Autonomous Decision Making in a Bioinspired Adaptive Robotic Anchoring Module

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Abstract— **This paper proposes a bioinspired adaptive anchoring module that can be integrated into robots to enhance their mobility and manipulation abilities. The design of the module is inspired by the structure of the mouth in Chilean lamprey (*Mordacia lapicida*) where a combination of suction and several arrays of teeth with different sizes around the mouth opening is used for catching preys and anchoring onto them. The module can deploy a suitable mode of attachment, via teeth or vacuum suction, to different contact surfaces in response to the textural properties of those surfaces. In order to make a decision on the suitable mode of attachment, an original dataset of 500 images of outdoor and indoor surfaces was used to train a visual surface examination model using YOLOv3; a virtually real-time object detection algorithm. The mean average precision of the trained model was calculated to be 91%. We have conducted a series of pull-out tests to characterize the module's strength of attachments. The results of the experiments indicate that the anchoring module can withstand an applied detachment force of up to 70N and 30N when attached using teeth and vacuum suction, respectively.**

I. Introduction

Adaptable anchoring modules that can be integrated into robots to enhance their ability in establishing and maintaining attachment to different environments while transferring across porous and impermeable surfaces are invaluable for a broad range of industrial applications. This includes attachment by mobile robots, e.g. climbing platforms, for the inspection and repair of buildings such as heritage sites, power plants and bridges, and disaster zones [1].

Physical anchoring onto well-grounded structures such as trees, rocks, or facades of buildings, is a biological approach for locomotion, standing against fluid flows, object manipulation, and energy management in natural organisms [1]. Using claws [2], small-scale adhesive fibers [3,4], curling around and enclosing of the body [5,6], and providing negative pressure [1,7] are some of the approaches that animals, insects, and plants use to attach to their environment. A range of animals from very small insects to large bears use spines, claws, or teeth to enable interlocking on to the surfaces on which they are climbing on [8,9]. Some animals use teeth as auxiliary appendages for locomotion, e.g. walruses use their long pointed teeth, often called tusks, to help them haul themselves out of the water and make the transfer onto the sea ice. They use the same tusks as an anchor preventing the animal from drifting away with the current [10,11].

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The arms of octopuses are covered with rows of independently controlled sucker organs enabling multiple functionalities as diverse as manipulating delicate objects within their environment (e.g. their egg capsules) to anchoring the body to hard substrates such as rocks in order to withstand storm surge and sea waves [1].

While some animals rely purely on a single mechanism for anchoring, some other ones use a combination of distinct mechanisms to anchor to their environments. For instance, cockroaches can climb over a wide range of surficial materials by using their claws in conjunction with sticky metatarsal pads [8]. The tapeworm (*Taenia solium*), often called parasite of the human gut, uses four suckers located around the head of the animal to approach the gut wall and a set of hooks to fully attach onto it [12].

Most prominently, the Chilean lamprey (*Mordacia lapicida*), a parasitic animal characterized by a toothed, funnel-like sucking mouth, is known for its strong adhesion force to the surfaces to which it clings. The structure of the mouth plays an important role in the animal's feeding. The sea lamprey, Fig. 1a, uses a combination of suction and several circular arrays of teeth with different sizes around the mouth opening to catch and anchor onto their preys which are usually larger than themselves [13].

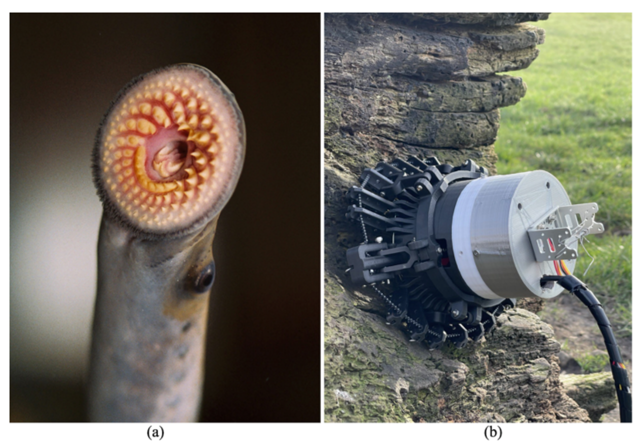

Figure 1. (a) The sea lamprey [Image CC-SA-BY T. Lawrence, Great Lakes Fishery Commission], (b) adaptive vision-based dual-mode anchoring module that can deploy a suitable mode of attachment (spiky teeth or vacuum suction) in response to variations in the textural properties of the contact surface.

Learning from nature, a number of researchers have developed anchoring devices based on claws, spines, and suckers; an omni-directional anchoring foot mechanism using microspines, where arrays of microspines with suspension

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flexures tolerating forces up to 100 N on natural rock surfaces [14]; an array of compliant rotary microspines integrated with a wheel structure was developed enabling the robots to climb rough vertical walls [15]; artificial octopus-inspired suckers developed which are actuated by negative air pressure [7], positive air pressure [16], shape memory alloy [17], and dielectric elastomer actuators [18].

Prominent examples of research on combining different modes of attachment include a self-aligning gripper based on combining gecko-like and electrostatic adhesive mechanisms where the two modes of attachment complement each other; while the gecko-like adhesives can typically provide high adhesion force to smooth surfaces with limited ability for attachment to rough surfaces, the electrostatic adhesives can enable attachment to a wider range of materials at a lower level of adhesion [19]. In [20], a worm-inspired wall-climbing robot utilizing an anchoring mechanism based on the composition of suction cups and microspines is proposed; their experimental results on the sucker-microspine composite structure indicates a 30% increase in the frictional resistance on rougher wall surfaces, as compared with the case of using suction cups only. The above approaches were based on concurrent activation of the two modes of attachment aiming at enhancing the chance or firmness of the anchor by using a combination.

However, in a range of applications, the use of certain modes of attachment can be ineffective or even damaging. For example, the activation of vacuum pressure-based suction cups on porous surfaces, such as the volcanic rocks, can be very inefficient, ineffective, and wasteful in terms of the robot's energy management. Similarly, the activation of artificial spines (or other forms of sharp appendages such as claws, teeth, etc.) on delicate substrates can damage the contact surface. In order to avoid this, the anchoring system should adapt effective methods to attach to different contact surfaces taking into account their surface properties. This requires different modes of attachment to be deployable independent of one another, as opposed to their simultaneous deployment [1, 21].

Hence, in this paper, we propose a dual-mode anchoring system that uses artificial intelligence to deploy a suitable mode of attachment, either using spiky teeth or suction mechanisms, based on the surface properties of the contact surface, Fig. 1b.

The overall configuration of the anchoring system takes inspiration from the co-located arrangement of curvilinear radiating rows of teeth and the suctorial oral disc in Chilean lamprey's mouth. Important biological observations including the animal's teeth being larger towards the periphery of the mouth [22] as well as their inward orientation to contain the prey and block it from sliding out [13], were also considered in our mechanical design, Fig. 1.

The contributions of this paper can be summarized as follows:

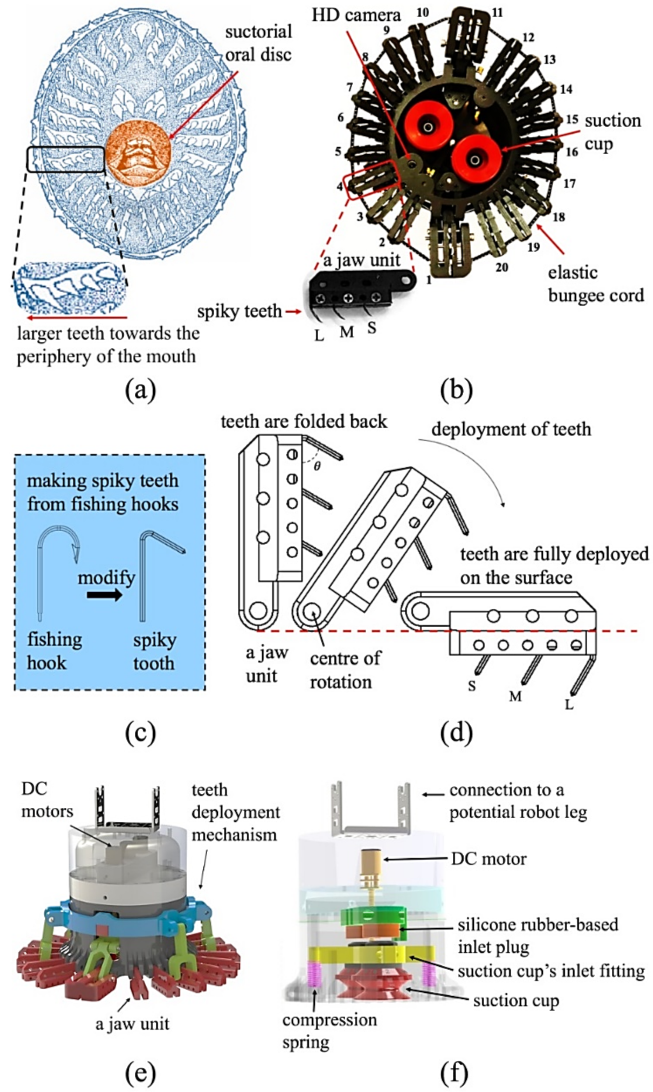

Figure 2. The arrangement of teeth in Chilean lamprey (*Mordacia lapicida)* [Adapted from image CC-BY-NC FAO, 23, 24], (b) the bottom view of the anchoring module with configuration of teeth inspired by the Chilean lamprey. Note that teeth are larger towards the periphery of the lamprey's mouth, (c) fabrication of the spiky teeth from standard fishing hooks, (d) the implementation of a jaw unit embedding three spiky teeth that become larger moving away from the jaw's centre of rotation, and the sequence of deployment, (e) configuration of the module when the teeth mechanism is deployed, (f) the internal structure of the module showing the integration of the suction mechanism, the inlets of suction cups are blocked and sealed using two actuated valve plugs made from silicone rubber.

(1) Creating an anchoring module with independently deployable mechanisms for vacuum suction and teeth attachment, Fig. 2.

(2) Adapting a you only look once (YOLO) v3 algorithm to detect the surface properties of the environment with which the robot is interacting with. This arrangement provides the possibility of autonomous decision-making on the suitable mode of attachment to the environment.

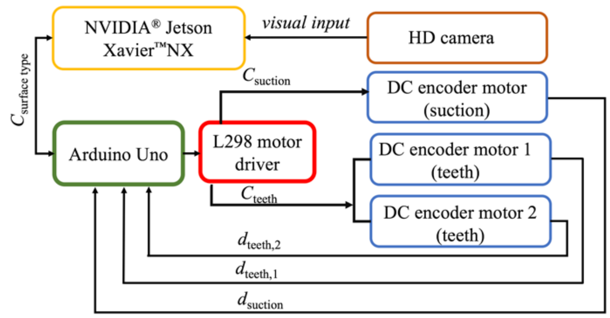

Figure 3. Electrical diagram of the anchoring module: NVIDIA® Jetson Xavier™NX is the main processing unit for running the surface detection algorithm; it is connected to motors driver and encoders via an Arduino Uno.

The contact surfaces studied are mainly those found in the natural environments including rocks and cliffs, various tree trunks, and muddy surfaces, in addition to some manufactured surfaces such as perforated metal sheets, glass and acrylic surfaces. Note that the anchoring module is integrated with an endoscopic HD camera, as shown in Fig. 3.

The remainder of this paper is organized as follows. In Section II, our approach in the development of dual-mode anchoring hardware is described. In Section III, the image pre-processing approach used in this study is explained and a model for detecting textural properties of contact surfaces was created using YOLOv3. The experimental testing of the anchoring module and respective results constitute Section IV. The conclusions and future works are presented in Section V.

II. Dual-mode anchoring module Hardware

The dual-mode anchoring module is integrated with two attachment mechanisms using spiky teeth and vacuum suction, Fig. 2. The spiky teeth are used to attach to porous surfaces, such as volcanic rocks, resin-bound driveways and certain types of buildings' facades, and the vacuum suction system is used to attach to a range of non-porous and smooth surfaces such as a window's glass, and a range of manufactured surfaces from metals or composites. In the following, the process of design, fabrication, and experimental testing of each anchoring mechanism is described.

A. Anchoring with spiky teeth

In order to construct a teeth mechanism inspired by the circular arrays of teeth in lamprey, we used standard fishing hooks (Crivit leader and hook set) at three different sizes of 2, 4, and 6. The standard fishing hooks are originally curved making them hard to detach once they are attached. Therefore, we modified them, as described in Fig. 2c, to ease detachment. The teeth mechanism consists of twenty jaw units each integrated with one large (L), one medium (M), and one small (S) spiky tooth, as shown in Fig. 2d. The size and arrangement of the spiky teeth facilitate engagement with the surface; the size is increased as we move away from the center of the anchoring module allowing for faster engagement of the three spiky teeth in each jaw unit with the contact surface, as the unit is angularly deployed, Fig. 2d and Fig. 2e. Two DC encoder motors running at 400 rounds per minute are used to actuate the jaw units. As shown in Fig. 2b, while the units 1, 4, 8, 11, 14, and 18 are connected to the motors using rigid links, the motion of the rest of the units is linked with them using a 5mm thick multi-core elastic bungee cord (EBC) that can tolerate tension forces up to 200N. The use of the EBC in the deployment mechanism enables elastic deployment of the spiky teeth over the contact surface leading to better engagement between the spiky teeth and dips and bumps of the contact surface. The jaw units, sliders and linkages are fabricated using Onyx materials via a Mark 2 3D printing machine, Markforged, USA.

B. Anchoring with Vacuum Suction

The vacuum suction attachment mechanism comprises two vacuum suction cups (B30-2, Piab, USA), a bespoke valve mechanism integrated with the cup. The valve mechanism is comprised of a cylindrical inlet plug made from super-soft silicone rubber (Ecoflex™ 00-50, Smooth-On, USA) that is pressed onto the inlet fitting on the top of the suction cup using two motorized sliders, as described in Fig. 2f. The inlet plug is used to block and seal the suction cup inlet when the cup is compressed. This creates a negative pressure inside the cup enabling attachment. Each slider uses a 4mm (outer diameter) compression spring with a spring constant of 50 N/m, Fig. 2f. The compression springs put the set of the suction cup and the silicone rubber-based inlet plug under transverse loading, leading to a better sealing of the suction cups' inlets which strengthens the anchor.

C. The module's electronics and processing unit

The electronics and processing unit of the module is in charge of processing the images from the contact surface, subsequent decision making on the deployment of a suitable mode of attachment, and generating relevant control signals for motor drivers. As it is shown in Fig. 3, an NVIDIA® Jetson Xavier™NX is used as the main control board and an Arduino Uno is interfacing it with the motor driver and encoders. An HD camera is connected to the processing unit to provide visual information of the contact surface. Our surface detection algorithm is run on the main control board and sends out commands for the suitable mode of attachment $C_{\text{surface type}}$ to the interface board. Then, the interface board sends the relevant commands for activating the attachment mechanisms, C_{teeth} and C_{suction}, to motors via an L298 motor driver. The DC encoder motors are used to deploy the two mechanisms of attachment, where the respective motor encoder signals, $d_{\text{teeth},1,2}$ and $d_{suction}$, were fed back to the Arduino Uno to stop motors when each mechanism is fully deployed.

III. Visual Examination of surface properties

In order for the dual-mode anchoring module to deploy the suitable mode of attachment, it should be provided with textural information of the contact surface. Hence, in this study, an algorithm based on YOLOv3 is designed and implemented on the NVIDIA® Jetson Xavier™NX, within the electronics and processing unit of the module. This arrangement enables answering the question of whether the specified region is suitable for attachment using teeth; if the answer is 'no' then the vacuum suction mode is deployed, which is associated with a probability value of less than 56% in our design. Note that, the main reason for choosing the YOLOv3 algorithm was the ability to run this type of algorithm on NVIDIA® Jetson Xavier™NX with low latency (virtually real-time) at a high precision [25]. In order to design and implement the algorithm a dataset of 500 images from environments that are suitable for attachment via spiky teeth is created via photography, then all images within the dataset are labeled. The mean average precision of the trained model was calculated as 91%. Fig. 4a presents six members of the dataset gathered based on the fit for spiky teeth attachment. Increasing the number of dataset members has a direct effect on the YOLOv3's model precision which clearly improves the surface examination accuracy. Note that all input images used for the network training were resized to 576×576 pixels.

A. *YOLOv3*

The YOLO framework is a highly fast object detection algorithm that works based on taking the entire image during the training and testing time, using a single convolutional neural network for both classification and localization of an object. Taking the whole image in a single instance, YOLO can predict the coordinates of the bounding box, a rectangle that encloses an object and related probability values. YOLOv3, a later variant of YOLO, has presented a substantial improvement over the YOLO to achieve a balance between speed and accuracy. This later variant applies a 1×1 detection kernel on feature maps of three different sizes at three different places in the network, as described in [26]. The improvement made the detection network suitable for detecting more complex objects and textures, and hence we have chosen this variant of YOLO as the main model for autonomous object detection in the anchoring module. Our research uses a configuration of YOLOv3 thoroughly discussed in [26,27]. In summary, we completed the following steps to adapt and implement the YOLOv3 detection algorithm for autonomous anchoring:

1. Collecting a database of 500 images from surfaces that are suitable for anchoring using spiky teeth, e.g. porous surfaces.
2. Labeling the database members using Microsoft's Visual Object Tagging Tool (VoTT), Fig. 4a.
3. Using our database, we train our model based on the YOLOv3 algorithm for the detection of surfaces that are suitable for anchoring using spiky teeth. Note that we use pre-trained Darknet-53 weights and convert them to YOLOv3 format, Fig. 4c.
4. Using the trained model to detect new surfaces.

The architecture of YOLOv3, as shown in Fig. 4b, is comprised of 16 residual blocks, each of which contains convolution layers, a batch normalization, and a rectified linear unit (see [26] for more details). Figure 4c shows the loss function of our YOLOv3 model's training and testing results which are close to zero indicating the effectiveness of our detection approach. Figure 4d shows some results of our surface detection tests on a perforated metal sheet, the body of a non-living tree and a red lava rock.

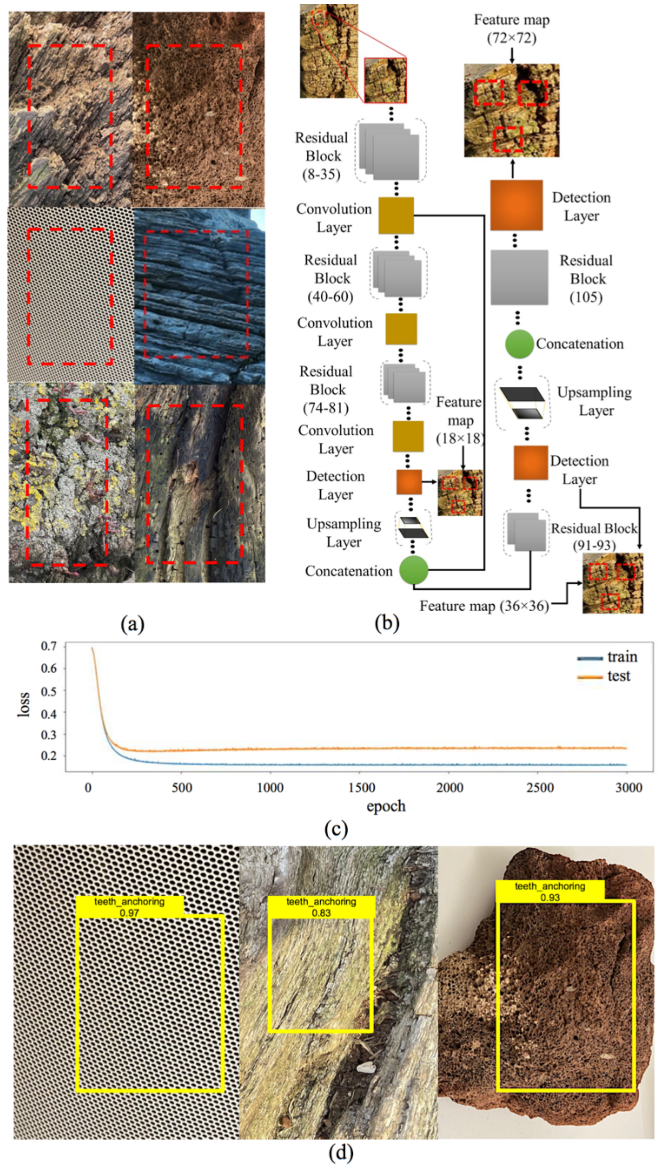

Figure 4. The visual surface examination model: (a) examples of labelled members of the dataset gathered based on the fit for teeth attachment, (b) the architecture of YOLOv3 algorithm used for autonomous surface detection in our study. Note that the Darknet-53 as is employed the backbone network of YOLOv3, (c) the loss functions for training and testing of the algorithm, and (d) the results of the surface detection tests on a perforated metal sheet, the body of a non-living tree and a red lava rock.

IV. Anchoring Strength: Experimental Load Testing and Results

An anchor can either be experimentally tested to its failure point with a destructive pull-out test, or tested to a proof load which is considered as a non-destructive test. In order to characterize the anchoring strength of the module in different modes, we have conducted a series of load testing experiments using the experimental setup shown in Fig. 5 and Fig. 6.

The failure tests of the anchoring module are shown in Fig. 5, where the module is attached to a digital scale from one side to enable the measurement of pulling force. In these tests, the ability of the module in anchoring to a perforated metal sheet and an acrylic surface were examined. In the experiment with the perforated metal sheet, the module was attached to it using the teeth mechanism. As the pulling force was increased above 60N, while the anchoring module remained attached, the perforated metal sheet surface started to deform, and therefore we limited the pulling force to 60N, as shown in Fig. 5a. In the other experiment on the acrylic surface using the suction mechanism, the anchoring module withstood a maximum pulling force of 30.5 N before detachment, see Fig. 5b.

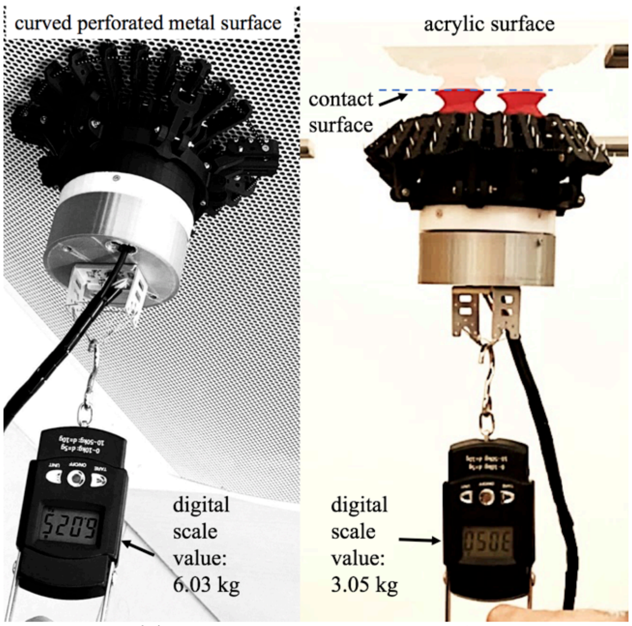

Figure 5. The destructive pull-out tests of the anchoring module when attached to (a) a perforated metal surface using teeth, and (b) an acrylic sheet using vacuum suction; during the destructive tests in the teeth mode, for pulling forces above 60N, while the anchoring module remained attached, the perforated metal sheet surface started to deform and we therefore limited the pulling force to 60N. In the attachment test to the acrylic surface using suction cups the module withstood a maximum pulling force of 30.5 N.

Figure 6 describes the proof test of the anchoring module. The experimental setup is comprised of a motorized linear guide with a fixed platform that is integrated with a Nano17 force/torque (F/T) sensor (ATI Industrial Automation, USA), and a moving platform used for mounting different types of contact surface samples. Note that the pulling force in the proof experiments were limited to the maximum measurable range by the Nano 17 F/T sensor which is 70N along the *Z*-axis. The module is attached to the contact surface, e.g. acrylic and lava rock surfaces, during the experiments and is under tensile force, measured by the F/T sensor, as the distance between the moving and fixed platforms changes, Fig.6a and Fig. 6b. Figure 6c shows the experimental proof test results. In the experiment using the suction mechanism, the module was detached when the pulling force reached the value of 30N. While the module is attached using the teeth mechanism it withstood pulling forces up to the maximum measurable range by the Nano 17 F/T sensor.

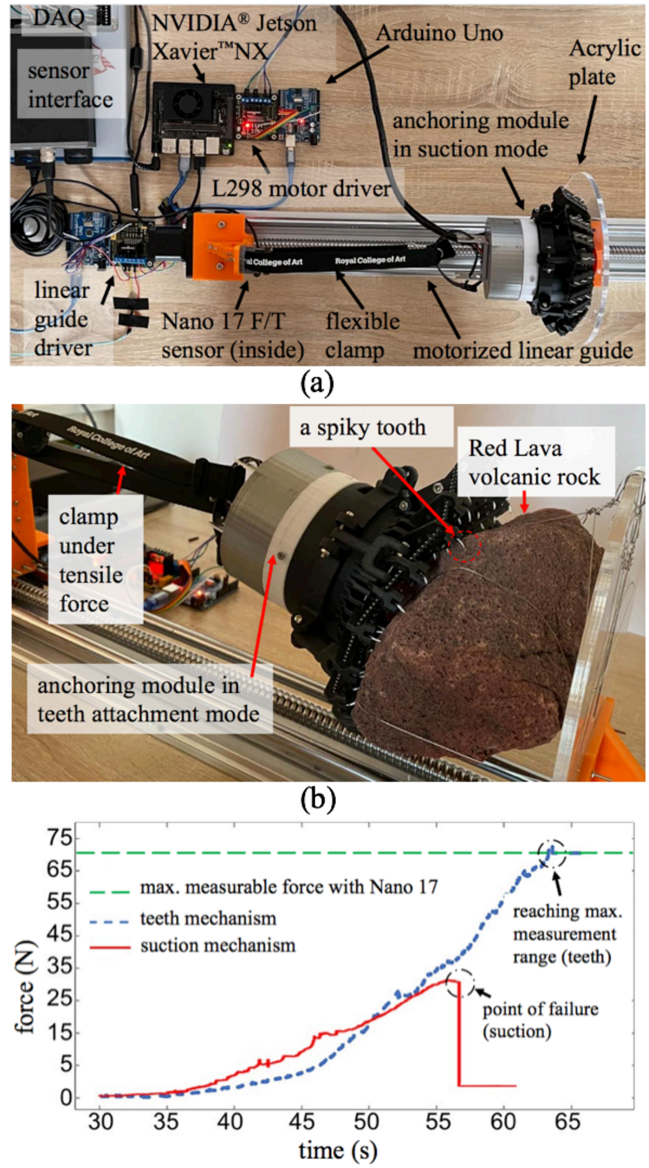

Figure 6. The configuration of the experimental setup for proof tests in (a) suction mode, and in (b) teeth mode. A motorized linear guide was used to move various contact surfaces away from the deployed (attached) anchoring module, while the module was mechanically linked to a Nano17 F/T sensor from the other end. (c) the results of experiments indicating that using teeth mechanism the anchor withstand pulling forces up to the maximum measurable range by Nano 17 F/T sensor, which is 70N along its *Z*-axis. Using the vacuum mechanism, the anchor can tolerate pulling forces up to 30N.

In addition, in order to evaluate the ability of the autonomous anchoring module in object manipulation, we have integrated the module into a robot arm [28] which is hanged from an elevated position. Within the workspace of the arm is a piece of red lava rock, as shown in Fig. 7. In order to attach to the surface of the rock and manipulate it, (1) the module takes a photo from the surface and made the decision on the suitable type of the anchor (decision: teeth mode to be activated), (2) the teeth mechanism is deployed and attached to the porous surface of the rock, (3) the rock is subsequently lifted using the arm, and (4) remained attached to the module while it is moved to multiple positions, taking different orientations, in the 3D space. Note that the weight of the rock is 1.1 kg.

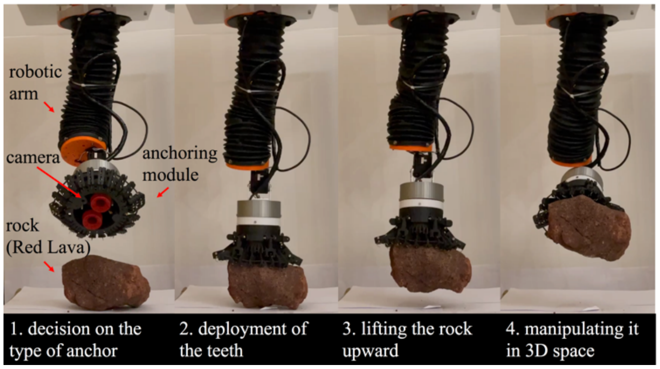

Figure 7. Demonstration of object manipulation using the anchoring module: (a) the surface texture of the object (a red lava rock) is captured by the camera and a decision on the type of attachment is made (teeth attachment is chosen in this case), (b) the teeth mechanism is deployed on the surface of the rock, (c) the rock is stably lifted, and (d) manipulated in 3D space without being dropped.

V. Conclusions

This paper presents an adaptive anchoring module that can be integrated into robots to enhance their mobility and manipulations abilities. The module autonomously acquires and processes visual information from the contact surfaces in the environment and deploys a suitable mode of attachment, either spiky teeth or vacuum suction, depending on the textural properties of the contact surface. In order to make a decision on the suitable mode of attachment, an original dataset of 500 images was used, and then a visual surface examination model was trained using YOLOv3. We conducted a series of pull-out tests to characterize the strength of attachments established by the anchoring module. The anchoring module was experimentally tested to its failure point as well as to a proof load. The results of the experiments indicate that the anchoring module can withstand an applied detachment force of around 70N and 30N when attached using spiky teeth and vacuum suction, respectively.

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