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Hard Shell, Soft Core: Binary Actuators for Deep-Sea Applications

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Abstract— **Deep-sea research represents invaluable opportunities to unravel hidden ecosystems, uncover unknown biodiversity, and provide critical insights into the Earth's history and the impacts of climate change. Due to the extreme conditions, exploring the deep-sea traditionally requires costly equipment, such as specific diving robots, engineered to withstand the high pressure. Our research aims to reduce the costs of deep-sea sediment sampling by introducing a novel actuation system for suction samplers, that capitalises the advantages of soft material actuators. At first glance, soft material actuators may not appear suitable for the harsh conditions that prevail in the deep-sea, but when combined with a rigid, bistable mechanism there is great potential for improving the accessibility of sampling and research in this challenging environment. The binary actuation system that results from this combination, is modular, scalable, lightweight, and low cost in comparison to existing solutions.**

I. INTRODUCTION

The vast depths of the ocean remain largely uncharted, yet they are attracting growing interest. This interest spans beyond the potential extraction of valuable resources like oil, gas, minerals, and food, and extends to concerns about environmental pollution, natural dangers, and the ocean's role in the planet's carbon cycle, particularly within the context of climate change.

One exploration technique that sheds light on the history of the ocean is the sampling of sediments, as sediments store information about changing conditions in the deep sea over time [1]. Among the various sediment sampling methods available, this paper specifically focuses on the method of suction sampling. This sampling approach not only allows for gathering sediment samples but can also be applied to collect water, bacteria samples or other small organisms [2]. The traditional suction sampler, as depicted in figure 1, mainly consists of a tube and a sample container compartment for the jars that hold the sediment samples. During operation, the tube is handled by a titanium hydraulic manipulator that is part of the standard equipment of an intervention class ROV (Remotely Operated Vehicle). Figure 2 depicts a rendering of the ROV Kiel 6000, which belongs to the GEOMAR Helmholtz Centre for Ocean Research in Kiel, Germany. In addition to the two titanium hydraulic manipulators and a suction sampler, it is equipped with a variety of tools. Due to the harsh conditions in the deep sea caused by the high pressure and the corrosive nature of salt water, ROVs, which represent the preferred option for research in the deep sea, have to be accordingly robust. It is worth noting that the size of the system alone makes it very costly to deploy the ROV. These types of remotely operated vehicles that are rated for 6000 m depth can weigh up to 5000 kg. Consequently, a large research vessel is required to deploy the ROV into the ocean using a crane attached to the ship [3].

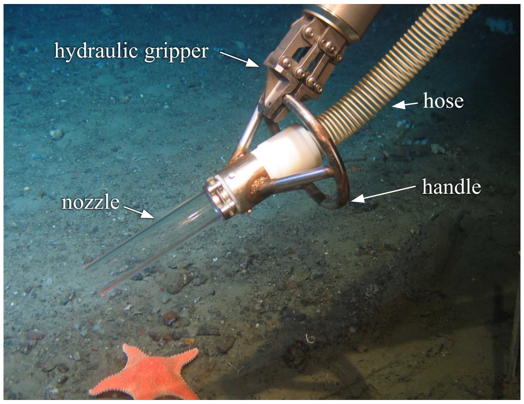

Fig. 1. Conventionally, a suction sampler is operated with the sampling tube being directed by a hydraulic titanium manipulator. However, with an alternative actuation approach, the manipulator could fulfill other tasks simultaneously to the suction sampling, or costs could be reduced by eliminating the need for the manipulator on the diving robot.

In order to lower the overall costs and thus making the process of sampling sediments in the deep sea more accessible to researchers, the currently used hydraulic titanium robot could be replaced or supplemented by an alternative actuation system that exploits the advantages of a soft robotic system, which are especially lightweight, easily scaleable, and reconfigurable [4]. This would allow for a more efficient usage of the ROV, as the manipulator and the suction sampler could be used simultaneously for different tasks. Another option for improving the efficiency of sampling with a lightweight actuation system is the potential to employ smaller diving robots for deep-sea research, thereby reducing the need for larger research vessels. If a smaller vessel would be sufficient to deploy the diving robot, the costs of sampling could be decreased even further.

A comparable approach to combine a soft material or continuous robot with a deep-sea ROV, as is depicted in figure 2, was already proposed in 1998 by Davies et al. in [5]. The authors suggested to attach a soft robot similar to an elephant's trunk to a deep-sea ROV and equip it with a camera so it can be used for exploration tasks that require

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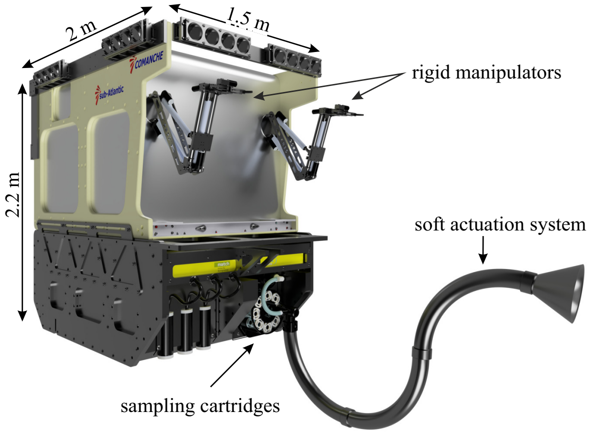


Fig. 2. This showcases the concept of the Kiel 6000, an intervention class vehicle rated for 6000m dept, in combination with a multi-segment soft actuator. The concept allows direct actuation of the suction sampling tube, eliminating the need for a conventional manipulator. The dimensions of the robot hint to the size of the ship that is necessary to transport and employ this robot.

high dexterity. However, they did not pursue the concept further. Since then, a few other underwater robots made from soft materials have been introduced: In Phillips et al., the authors present a soft robotic arm that is intended for handling delicate samples in the deep sea [6]. Li et al. presented a untethered soft robot for deep-sea exploration that was inspired by a snailfish and is sufficiently pressure-resistant to explore the Mariana trench [7]. In general, the usage of soft robotic systems have proven to be especially advantageous in the area of handling delicate samples [8] and the authors in Arcraci et al. emphasize the importance if interdisciplinary research that results in new concepts for deep-sea robotics [9].

In the category of snake-like underwater robots, the most prominent example is the Eelume robot, which is inspired by an eel and can be deployed into depths of up to 150 m for inspection and maintenance of, e.g., pipelines. However, due to its thruster-based propulsion, it is not suitable for conducting deep-sea sediment sampling [10].

Despite many underwater soft robots and snake-like robots already presented in research, to our knowledge, there is no deep-sea appropriate design that is intended to be used as a manipulator for suction sampling. Instead, most concepts focus on grippers or untethered biomimetic robots, which are rarely sufficiently pressure resistant to be deployed into depths beyond a few meters [8] [9].

The design proposed in this paper is partially inspired by another example for a binary manipulator designed for extreme environments: the BRAID (Binary Robotic Articulated Intelligent Device). This manipulator consists of a serial arrangement of three parallel binary actuators and was designed for space application. The binary approach was selected by the authors to eliminate the requirement for sensors within the structure [11], which would also beneficial for a robot operating in deep-sea conditions. While the BRAID manipulator consists only of rigid materials, our design for the new suction sampler actuation is a mixture between a binary, snake-like structure and soft material actuators. It consists of circular modules that enclose the tube of the suction sampler. Each module is composed of three binary actuators that contain linear soft actuators, whose elongation would result in the bending of the tube into the respective direction. The goal is to develop highly reliable actuators ensuring that the system remains operational even in the event of a single actuator failure. To repair an actuator, the diving robot would need to make its way 6000 m up to the deployment ship, which should be avoided in order to not waste money and time on the repair.

In the following paper we focus on the design of the bistable actuators that are the main component of the overall binary actuation system. The concept combines soft actuators with a hard shell, which results in a lightweight but still precise actuator. The design of the bistable mechanism is inspired by the most commonly used bistable mechanism: the retractable pen.

In summary the contributions of this paper include:

1) The concept for a binary actuation system for deep-sea suction sampling.
2) The design of a deep-sea appropriate bistable mechanism inspired by the bistable mechanism of a pen.
3) The presentation of a proof of concept that combines the soft linear actuators and the binary concept into one actuation system.

II. CONCEPT

A. Requirements for the Overall System

The requirements for the actuation system where analysed in collaboration with expert users of the current suction sampling system at the GEOMAR. Most requirements result from the necessity of the system to be combined with the ROV Kiel 6000, but an adjustment of the system to a smaller host ROV is also being considered. The most important requirements that concern the mechanical design are listed below:

- The system should operate at 6000 m depth, so a pressure neutral design would be desirable.
- The system and subsystems must be scalable in their dimensions, layout, and fabrication process. External components (e.g., motors) must be sourced from a scalable line of products. This is in order to adapt the system to various sizes of host vehicles
- The entire system shall be close to neutrally buoyant. Thus, no metal parts should be used in the design.
- Broken segments need to be easily replaceable.
- Instead of a traditional hydraulic system, seawater hydraulics should be considered.
- The final version of the actuation system needs to be as long as the existing tube that is used for sampling, which currently is 2-3 m long.

In addition to the listed requirements, it is desirable that the system is energy efficient, as the power supply via the 6000 m cable is restricted. This issue and additional requirements for the control of the system will be addressed in future work.

B. Binary Manipulator

Considering all the requirements mentioned above, the concept for the active suction sample consists of a binary structure that encloses the sampling tube and thus allows the direct control of the tube without needing an additional manipulator. Using binary actuators decreases the need for sensors within the robotic structure and increases the mechanical robustness of the system [12]. These benefits are accompanied by a downside: The computational power required for the kinematic representation of binary manipulators grows exponentially as the number of actuators rises. The total count of potential configurations for a binary is equivalent to 2^n, where n represents the quantity of manipulators. Consequently, the robot's operational space becomes a collection of discrete points rather than a continuous entity [13]. This reduces the positions that the end-effector can reach compared to a continuous system. However, as the actuation system is only to be used for taking sediment samples, the lack of dexterity is acceptable.

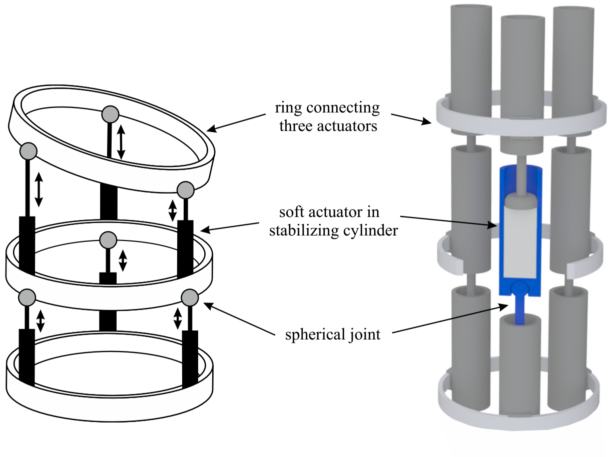


Fig. 3. The concept for the binary actuation system consists of circular stacked modules with three binary actuators each. The actuators within a module are linked by a connecting ring. The connection between the modules is established by spherical joints between the stacked actuators. This design leaves space in the center to place the suction samplers tube.

The proposed concept consists of stacked modules that consist of three binary actuators each. The actuators are arranged in a circle and connected by spherical joints, which allows for eight different configurations of each module. In figure 3 the concept for the binary manipulator is depicted. The stacking of the modules allows the adaption of the systems length to any host system and allows for broken segments to be replaced. To keep the system lightweight and pressure neutral, the materials anticipated for manufacturing the system are mostly resin and silicone.

C. Bistable Mechanism

The first step to develop the binary system is the design of the binary actuators. To ensure reliability but still exploit the advantages of soft robotic actuators, it was decided to combine a linear soft actuator with a rigid bistable mechanism.

The proposed bistable mechanism for the binary system draws inspiration from the well-known mechanism of a retractable pen. Unlike many other bistable mechanisms that depend on flexure bearings [14], the bistable nature of this mechanism is achieved by the circular motion of rigid pins. Originating from Parker, the retractable ballpoint pen's mechanism was patented in 1965 and has showcased its exceptional durability over time [15].

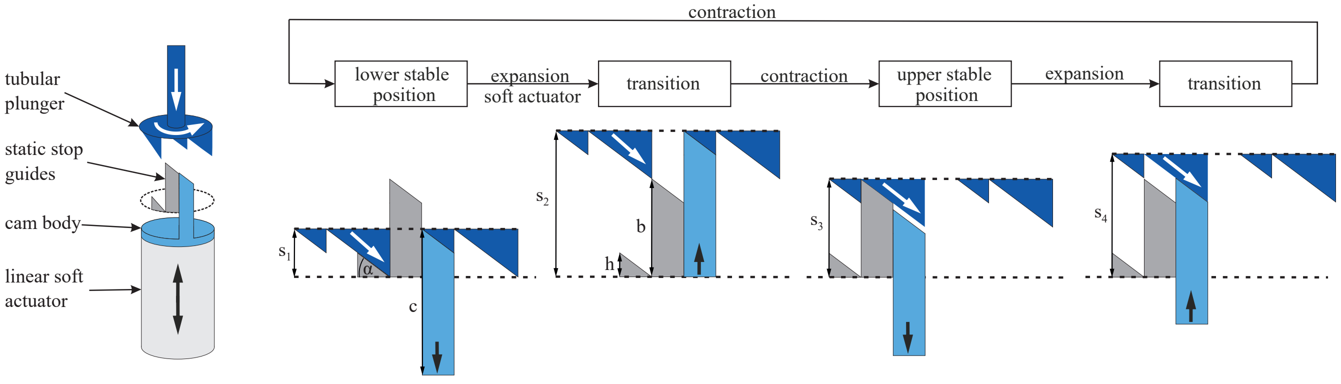
The proposed mechanism consists of three main components, which are illustrated in figure 4: The cam body that translates the motion of the soft actuator into the mechanism and pushes up the tubular plunger, which then rotates into the next stable position which is defined by two static guide pins that are located on the inner wall of the cylinder. The mechanism was adapted in a way so that the maximum elongation of the whole actuator is achieved, while keeping the mechanism as small as possible. Compared to the original application of the mechanism, one could analogize the soft actuator to a finger pushing the button of a pen.

In figure 4 the different stages of the motion of the mechanism is depicted in detail. In the first illustration, the plunger is situated in the lower stable position. To make the transition to the upper stable position, the linear soft actuator is employed to push the plunger upward, causing it to glide along the fixed guide pin. As a result of the plunger being pressed downward by springs or rubber bands, the pins on the plunger initiate a rotational motion. Once the soft actuator is retracted, the plunger continues to rotate until the second stable position is achieved. This cyclically causes the plunger to alternate between the stable positions each time the soft actuator is extended and retracted. When no motion is required, no pressure needs to be exerted on the soft actuator. In the event of a malfunction in the soft actuator, the mechanism will remain in the current stable position, ensuring the overall system's continued functionality.

This design has the advantage that the actuator is able to keep its position even if some part of the hydraulic system fails. On the other hand, this feature comes with the disadvantage that the mechanism cannot exploit the full stroke of the soft actuator because the rotating pins need to be lifted over the stop guide in order to slide into the next stable position. This implies that each actuator extends to its maximum length initially before slightly contracting again to achieve the stable position. When controlled module by module, the positioning error resulting from this behavior is not anticipated to impede the suction sampling task.

D. Design Parameters

The following equations describe the design parameters for the actuator based on the characteristics of the soft actuator that is supposed to be integrated into the bistable mechanism. The height of the fixed guide pins inside the cylinder b results from the minimum (s_{min}) and maximum (s_{max}) length of the soft actuator.



(a) Isometric view

(b) Two dimensional schematic illustration of the different stages of the bistable meachnism

Fig. 4. The bistable mechanism consists of two moving and one fixed part. In (a) the isometric perspective shows a simplified version of these three parts. As the linear soft actuator is expanding and contracting, it turns the tubular plunger from the lower stable position to the upper one. The total elongation depends on the elongation ratio of the soft actuator. The measures of the cam body and the fixed stop pins are adjusted accordingly. In (b) the different phases of motion are described. The sequence starts with the mechanism in the lower stable position. If the soft actuator is elongated, the tubular plunger is lifted over the stop guides and rotates into the second stable position. To switch back to the lower stable position, the soft actuator is again expanded and contracted to rotate the plunger.

$$b = s_{max} - s_{min} \tag{1}$$

In order to determine the value of c, which characterizes the height of the cams that translate the soft actuators motion into the bistable mechanism, it is essential to first define the values of angle α and number p, representing the frequency of pattern repetition along the circumference. These parameters, p and α, enable the computation of the effective elongation e for the mechanism. The subsequent equations highlight the advantage of minimizing parameter h, as it directly influences the extent to which the soft actuator's stroke can be utilized for the elongation of the whole actuator.

$$h = \frac{\pi r}{2p} \tan(\alpha) \tag{2}$$

$$e = b - 2h = s_3 - s_1 \tag{3}$$

$$c = b + 2h = s_2 - s_1 \tag{4}$$

The values of s_1 to s_4 represent the position of the plunger in relation to the static guide pins. They subsequently result from the maximum stroke of the soft actuator. The plunger has to reach the height of s_2 as well as the lowest point of s_1. The illustration of the mechanism's motion sequence shows that the necessary stroke to switch from the upper to the lower position is smaller that the stroke necessary for the opposite motion from the lower position to the higher position.

E. Requirements for the Soft Actuator

This bistable mechanism holds potential for compatibility with a variety of linear soft actuators, functioning as a cost-effective and lightweight counterpart to hydraulic pistons. When considering its application with a seawater hydraulic system, comprehensive material testing is necessary to assess their performance in contact with cold saltwater. Existing literature indicates that silicone-based materials tend to exhibit resilience against the corrosive attributes of saltwater [8].

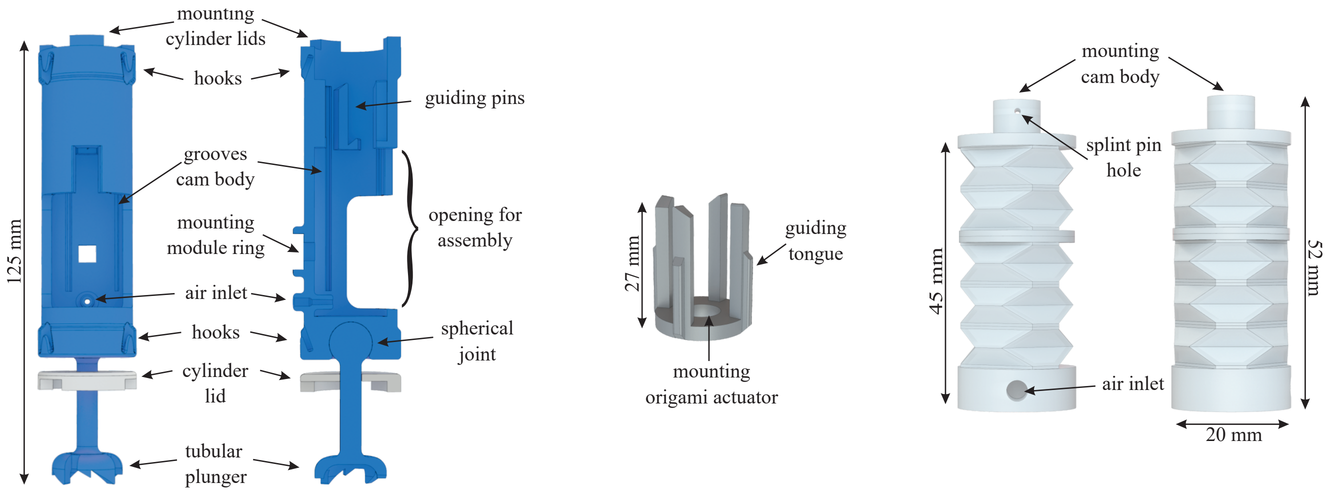
III. PROOF OF CONCEPT

A. Design

To validate the concept, a prototype was developed, integrating an origami soft actuator, wich was presented in previous work [16]. For this first proof of concept, a pneumatic system is used, which is of course not applicable to the deep sea but is sufficient to test the bistable mechanism and the overall concept. The design would, however, stay the same even if actuated hydraulically. As depicted in figure 5 the bistable mechanism consists of two parts, the cylinder (a) and the cam body (b). Both are designed to be manufactured from resin with an ink-jet printer and then assembled. The linear soft actuator (c) is printed with the same method, but instead of resin, a UV-reactive silicone rubber is used.

To maximize the exploitation of the soft actuator's stroke, the pattern that is presented in figure 4 is not only repeated twice, which is customary in retractable pen designs. Instead, it is arranged around the circumference of the cylinder four times. This arrangement reduces the width of the guide pins and thus reduces the high h, which depends on α and the width of the pins, as shown in equation (2). Reducing h, the height of the first static stop guide, results in a greater overall elongation of the actuator in relation to the maximum potential elongation of the soft actuator (see also equation (3) and figure 4). Reducing the height h could also be achieved by increasing the angle α, but this might compromise the reliability of the mechanism, as the guides may not be steep enough to effectively induce the rotation of the plunger.

The upper portion of the cylinder features hooks to connect the stacked cylinders to each other using rubber bands to apply enough pressure on the mechanism, thereby inducing



(a) Main cylinder with tubular

(b) Cam body

(c) Linear origami actuator

Fig. 5. This design resulted from the parameters of the linear origami soft actuator that was integrated into the bistable structure. The rendered images also portray the components into which the mechanism was divided for printing, ensuring a straightforward assembly. Given the intricate design, an inkjet printer was utilized to produce the components with sufficient accuracy.

the intended rotational movements. Positioned within the cylinder is the static segment of the pattern, described in figure 4. Below the bistable mechanism, the chamber for the soft actuator is located. To ensure precise linear motion, the cylinder's inner wall incorporates grooves that serve as guides for the soft actuator's movement. Towards the lower part of the cylinder, the air inlet was positioned. This configuration allows for the soft actuator's placement within the cylinder without gluing the pneumatic tube into the actuator. The slight edge within the cylinder applies pressure to secure the soft actuator against the air inlet. For pneumatic tubing attachment, the back of the cylinder features a threaded area, offering a convenient connection point.

The tubular plunger, which is the rotating part of the bistable mechanism, is attached to the cylinder with a spherical joint. The joint as well as the lid for the cylinder are printed in place to avoid wasting support material and to simplify the assembly. In total, the cylinder has a length of 125 mm, which is quite long in comparison to the effective elongation, but this design is only supposed show the functionality of the mechanism. The optimization of design parameters will be part of future research.

In table I the soft actuator's dimensions are listed together with the resulting dimensions for the bistable mechanism. Due to manufacturing inaccuracies, the calculated dimensions for the construction had to be adjusted slightly to enhance the mechanisms robustness against this lack of precision. The adjusted measurements are enclosed within brackets following the originally calculated values.

B. Manufacturing

The whole prototype was manufactured with 3D printers: For the more intricate parts, the Keyence agilista was used. This printer utilizes resin inkjet technology to achieve high levels of accuracy but has the disadvantage that the printing resin is very costly in comparison to other 3D printing materials, and a high amount of support material is needed. The rigid parts were manufactured using the material Acryl AR-M2 and the soft actuators are made from Silicon AR-G1H (both materials were purchased from KerCon GmbH & Co.KG). For other parts that require less precision, a Prusa MKS3+ and thus Fused Deposition Modeling (FDM) was used for manufacturing.

TABLE I
DIMENSIONS PROTOTYPE

Dimensions soft actuator		
Radius	r	10mm
Length contracted	s_{min}	25mm
Length elongated	s_{max}	45mm
Resulting dimensions bistable mechanism		
Height static stop guides	b	20mm (18mm)
Height cam body	c	24.6mm (23mm)
Effective elongation	e	15.4mm (13mm)

To assemble the actuator, the cam body is placed inside the cylinder so it can move up and down following the guide grooves. Next, the soft actuator is placed inside the cylinder. Using a splint, the top of the actuator is mounted to the cam body. It is important to pay attention to the fact that there can not be any friction between the rigid cylinder and the origami folds, as this leads to the origami's rupturing quickly. To ensure an airtight connection, the origami was glued into the cylinder using silicon glue. Because the glue can easily be removed, this still allows the origami to be replaced in case of malfunctioning. Stacking the modules involves positioning the plunger of the upper cylinder into the mechanism of the cylinder below it. The lid of the cylinder guides the plunger's movement to be strictly linear. After the cylinders are attached to the module rings, the rubber-bands that push the plunger into the bistable mechanism from above are added. As is depicted in figure 6 the first prototype to prove the presented concept consists of six actuators arranged into two modules. This allows bending in six directions for each module.

C. Testing

For testing the assembled prototype, a pneumatic system was used. It consists of variable pressure valves, with an operational pressure range spanning from -100 kPa to 100 kPa, controlled by signals ranging from -10V to 10V. The valves are connected to a CompactDAQ chassis, equipped with analog input/output modules. The CompactDAQ system is controlled using a MatLab/Simulink interface.

Figure 7 depicts the air pressure that is applied on the linear soft actuator for changing the state of the bistable mechanism. To obtain this data, the pressure was simply increased or decreased (depending on the current phase) until the pressure allowed the piston to turn into the next position. This procedure was carried out with the six actuators that were manufactured. It is noticeable that the required pressure changes depending on the stable state the piston currently is in. To control the mechanism, it would be sufficient to only switch between the maximum values. But with this approach there is no possibility to determine which position the piston is at. If the previously identified pressure values are used, the mechanism will go back into the desired position after one cycle motion is completed even if one change of positions did not work. This sequence also acts as a reset sequence in case it is not clear in what stage the individual actuators are in.

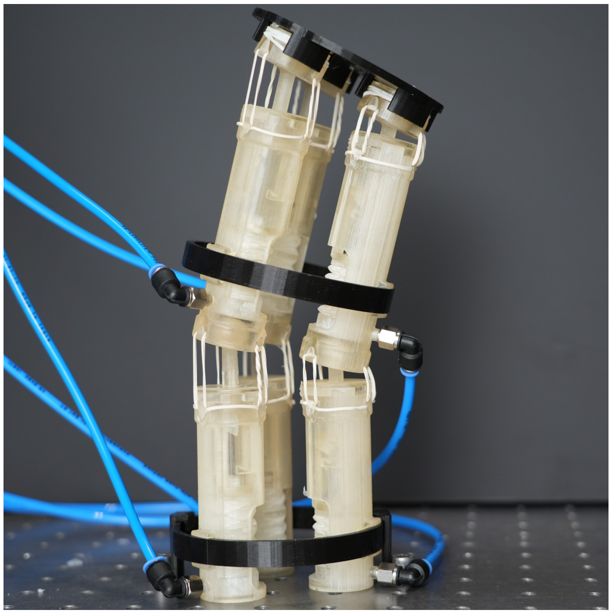


Fig. 6. The prototype consists of two modules with three binary actuators each. By controlling each soft actuators within the bistable mechanism individually, $2^6 = 64$ different configurations can be achieved. This successful prototype underscores the viability of the concept for binary actuation systems.

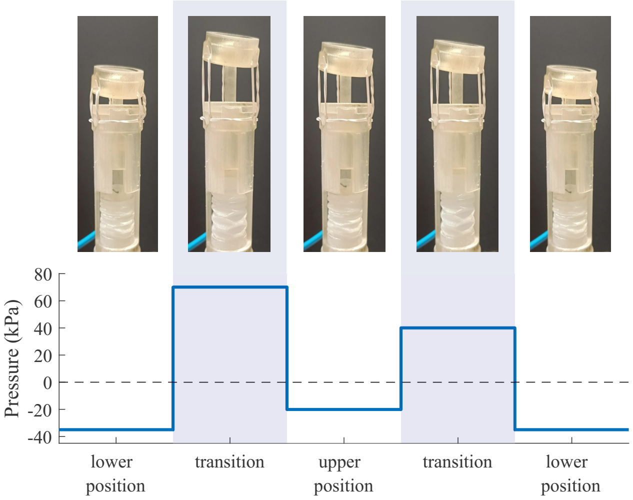


Fig. 7. This plot describes the different pressures that are necessary to transition the bistable mechanism from one stable position to the next one. If the whole sequence is applied to the actuators, it acts as a reset sequence. In case the current position of the actuator cannot be identified, the sequence resets state of the actuator.

Overall, the demonstrator showed that the concept for the bistable mechanism is very reliable. It is expected that the payload is going to vary a lot with the underwater currents, and as the force of the actuator is restricted to the soft actuator's force, there might be instances in which movement is not possible. In these situations the structure is expected to keep its original position. To go back into the operational mode, a reset sequence can be applied.

IV. CONCLUSION AND FUTURE WORK

In this paper we introduced a concept for a lightweight, modular, and low cost actuation system of a deep-sea suction sampler. Furthermore, we presented a bistable mechanism, adaptable to various soft actuators. A prototype was produced to assess the viability of this bistable mechanism and the overall concept, demonstrating its robustness. The next steps to developing a complete deep-sea actuation systems include a parameter optimization for the bistable mechanism. Additionally, different linear soft actuators will be tested, because despite the successful integration of the origami actuators, their manufacturing cost remains a challenge. Furthermore a hydraulic actuation system needs to be implemented, which allows the system to be tested underwater. When the desired scale of the system is achieved, different control algorithms for binary robots will be tested as the brute force approach would exceed the available computation power.

In summary, this paper establishes a proof of concept for an innovative actuation approach in deep-sea suction sampling by combining linear soft actuators with a robust bistable mechanism and thus, offering the potential to reduce costs and enhance accessibility to deep-sea sediment sampling.

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