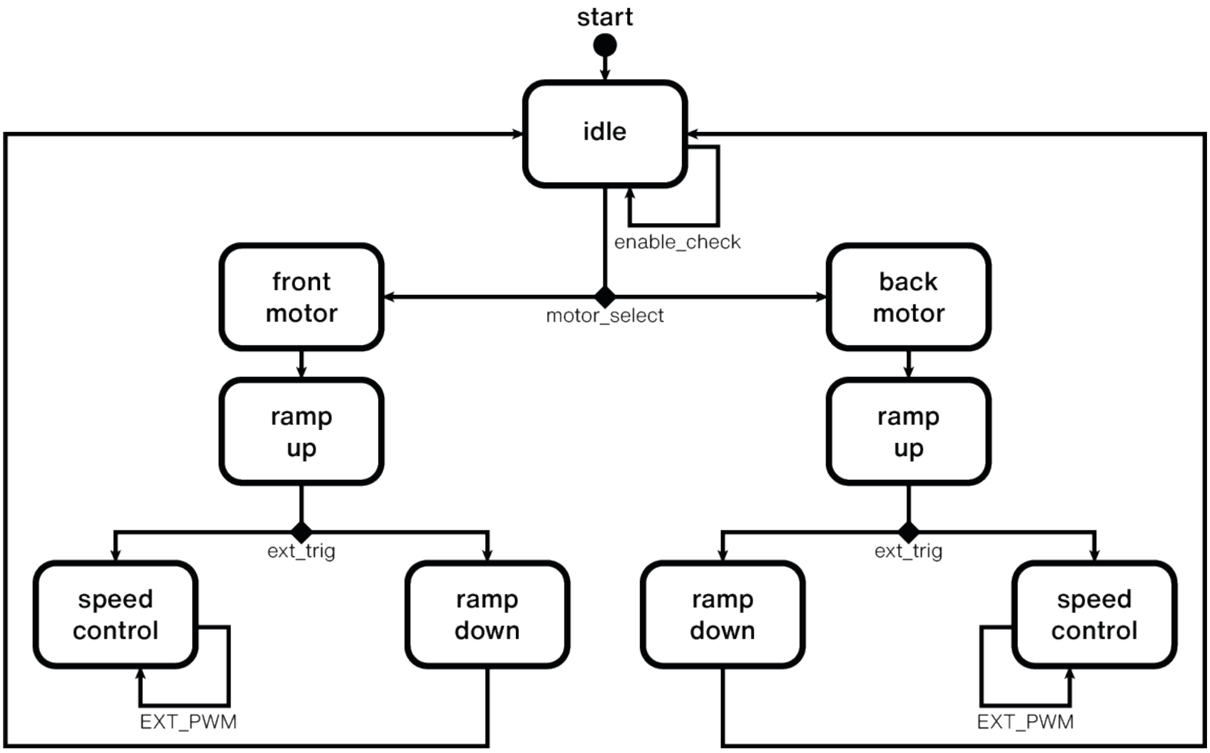

Figure A.8 A comprehensive overview of the controller board's FSM implementation. When the system receives the command to move, it activates the rear motors in the actuating assemblies. The controller board requires an external signal (enable_check) before powering on the redundant actuating assemblies. When the enable signal is received, the controller activates the front motor by default, ramping up to a pre-set threshold. The motor's speed can be changed in real-time via the EXT_PWM signal, which modulates the actuator's speed. If the controller board receives a warning about a possible motor failure via the ext_trig input, it will safely reduce the motor's speed and idle. The back motor can be activated at this stage, following the same procedure described before.

The actuating assembly introduced in this chapter is novel in three ways. From a mechanical standpoint, it introduces a new degree of freedom to off-the-shelf BLDC motors by employing a machined axle coupling. From a software standpoint, it combines deep learning and Edge computing techniques to predict motor failure. Finally, the actuating assembly shows how the guidelines of sensory layering led to novel systems when applied to human-made agents.

B. Appendix B

Hardware Configuration

After determining and prototyping the wearable body-moulded shape, I prototyped the electronics. The wearable employs Lithium-Polymer (LiPo) batteries for power. These devices are susceptible to over-current, over-discharge, under-voltage, balancing (when multiple cells are used) and short circuits. To prevent these issues, the design includes a TP4056 miniature single-cell Lithium Polymer charge management integrated circuit, providing a constant-current and constant-voltage charger for a single-cell LiPo battery. For additional safety, two other ICs were added (the FS312F-G and the dual MOSFETs FS8205) for current sensing, reverse discharge protection, programmable charge current, thermal regulation and cell balancing. The LiPo battery provides a voltage between 4.2V and 3.9V, which needs regulating to provide a stable 5V for the microcontroller. To achieve the regulation, I implemented a boost regulator using the MT3608, a 1.2MHz constant frequency step-up converter, which can deliver up to 4A to power the circuitry. See Figure B.1 for the schematic of this section.

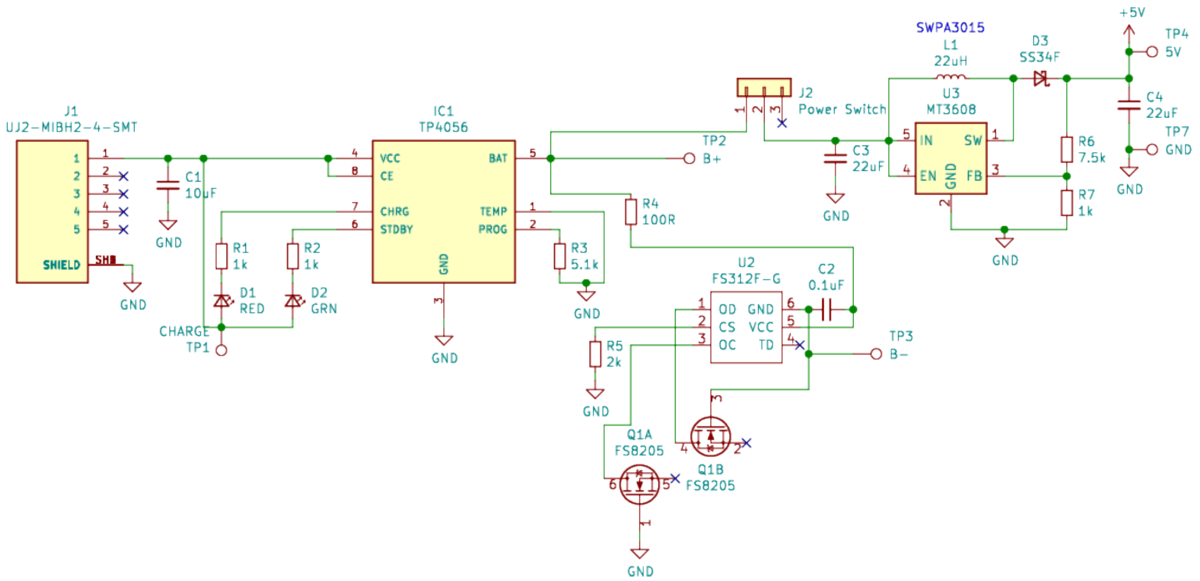

Figure B.1 The power management section of the wearable system. The battery is recharged from a micro-USB constant 5V (top-left, labelled J1). Two LEDs determine the battery status: charging (red LED) or charged (green LED). The TP4056, FS312F-G and FS8205 provide the safety features required for this application. The battery's unregulated voltage (seen entering the leftmost pin of J2 – the power switch) is then regulated to a constant 5V by the MT3608 (on the right) and decoupled through C4. Test points (labelled TP) were added to the board to debug the board easily after manufacturing.

Given the ultra-low-power requirements for such an always-on system, Nordic Semiconductor's nRF52840 microcontroller (MCU) was employed. This MCU is recommended for safety-critical applications, is clocked at 64MHz and has low power consumption when power savings are active. This MCU is available in multiple form factors, but the Arduino Nano 33 BLE platform was employed in this project. Programming of the MCU can be achieved through Atmel Studio, which supports C and C++ languages. See Figure B.2 for the schematic of this section. The choice of using an Arduino board instead of a discrete solution was twofold. On one side, the ongoing integrated circuit shortage resulted in over 52 weeks of lead time on purchasing components. At the same time, the Arduino Nano 33 BLE employed in this prototype features an onboard LSM9DS1, a 9 degrees of freedom IMU consisting of an accelerometer, a gyroscope and a magnetometer. Having the sensor preinstalled on the board allowed me to quickly prototype the wearable's electronics, as I did not have to design a custom sensor implementation. All three sensors in this integrated circuit communicate with the microcontroller via the I2C protocol, similar to chapter 4. In the next section, I will describe how the data from the sensors are fused to determine the wearer's facing direction.

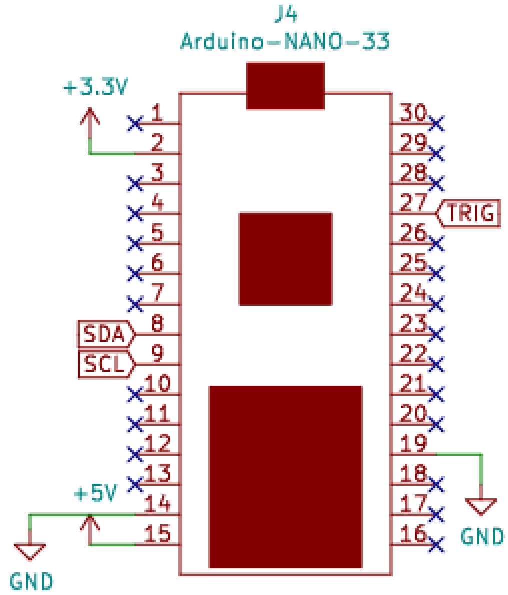

Figure B.2 The Arduino Nano 33 BLE. The board receives the regulated 5V on pin 15, which is then stepped down to 3.3V through an internal Low-Dropout Regulator (LDO) for powering other devices on the I2C line (pin 8 – SDA and pin 9 – SCL).

This wearable system signifies to the user that they face North through haptic feedback. For this, a suitable vibration motor and supporting circuitry were integrated into the design. The DRV2605 haptic driver integrated circuit was selected to actuate the vibration motor, as it supports the I2C communication protocol and has an in-built library of 123 different vibration patterns, which can be user-selected and changed at will. The vibration motor selected for this application is an eccentric rotating mass DC motor weighing 0.8gr but able to spin at 10.000rpm when supplied with 3V. Figure B.3 shows the schematic of this section. The final printed circuit board was designed to fit within the wearable's back housing, as shown in Figure B.4.

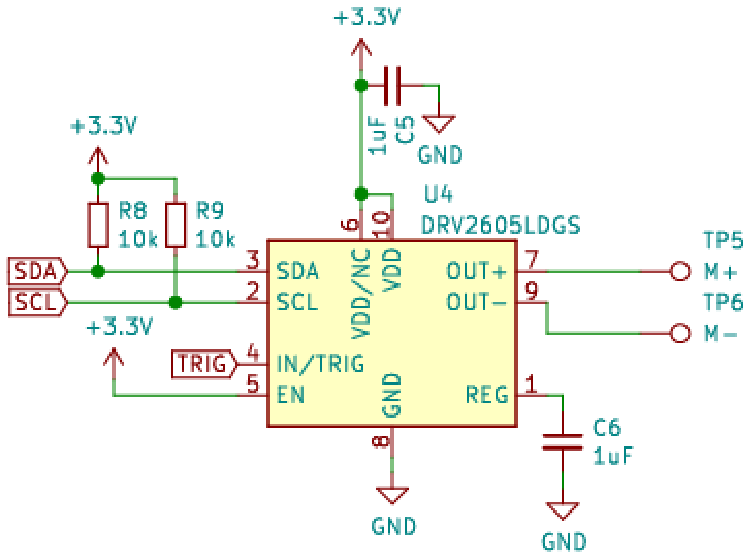

Figure B.3 Motor driver section of the wearable system. The chip communicates with the MCU through the SCL and SDA lines, pulled high to 3.3V through R8 and R9. The vibration motor is attached to this IC through two solder pads (labelled M= and M-, on the right-hand side of the schematic).

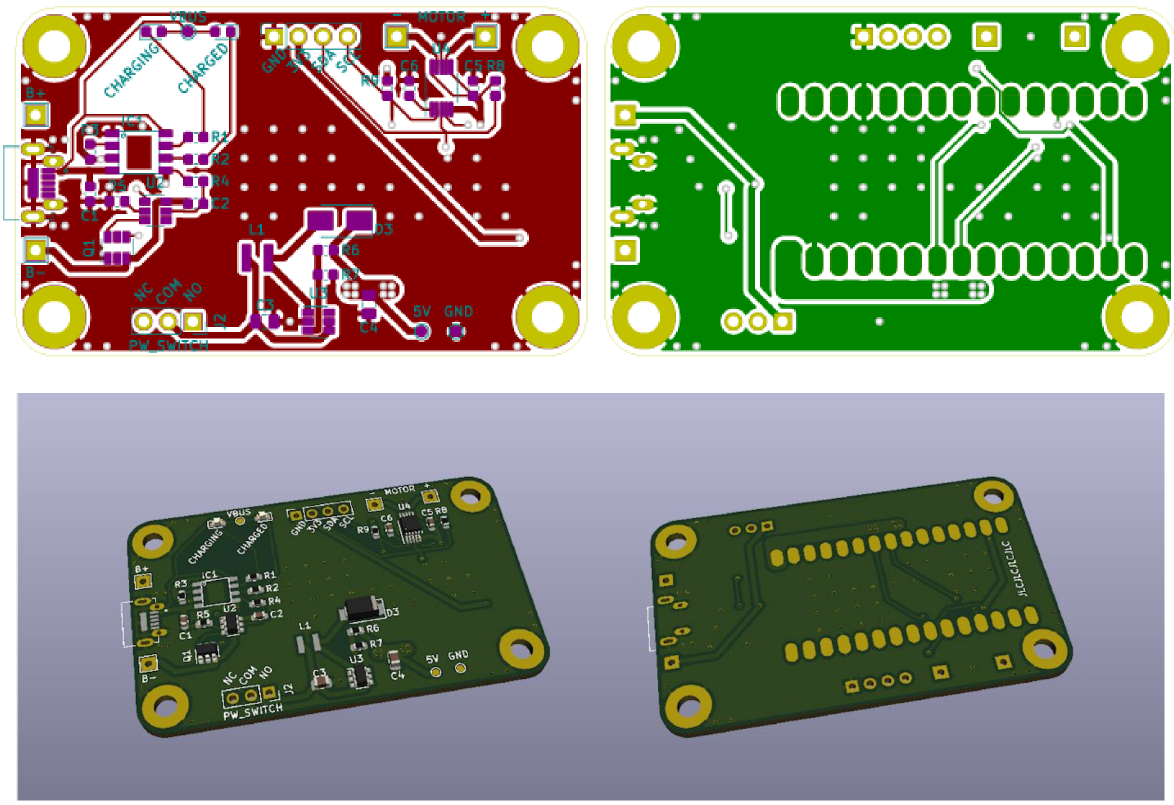

Figure B.4 Error! Reference source not found.A (top) depicts the printed circuit board layout of the wearable system. The top layer is shown on the left, and the bottom layer is shown on the right. B (bottom) depicts a render of the board layout, showing the board populated with components. The board measures 59mm in width and 36mm in height.

Software Implementation

To be accurate, calculating heading in robotics applications presupposes combining data from multiple sensors. Sensory fusion is the integration obtained from multiple sensors to improve the reliability and precision of an output (Gravina et al., 2017). Various levels of accuracy can be attained when determining an object's position in 3D space using different sensors: if only pitch and roll estimations are required, a single accelerometer (Ambar et al., 2017; Vogel et al., 2013) or combining data from an accelerometer and a gyroscope prove sufficient (Hoang and Pietrosanto, 2021). A magnetometer is required if the application also requires yaw calculation (Bhardwaj et al., 2018; Nazarahari and Rouhani, 2021). The use of three sensors is required to minimise the intrinsic limitations of individual sensors. Accelerometers, in particular, measure acceleration but are sensitive to errors induced by vibrations. Gyroscopes are used to detect angular velocity; however, they suffer from significant drift over time. Magnetometers detect The Earth's magnetic field and can be used to establish orientation relative to it; however, they must be calibrated carefully as ferromagnetic structures can impact them in the environment. The data fusion of the three sensors forms an Attitude3w and Reference System (AHRS), which provides comprehensive orientation information relative to the Earth's magnetic field and the direction of gravity (Madgwick et al., 2011).

As Han et al. (2020) exhaustively analysed, many sensor fusion algorithms exist in the literature. Simple filter algorithms, Kalman-based Algorithms, or a Madgwick filter are examples of potential algorithms for building an AHRS suited for a wearable enhancement system. Simple filter algorithms, such as fading memory filters (Nazemipour and Manzuri, 2018; Saho and Masugi, 2015) or morphological filters (Wu et al., 2018), perform as low-pass filters to reduce noise in individual sensor data. These filtering algorithms are mathematically concise and computationally fast, but they are insufficient for addressing sensor biassing independently (Han et al., 2020). Kalman filters and their variants, such as Extended Kalman filters (Hu and Gallacher, 2016), Incremental Kalman Filters (Chu et al., 2017) and Discrete-Time Kalman Filters (Xue et al., 2015), are recursive filters with two calculation loops that compute time updates and sensor status upgrades. Kalman-based filters are the most common sensor fusion algorithms for reducing noise and bias in AHRSs (Han et al., 2020). On the other hand, Kalman-based filters are difficult to implement and require high sample rates, ranging from 512Hz (Xsens Technologies B.V, 2009) to 30kHz (MicroStrain Inc, 2011), to track human motion accurately. This last factor is critical for building an AHRS for the prototype described in this chapter because the LSM9DS1 IMU has a fixed frequency update of 104Hz for the accelerometer and gyroscope and 20Hz for the magnetometer (STMicroelectronics, 2015), which is far lower than what is necessary for Kalman-based algorithms.

The Madgwick filter (Madgwick et al., 2011) is the final suitable algorithm. Rather than relying on Euler angles, this filter represents orientation in three dimensions using quaternions, a mathematical representation with four components – x, y, and z denoting the rotation on which axis the rotation happens and w expressing the amount of rotation on each axis. Although it requires a substantially lower sample frequency, this filter performs as well as commercial Kalman filters (Madgwick, 2018; Sarbishei, 2016). Furthermore, using quaternions to describe orientation avoids the singularities in Euler representations, such as gimbal lock (Challis, 2020). Finally, Madgwick (2018), who created the Madgwick filter as part of his Doctoral research, provided an open-source software library optimised for embedded systems like the microcontroller used in this prototype.

The code developed for the wearable uses the Madgwick AHRS library to determine whether the wearer is facing North, within a spherical wedge of ±2 degrees, as seen in Figure B.5. If the condition is met, the microcontroller engages the haptic feedback driver. The vibration motor then plays the haptic waveform, completing the feedback loop with the wearer. The code includes several user-selectable waveforms with varying intensities. As previously stated, the sensors inside an IMU develop biases and errors over time. Thus, the code includes a calibration method to account for these errors. The calibration procedure runs when the wearable is powered on, setting an offset and slope for each sensor in the IMU.

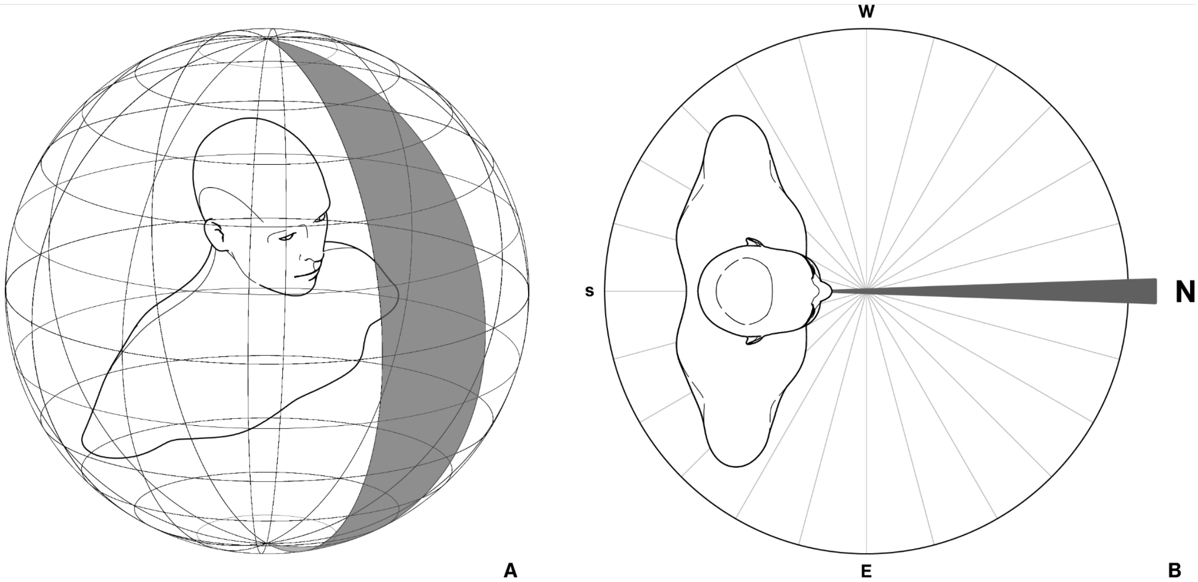

Figure B.5 ***A*** *shows how the wearable works: the IMU identifies the wearer's orientation in space and whether they face north within a spherical wedge of view. B depicts a top view of the wearable compass, emphasising the ±2 degree detecting spherical wedge. This value is software-definable and can be tweaked for greater or lesser sensitivity.*

Experimental Results

The finalised body-moulded wearable compass was calibrated and tested to record its performance. As an initial test, the IMU's raw sensor data were recorded to verify their standard deviation before applying the Madgwick filter discussed in the previous section. The accelerometer presented a low standard deviation (0.6847), as shown in Figure B.6. Next, the same procedure was repeated for the magnetometer, as shown in Figure B.7. This sensor presents a higher standard deviation (14.3791) but was still consistent with the IMU's datasheet (STMicroelectronics, 2015, p.12). Subsequently, the Madgwick filter was applied, and the completed device's total standard deviation was recorded. After around 5.7 hours, the standard deviation (expressed in degrees) was an acceptable 0.38544°, as shown in Figure B.8. In conclusion, the wearable system's precision and drift are adequate for its application, which requires ±2 degrees of accuracy.

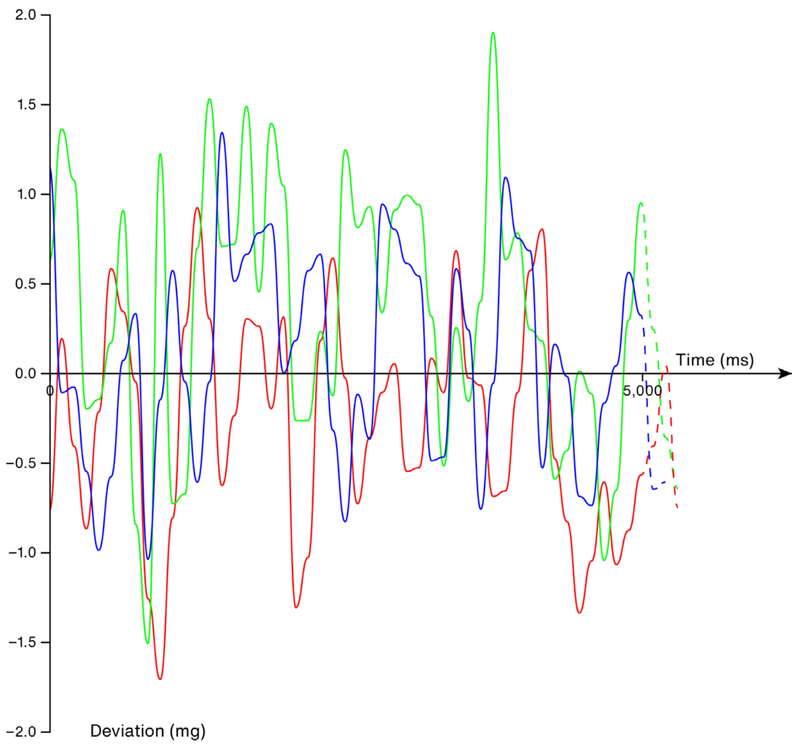

Figure B.6 An extract from the accelerometer's unfiltered values for the X, Y and Z axis. The deviation (y-axis) is reported in standard gravity (g).

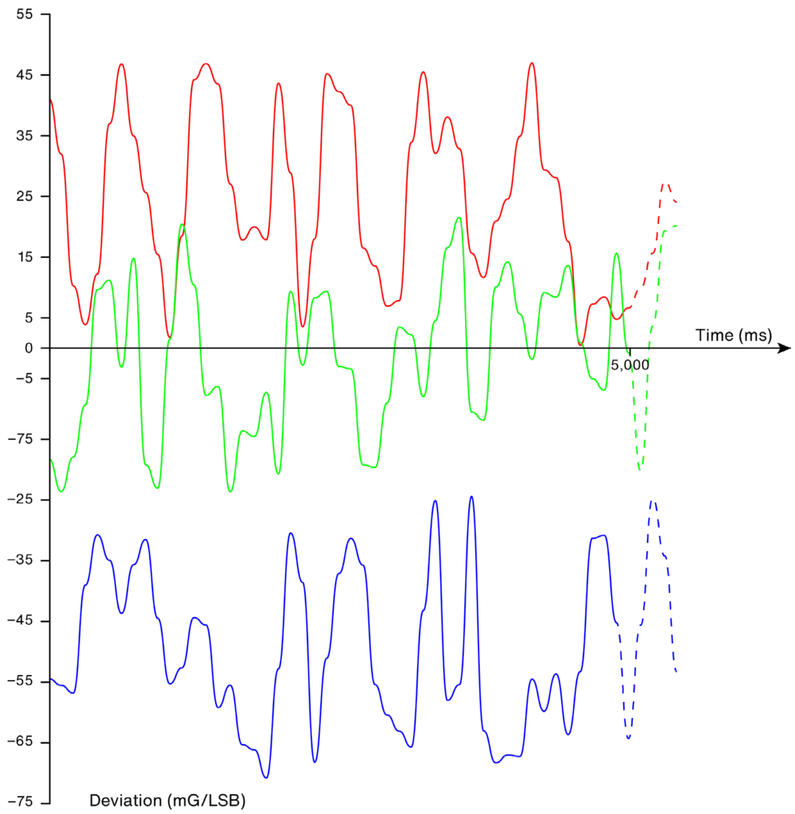

Figure B.7 Extract of the unfiltered magnetometer values for the X, Y and Z axes. The deviation (y-axis) is reported in milliGauss divided by the least significant bit (mG/LSB).

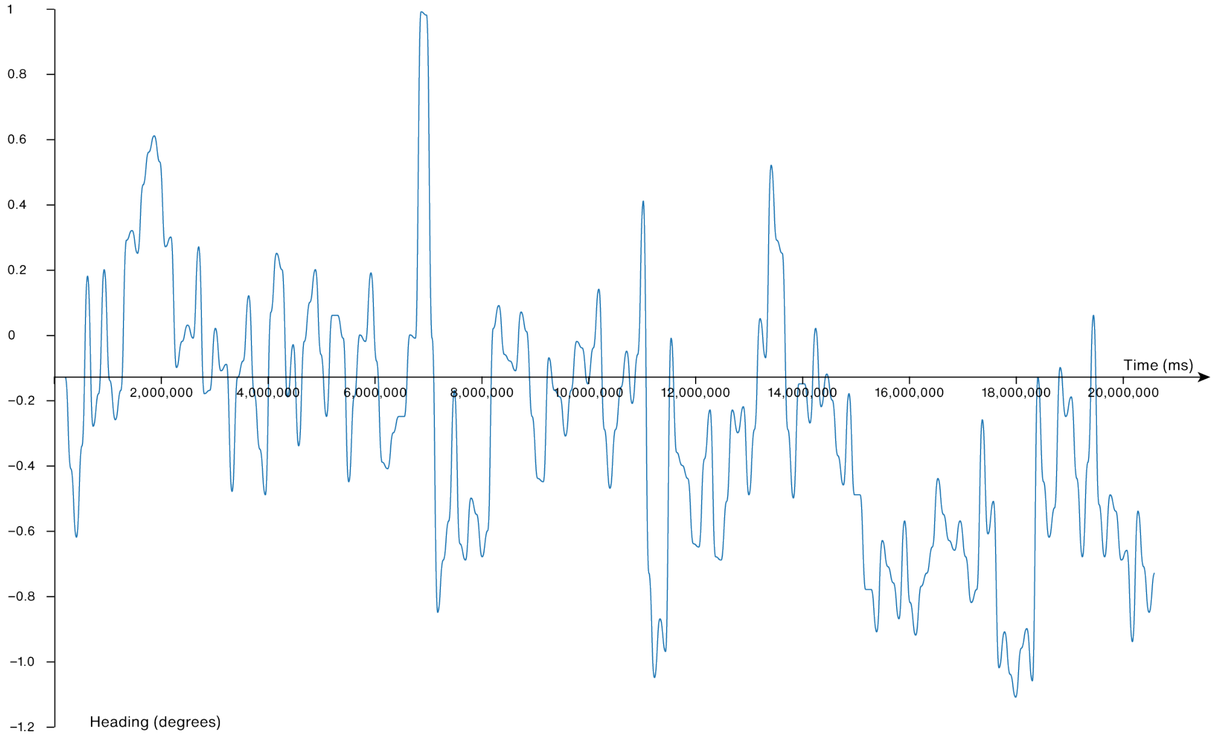

Figure B.8 Average heading drift standard deviation, expressed in degrees.

As a final note, the wearable's responsiveness is limited by the duration of the haptic feedback. For example, if the wearer decides to twirl while wearing the device, the haptic feedback will be triggered the first time they face North. The haptic feedback will then be played and can be re-activated only after completion.

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C. Appendix C

Experimental Setup

Existing research aimed at analysing bone conduction equipment for medical applications and non-medical contexts mainly focuses on determining hearing thresholds, usually using a single transducer placed on the forehead or the mastoid recess held in place with a static force of 5N. However, this type of test heavily depends on the design of the transducer, its positioning, whether the auditory canal is occluded or not, and the instrumentation used in the detection phase (Studebaker, 1962). It should be noted that the tested frequencies in bone conduction typically range from 6kHz to 8kHz, as in this frequency band, most of the human speech can be recognised. Recent attempts to create bone conduction headphones with a greater dynamic range have failed to correctly and consistently reprogram sounds below 50Hz (Walker and Lindsay, 2005). On the other hand, research in soft tissue conduction employs transducers uncoupled from the body (e.g., immersed in water) or loosely held in place on the skin (i.e., 0N application force). Following the research presented here, I opted for having the bone conducting transducer held in place with an ear hook (as shown in Figure 6.7) and the soft tissue conducting transducer loosely attached to the cheek with the provided tape.

The audiometric test used for this study was designed by the University of New South Wales (Wolfe et al., 2013). The test is aimed at determining equal-loudness level contour curves. This contour measures sound pressure over the spectrum of frequencies that the listener perceives as having equal loudness (International Organization for Standardization [ISO], 2003). The test does not represent thresholds of hearing with bone conduction headphones. Instead, it represents the intensity levels needed to drive the sound transducers to produce equally loud sounds across the spectrum. The test was conducted in a controlled environment to minimise external noise from operating machinery, computers and conversations.

The experiment consists of playing 19 digitally generated pure sine wave tones of varying intensity, sampled at a frequency of 44.1 kHz with 16-bit resolution. The following set of frequencies was used in this study:

f= {30Hz, 45Hz, 60Hz, 90Hz, 125Hz, 187Hz, 250Hz, 375Hz, 500Hz, 750Hz, 1kHz, 1.5kHz, 2kHz, 3kHz, 4kHz, 6kHz, 8kHz, 12kHz and 16kHz}.

I performed the audiometric test on myself to determine the relative sensitivity of my hearing at different frequencies. I initially calibrated the 1kHz reference tone by adjusting the sound intensity (measured in dB, where -99dB represents no sound signal emitted from the sound card and 0dB is the sound card's maximum output). Each tone frequency was then tested sequentially so that the perceived loudness would match the 1kHz tone as a reference. The tests' goal was that (i) the tone was not uncomfortably loud, and (ii) the tone was audible over the background noise. The duration of each audiometric test was approximately 30 minutes.

The off-the-shelf air conduction and bone conduction products used for comparison in this study are as follows:

- The air conduction system: Over-ear headphones (Beats 3, Apple, USA),

- The bone conduction system: Commercially available bone conduction headphones (Trekz Air, Aftershockz, USA).

The experiment was repeated at three stages, following this order[28]:

1. Test with headphones,
2. 10-minute break,
3. Test with commercially available bone conduction headphones,
4. 10-minute break,
5. Test with experimental hybrid bone/soft tissue conduction headset mechanism,

Experimental Results

Figure C.1 depicts the averaged outcomes of the three tests. The preliminary results show, as expected from the previous literature, that headphones present the lowest hearing thresholds[29], given their higher insulation from the external world's noises and interferences. The commercially available bone conduction headphones behaved well in the frequency band between 700Hz and 8kHz but lacked bottom end and could not reproduce frequencies below 125Hz correctly and consistently.

Although the experimental bone/soft tissue conduction headset underperformed in the narrow frequency bands between 187Hz and 375Hz and between 750Hz and 1.5kHz, it outperformed commercially available bone conduction headphones in the remaining frequencies. The experimental headset's ability to reliably and consistently reproduce lower frequencies, down to 45Hz, should be emphasised. However, playing low frequencies generates excessive heat, which damages the exciter below 45Hz. Compared to standard bone conduction units, including a piezoelectric element as a bone conductor produced a significantly enhanced frequency response in the higher range between 3kHz and 16kHz.

In conclusion, while the experimental bone/soft tissue conduction headset shows promising improvements in frequency range and sound reproduction compared to commercially available alternatives, particularly in lower and higher frequency bands, its performance gaps and heat management issues highlight areas for further refinement. These findings suggest that, with targeted adjustments, the experimental design can surpass current commercial options across a broader spectrum of audio applications.

[28] The procedure described here would present risks to its validity if it were to be applied to user testing. For example, if the test is always performed in the same sequence, the test-taker may become familiar with the sequence of items and be able to anticipate what will come next, which could affect their performance on the test. This could lead to the test not accurately measuring the skill or ability it is intended to assess. Therefore, it is essential for other practitioners wanting to replicate my exploration to try to counter this potential problem by using various test forms or by randomly presenting items in a different order each time the test is administered.

[29] The hearing threshold is the minimum sound pressure level – measured in Decibel (dB) – that must be imposed on a sinusoidal signal in order for it to be perceived in a quiet environment (Heil and Matysiak, 2020).

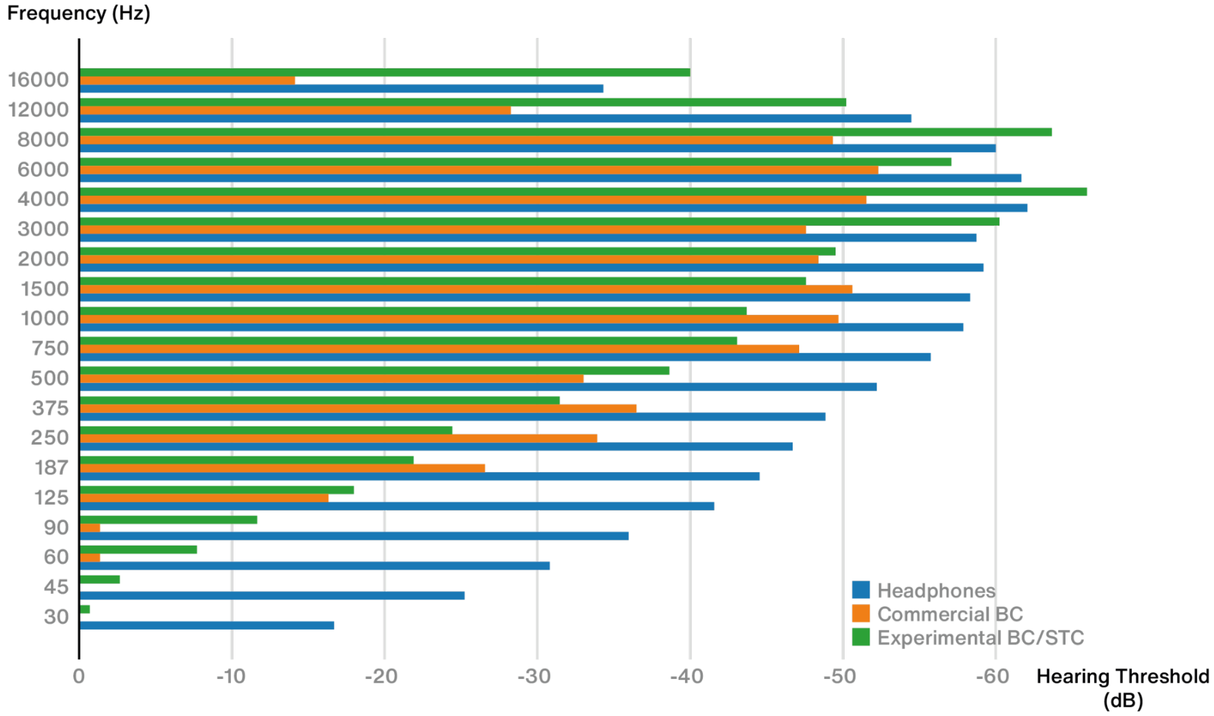

Figure C.1 The results of the three systems' testing, demonstrating the generated equal-loudness contour curves. It can be seen how the proposed mechanism (in green) outperforms the response of commercial bone conduction headphones (in orange) in the frequency bands 45Hz to 187Hz, 375Hz to 750Hz, and 1.5kHz to 16kHz.

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D. Appendix D

In Depth: Real Time Location Services

I complement the hybrid bone and soft tissue conduction wearable with an indoor localisation system and a simulation running in Unity to feedback targeted audio cues to the agents exploring the space. This section explains the rationale behind the hardware and software technologies employed in the overall system. A system that identifies and tracks people and objects in real-time is called a Real-Time Locating System (RTLS) (Thiede et al., 2021). Several applications benefit from an RTLS, ranging from industrial automation (Thiede et al., 2021) to logistics (Gutewort et al., 2021), healthcare (Pancham et al., 2017), and tourism (Płaza et al., 2018). Depending on the implementation scenario, RTLS systems can be built using various technologies, depending on whether the system will be deployed outdoors or indoors.

Outdoor localisation is primarily based on Global Positioning System (GPS) technology. Localisation based only on consumer-grade GPS has an accuracy between 7 and 13 m (Hameed and Ahmed, 2018; Merry and Bettinger, 2019), but when integrated with other technologies, the accuracy can be improved to be between a metre and a few millimetres (Ayhan and Almuslmani, 2021; Vatansever and Butun, 2017). However, these methods require complex hardware configurations or substantial post-processing (Vatansever and Butun, 2017). Further, GPS technology can only be utilised outdoors, as it depends on data received from satellites, which is severely degraded when it needs to traverse solid objects. Conversely, as summarised in Table D.1, indoor localisation can be obtained using Bluetooth beacons (Giuliano et al., 2020), W-Fi networks (Dai et al., 2020), passive ultrasound (Hoeflinger et al., 2019) or infrared sensors (Arbula and Ljubic, 2020) or specialised sensors, such as ZigBee (Ulusar et al., 2018), Radio Frequency Identification (Motroni et al., 2021) and Ultra-Wideband nodes (Schmidt et al., 2018). Table D.1 compares these technologies' pros and cons, as per Arbula & Ljubic (2020), Delamare et al. (2020), Zafari et al. (2019), Alinsavath et al. (2019), Sadowski and Spachos (2018), and Merriaux et al. (2017).

Technology	Maximum Range	Precision	Power Consumption	Advantages	Disadvantages
Bluetooth	100m	2-5m	Low	Low energy consumption, reception range	Noise, low accuracy
WiFi	35m	2.5m	Moderate	Does not typically require extra hardware, high accuracy	Noise, requires slow post-processing
Ultrasound	2-10m	0.3m	Low-moderate	Low signal degradation	Sensor placement is fundamental, works only in two dimensions
Infrared	< 1m	1m	Low	Low cost, scalable	Low range, interference between sensors
ZigBee	75m	0.51m	Low	Low power, secure	Requires dedicated hardware
RFID	200m	1.7-2m	Low	Low power, wide range	Low accuracy
Ultra-Wideband	10-20m	0.1m	Moderate	Immune to interference, high accuracy, scalable	Range, requires dedicated hardware
Vicon (motion capture)	Variable	0.15mm	High	Extreme precision, error variability of 0.015mm	Requires dedicated infrastructure, high cost

Table D.1 Comparison of indoor localisation technologies.

Ultimately, I chose to use Ultra-Wideband (UWB) nodes to track agents exploring the space. As illustrated in Table D.1, although UWB requires dedicated hardware and has a medium range, its highest degree of accuracy and its immunity to interference are enticing features for mixed reality applications, where continuity between physical and digital worlds is essential. Finally, UWB technology has been successfully employed for mixed reality applications (Cirulis, 2019; Russell et al., 2016).

To give a short overview of this technology, UWB is a data transmission technique that depends on the transmission and reception of pulsed radio frequency signals. Thanks to its characteristics, it can overcome the downsides of other localisation systems and allows centimetre-level accuracy (Tariq et al., 2017). UWB localisation is characterised by n fixed nodes of known position that allow the localisation of a mobile object, the tag. Both the fixed notes and the tag can, at the same time, transmit and receive data. The tag transmits impulses characterised by spherical waves. With a minimum of four fixed nodes in space, it is possible to identify the tag's position unequivocally in 3D space. UWB nodes are used to establish a RTLS via multilateralisation, as described in Figure D.1.

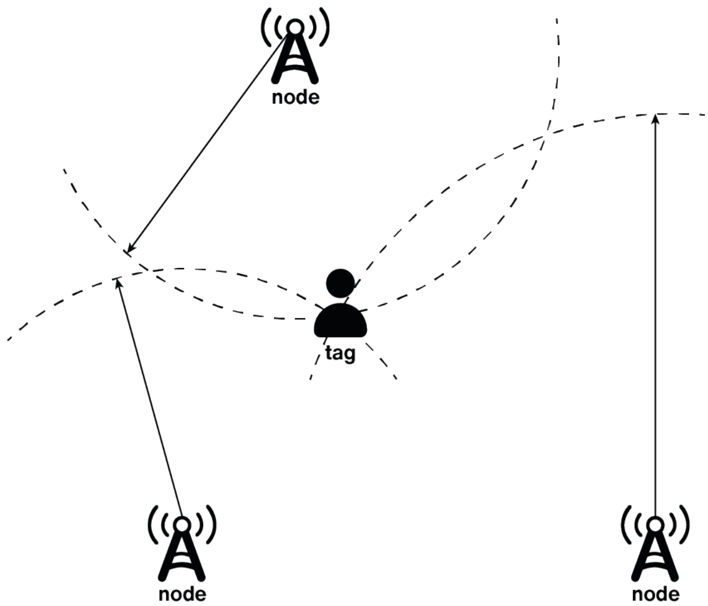

Figure D.1 How multilateralisation allows for position tracking with UWB nodes. Multilateralisation measures the Time of Arrival (ToA) of radio waves emitted by the fixed nodes. These waves have a known length and propagation speed, allowing to easily infer the tag's position based on the ToA to the tag.

Several manufacturers provide UWB nodes and tags with various prices and features. I chose to employ Decawave's MDEK1001 system, as it offers a relatively low-cost solution that is open-source, supports multilateralisation out of the box and presents data in a platform-agnostic format, JSON[30], with the following format:

```
{
       "position" : {
          "x" : 0.0000000,                    // x position, in meters
          "y" : 0.0000000,                    // y position, in meters
          "z" : 0.0000000,                    // z position, in meters
          "quality" : 99                      // signal strength, between 0 and 99
       }
}
```

All the tags and stationary nodes are connected to a central system, the bridge, which streams the JSON-encoded information to other devices connected to its WiFi access point. The bridge uses the Message Queuing Telemetry Transport (MQTT) protocol to publish the network data. MQTT (International Organization for Standardization, 2016) is based on the publish/subscribe model, where clients can be kept separate so that a particular client, the publisher, can send a message while other clients, the subscribers, can receive it. This way, the publisher and subscriber can ignore the existence of other clients. In addition, a new actor, the broker, is able to filter and distribute communications between publishers and subscribers. The broker manages the data flow in the system. For this project, the tags are configured as publishers, transmitting their location to a Raspberry Pi microcomputer, configured as the broker publishing the location streaming data on an ad-hoc WiFi network. This arrangement allows any computer connected to the same wireless network to subscribe to the tag's location information. As described in the next section, a simulation in Unity3D, running on a computer connected to the WiFi network, receives the tag's location data.

[30] JSON (JavaScript Object Notation) is a text format ideal for information exchange as it is supported by all modern programming languages. A JSON object, enclosed between {}, stores data as name/values pairs.

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E. Appendix E

Experimental Setup

The software implementation for this prototype requires the audio information to be spatialised, as discussed previously. Unity offers support for spatialised audio, with several third-party libraries available to simplify or extend the basic utilities in the editor. Table E.1 offers an overview of the libraries analysed. I selected Resonance API (Kammerl et al., 2018) for this prototype, an open-source toolkit explicitly developed for immersive virtual realities. Further, this API supports standard stereo audio recordings rather than specialised formats, such as ambisonics (Gerzon, 1985) files, that require complex and ad-hoc recording solutions (Patricio et al., 2019; Zaunschirm et al., 2018). Resonance allows importing audio files, assigning them to objects in the environment and fine-tuning their sound emission characteristics. Although the Resonance API was last updated in 2018 (Kammerl et al., 2018), it is still compatible with current versions of Unity.

Library	**Pricing**	**Advantages**	**Disadvantages**
Unity Ambisonics	Included with Unity Editor	Seamless integration with the editor	Basic functionality, supports only ambisonic file formats
OpenAL	Open-source	Cross-platform, simple implementation	Aimed at surround systems rather than mixed reality
FMod	Freemium (up to $15,000)	Seamless integration with editor, replaces the default audio tools in Unity	Closed-source, expensive, not specific for spatialised audio
PortAudio	Open-source	Cross-platform, flexible file formats accepted	Written in C++ rather than C#, not specific for spatialised audio
LibSpatialAudio	Open-source	Cross-platform, includes an encoder, a decoder and a binauralisation engine	Written in C++ rather than C#, accept only specialised file formats
Resonance	Open-source	Designed for real-time VR applications, flexible file format requirements	Updated last in 2018

Table E.1 Comparison of spatialisation libraries and plugins for Unity.

Finally, although Ultra-Wideband technology allows physical location tracking, it does not track the wearer’s direction. The facing direction is crucial in this application, as it allows Unity to reproduce the spatialised audio correctly. As mentioned at the beginning of this section, Unity supports multiple devices, including Android mobile phones. I therefore took advantage of the gyroscope embedded in a smartphone to track the wearer’s facing direction. My implementation requires the user to point their phone towards their moving direction. Figure E.1 summarises the system, outlining how all the prototype’s elements interact with each other to create an immersive, audio-based mixed reality experience. The code was packaged into a self-contained application that can be installed on any Android phone or tablet. Figure E.2 shows the testing environment and the location of the UWB nodes therein.

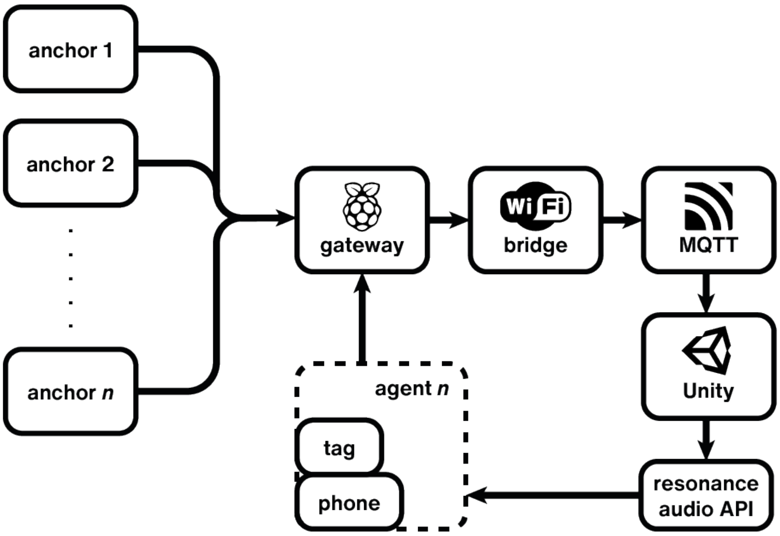

Figure E.1 Summary of the prototype. Together with the tag on the wearer stream, the anchors in the environment position data to a gateway hosted on a Raspberry Pi microcomputer. The position data is published via MQTT onto a local WiFi network. A computer connected to the same WiFi network subscribes to the location information, tracking the wearer's location in a Unity simulation. Virtual agents move within this digital replica of the physical environment, generating spatialised sound as they move. The wearer receives contextual audio information based on their position in space and their facing direction, as reported by a mobile device's gyroscope.

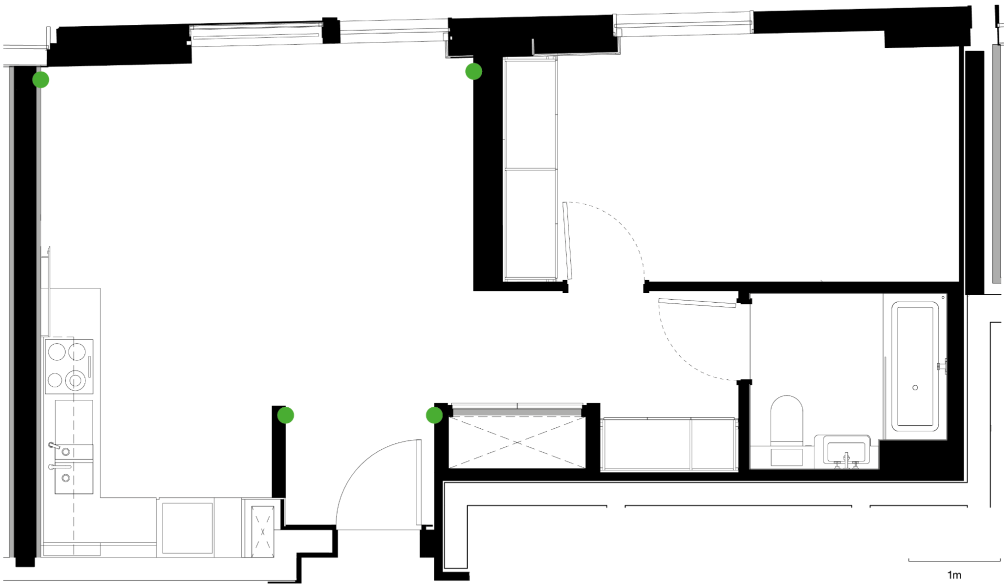

Figure E.2 Experimental setup. The image depicts in green the position of the four UWB tags in the space.

Experimental Results

Once the system was put in place in the space, I tested its overall performance by creating a simple demo environment in Unity. As shown in Figure E.3, I recreated the walls and floors if the apartment following the floorplan depicted in Figure E.2. I added two virtual agents in the environment with basic navigation abilities. These agents move along a predetermined path determined by waypoints. While moving through the environment, the agents generate footstep sounds, as shown in Figure E.4. These footsteps result from a looping sound clip, spatialised through the Resonance API.

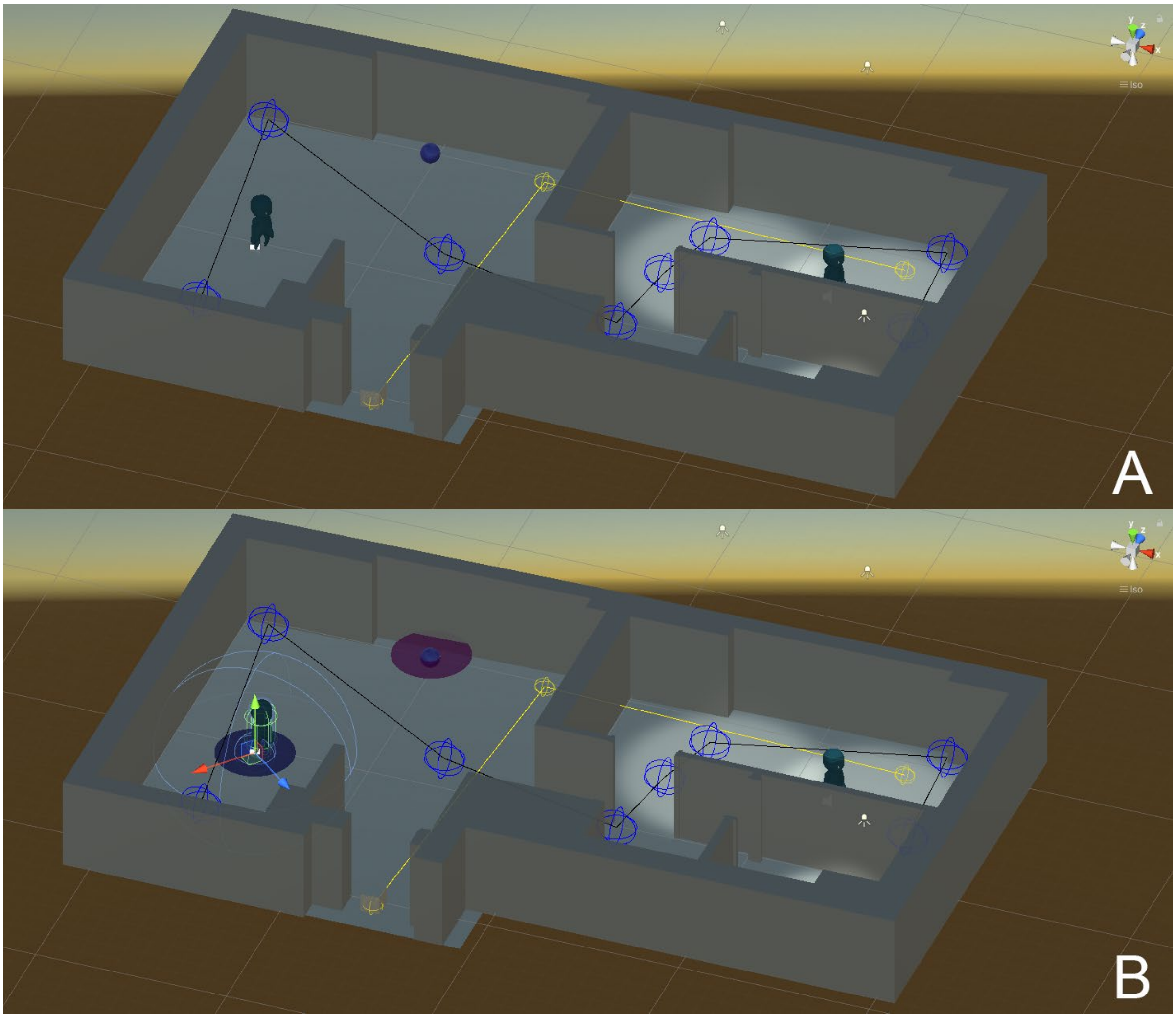

Figure E.3 The scene as set up in Unity. Figure A shows the overall scene, featuring the player placeholder (blue sphere) and two virtual agents with their waypoints, highlighted in blue and yellow spheres connected by lines. When the experience is initiated, the player's blue sphere position moves following the position data sent from the UWB system. At the same time, the two virtual agents walk along their predefined paths. Figure B shows one of the virtual agents selected, highlighting the imaginary sphere where the footsteps audio loop is played. Figure B also highlights the player's hearing zone in purple on the image.

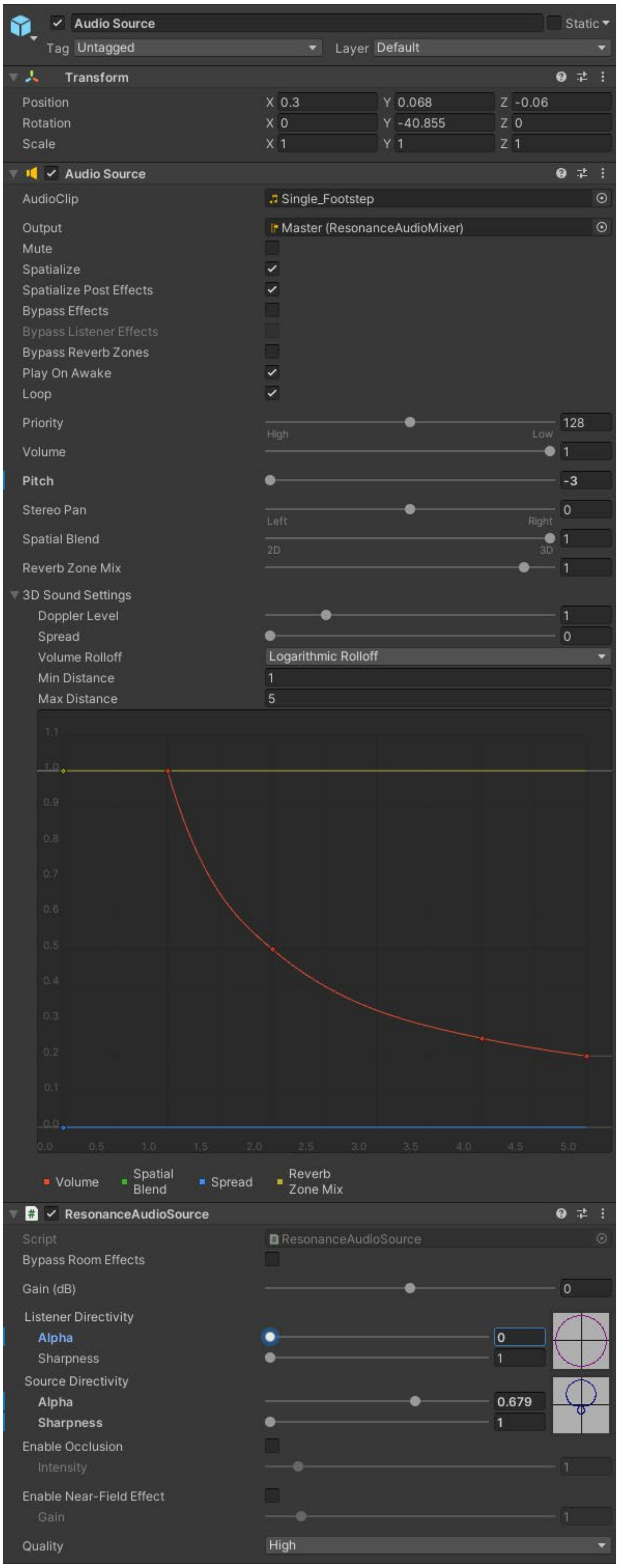

Figure E.4 Detail about the spatialised audio loop. I employ a stereo recording of a single footstep, looping continuously. The audio file is then output in the Resonance Audio Mixer, where I modified its spatial parameters to match the source directivity of footsteps in the physical world.

Further, I modelled the apartment's room materials via the Resonance API. Figure E.5 depicts an example of this process: the combined living room and kitchen is modelled to have three brick walls, one glass wall (to represent the windows), a ceiling of noise-dampening tiles and wooden floors. The same process is repeated for the other three areas of the apartment: the bedroom, the corridor and the bathroom. The first two spaces were assigned identical properties to the living room, while the bathroom was modelled as having ceramic tiles throughout.

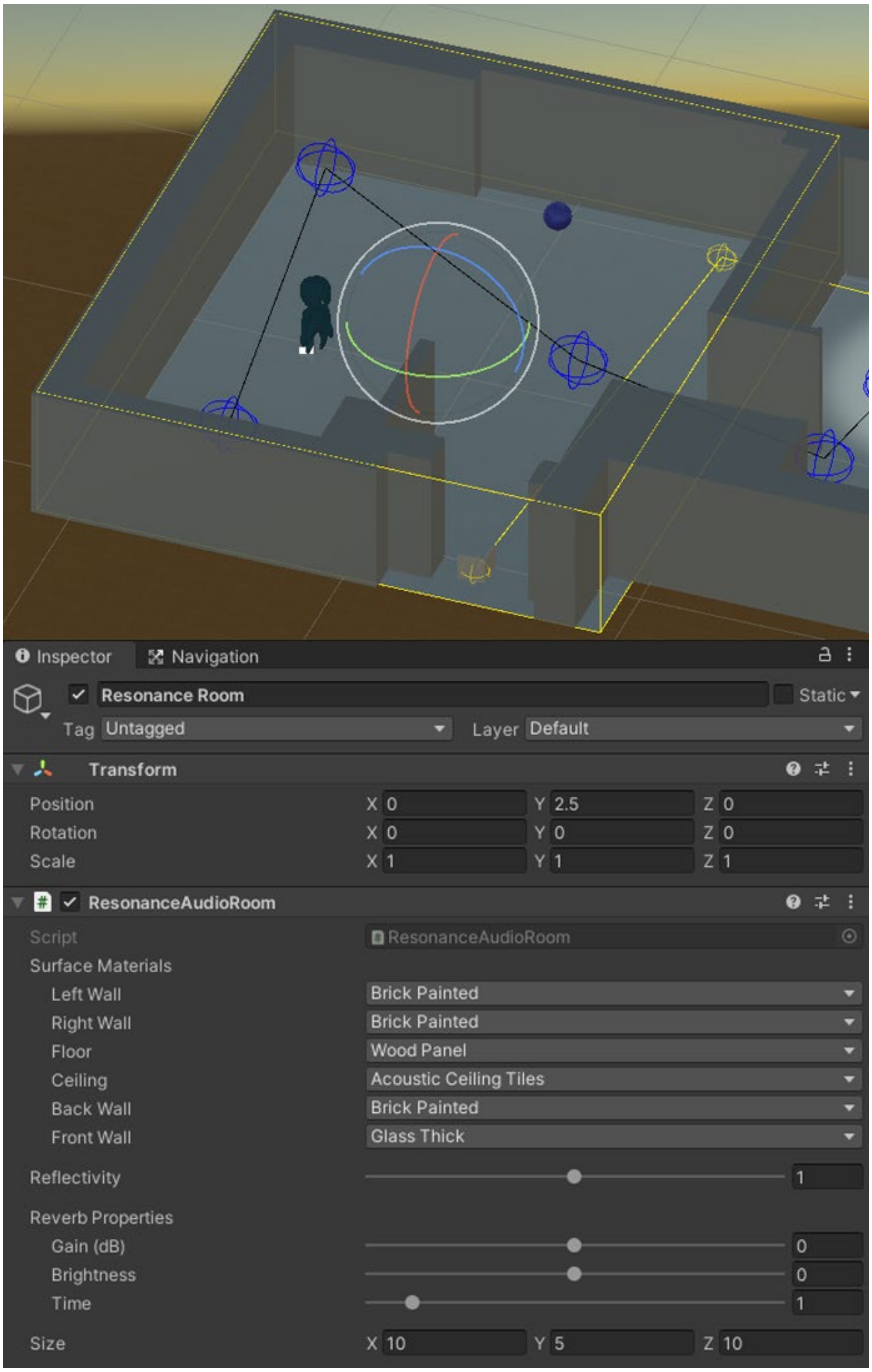

Figure E.5 Detail of the setup for an Audio Room with the Resonance API. The Resonance room, highlights in yellow in the image, is used to compute reverb, echo and other sound refractions. The ResonanceAudioRoom script allows for assigning materials – and, consequently, their audio characteristics – to the six sides of the room.

I employed a separate piece of software, MQTT Explorer (Nordquist, 2022), to verify the correct functioning of the Ultra-Wideband sensors, as shown in Figure E.6. As mentioned in section 6.2.2, the sensors stream position data via a Raspberry Pi acting as an MQTT broker. Once I verified that the Ultra-Wideband sensors were correctly streaming position data, this information could be passed onto Unity to move the characters via a custom script, as shown in Figure E.7. Finally, the application was built and packaged as standalone Android software and installed on a Pixel 3 device (Google, 2018). Figure E.8 depicts some screenshots of the application running on the smartphone.

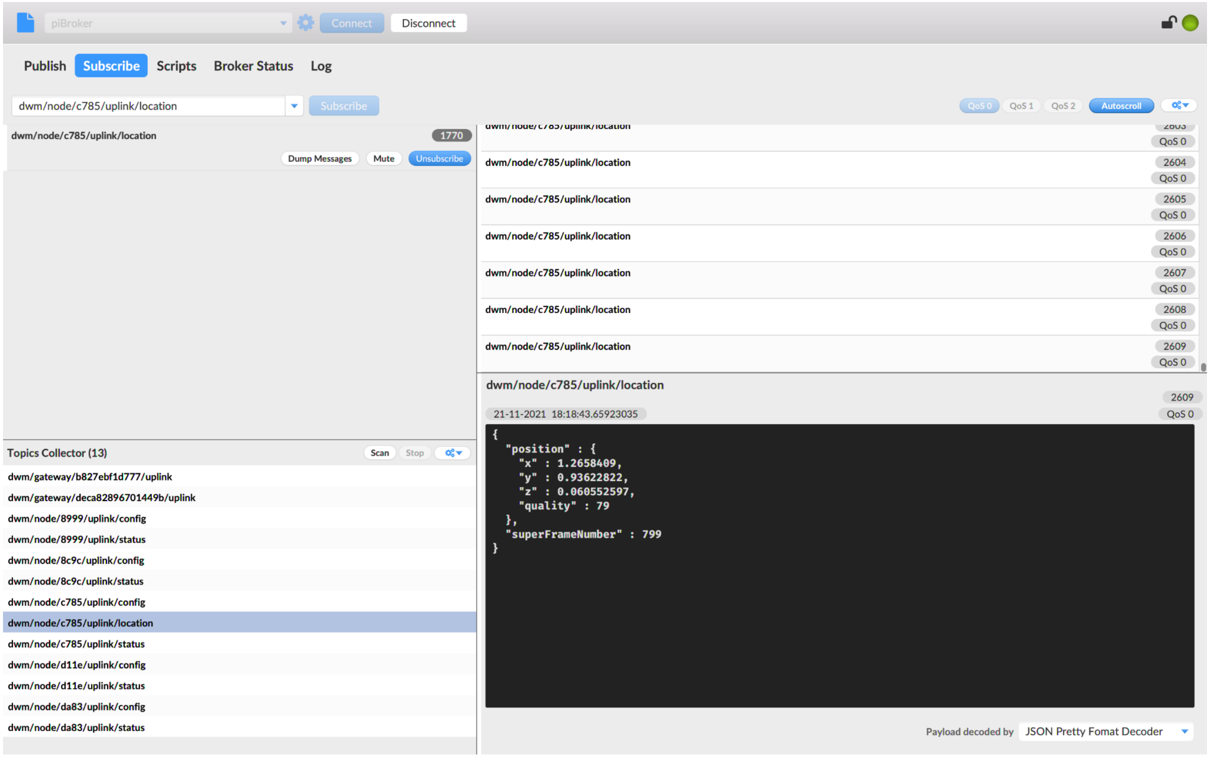

Figure E.6 MQTT Explorer screen grab. This software allows scanning the local network for MQTT-enabled devices and reading the data they stream. This software enabled me to quickly identify the unique ID for the UWB tag used to track the human agent's position (c785) and verify that the JSON file it generated was correct.

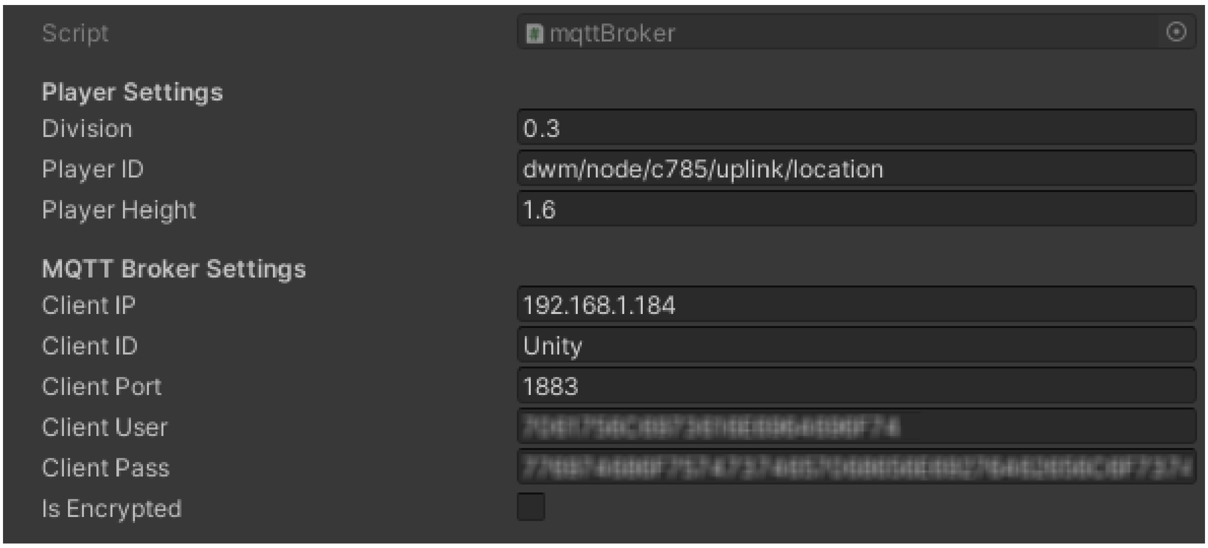

Figure E.7 The MQTT listener script in Unity. This custom script securely connects to the Raspberry Pi broker on the local network and allows for assigning a UWB tag to each player.

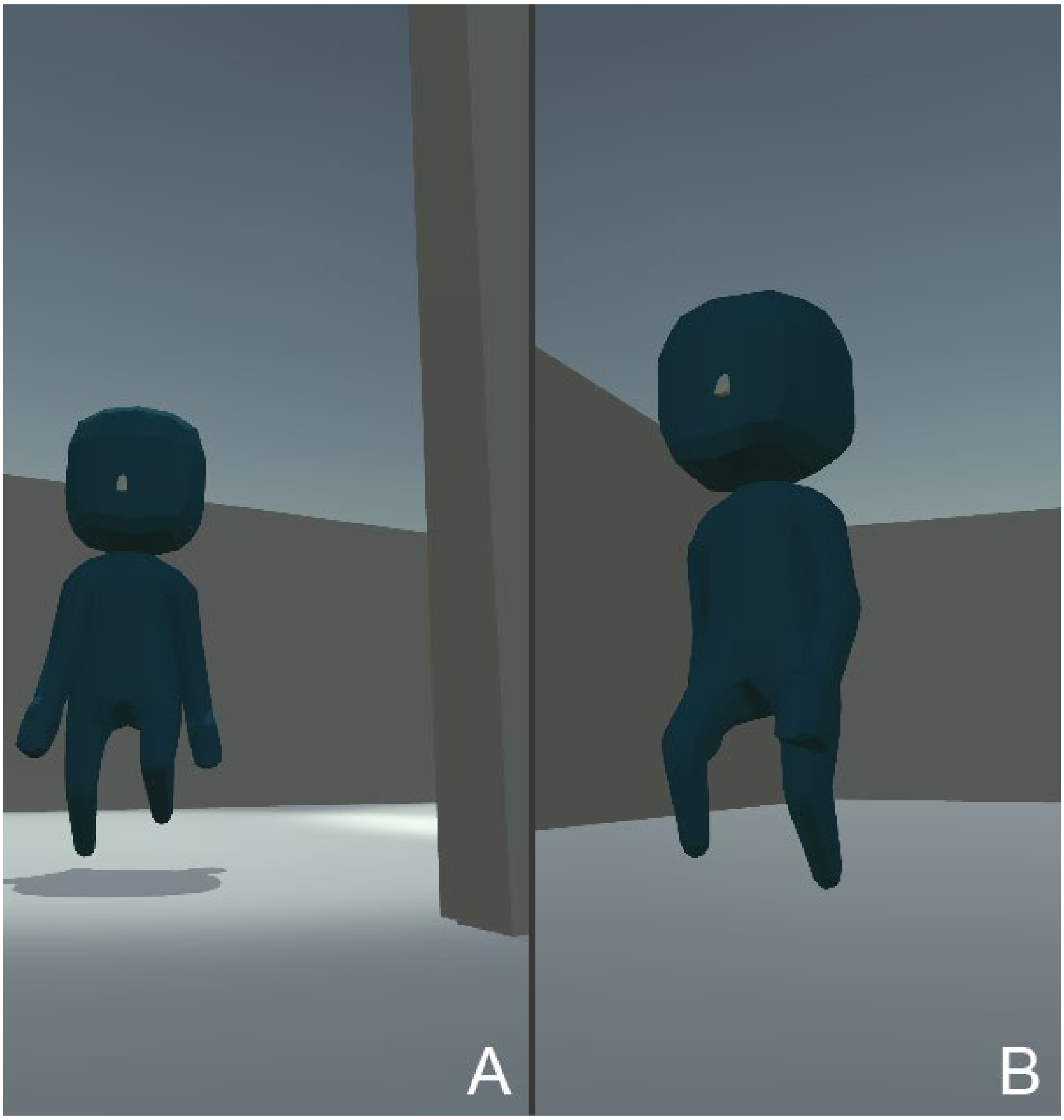

Figure E.8 Screenshots from the application running on an Android smartphone. The user's movements are tracked via UWB and MQTT, while the smartphone's onboard gyroscope allows tracking the user's orientation in space. Figure A and B show the two virtual agents in their respective rooms. Figure A shows the agent in the bedroom, while Figure B the one in the living room.

The experiment effectively proved the concept, with the Ultra-Wideband system accurately tracking the user's movements and the Resonance API delivering immersive spatial audio. Integrating smartphone gyroscope data ensured the sound adjusted correctly with the agent's orientation. However, I noted some limitations, such as minor latency issues in syncing audio with rapid movement, and occasional glitches from looping footstep sounds.

Despite these challenges, the case study demonstrated that combining a hybrid bone and soft-tissue conduction headset with UWB, smartphone sensors, and spatial audio can effectively feedback to the wearer hidden digital affordances, meeting the objectives of the design brief. Further, this case study explored the tension between body-moulding and applicability to a larger subset of human bodies, which informed my refining of the Guidelines, as discussed in chapter 6's conclusions and throughout chapter 7.