

# A Nitinol-embedded Wearable Soft Robotic Gripper for Deep-sea Manipulation

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**Abstract**— Soft robotic gripper systems that can safely and nondestructively collect biological and artifact samples and perform deep-sea manipulation tasks are essential for deep-sea science and engineering applications. In this paper, we implemented a soft robotic gripper composed of nitinol-embedded soft fingers and an in-situ wearable mechanism that allows the soft gripper to be put on and removed from the traditional rigid gripper according to the deep-sea tasks. We apply finite element simulation to investigate the influence of nitinol wires' diameter on the soft finger and then examine the strength and grasping ability. The results indicate the soft gripper's maximum horizontal and vertical pulling forces can reach 75.5N and 135.7N, respectively. We show that the gripper can perform nondestructive sampling tasks, including picking and placing fragile porcelain and operating a precision instrument at a depth range of 1410m to 3600m by a human-crewed deep-sea submersible (Deep Sea Warrior). The results from this study may provide new design insights into the creation of next-generation deep-sea intelligent robotic systems that can perform dexterous manipulation.

## I. INTRODUCTION

Until now, eighty percent of the deep-sea territory remains uncharted, presenting formidable challenges to human and technological exploration due to the extreme conditions of low temperature and high pressure. For example, the deep sea constitutes abundant biotic and mineral resources, as well as wrecks and archaeological sites [1][2].

To explore and study deep-sea ecosystems and perform engineering missions, engineers commonly install rigid mechanical arms and grippers on the foredeck of human-crewed or unmanned deep-sea submersibles [3]-[5]. These robotic arms and grippers are made of anticorrosive metal materials for the extreme deep-sea environment. The tissues of deep-sea organisms are primarily composed of low modulus materials such as water and collagen proteins. The traditional rigid gripper may cause damage to biological samples during the grasping process.

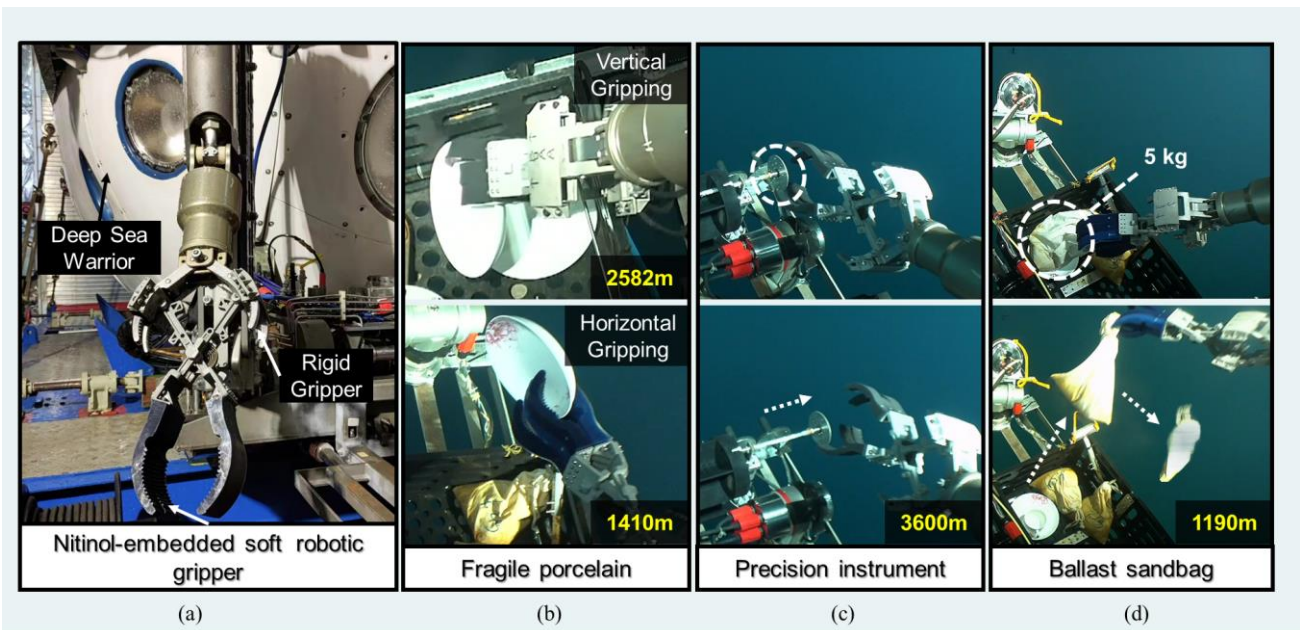
The advantage of soft grippers compared with rigid ones lies in their ability to establish gentle contact with the captured target [6][7]. Although traditional pneumatics are not suitable [8][9], predecessors have employed soft actuators based on various principles, including dielectric elastomeric actuator-based [10] and hydraulic actuator based [11] soft grippers to explore the deep sea. In particular, various soft robotic techniques such as the soft jamming gripper [12], the hydraulic Boa-type gripper, the hydraulic Bellows-type gripper [12][13], and the Rotary Actuated Dodecahedron (RAD) gripper [15] have been implemented to explore the deep sea. These innovative soft gripper designs and actuating methods have proven effective in handling and sampling these marine organisms without causing damage to them.

Despite demonstrating inspiring flexibility and non-invasive sampling capabilities in the deep-sea environment, soft robotic grippers often have low stiffness and strength due to the nature of their soft materials. Deepsea engineers working on the front line argue that soft grippers made of

pure soft materials are too "weak" and are quite limited in force production, load capacity, and operational ability in real deep-sea environments. For example, operators usually require the onboard robotic grippers to operate crucial, heavy tasks, such as digging the sampling tube into the soil and taking samples or discarding ballast sandbags to enable the submersibles to ascent the surfaces. For specialized deep-sea operations, such as archaeological exploration, large forces are required to pull out the heavy and fragile ceramic artifacts buried in the seabed mud. However, these tasks cannot be done using state-of-the-art soft robotic grippers and require soft robotic grippers that simultaneously provide substantial output force and soft contact.

On the other hand, various operations, such as gentle and delicate collection, high-force digging, and careful handling, are required in a single deep-sea dive mission [16]. These operations were too challenging for the soft grippers to execute alone, and the deep-sea vehicle operators hoped to switch between the soft gripper and rigid gripper as needed. Previously, the soft grippers must be fixed on rigid mechanical arms before the submersible enters the ocean. This raised another issue with the soft gripper besides the strength problem. If soft grippers are designed as wearable and can be switched in situ in the deep sea, the operator can choose the soft gripper that matches the task according to requirements. Therefore, we consider a switchable soft gripper which notably improves operational capacities during deep-sea exploration.

In this paper, we propose a novel design of a deep-sea soft gripper incorporating nitinol wires with a low austenite-finish temperature into the silicone (Figure 1a). Our soft robotic gripper consists of fingers with nitinol embedment and a wearable mechanism. The superelasticity of the nitinol wires with a low austenite-finish temperature provides sufficient strength to grasp and manipulate various objects while maintaining the adaptability and flexibility of the gripper. The performance of the soft robotic gripper has been successfully demonstrated. Employing the Deepsea Warrior submersible, we showed that the soft robotic gripper has successfully achieved the grasping of fragile porcelain objects such as plates and cups at a depth of at least 2582m in the South China Sea. It can perform vertical and horizontal grasping techniques to hold the porcelain items (Figure 1b) securely. We also showed that operations, such as deep-sea precision instruments, including pushing, pulling, and manipulating rods, can be successfully carried out at a depth of 2817m in the deep sea. The soft gripper has demonstrated its capability to handle and manipulate the intricate components of deep-sea instruments (Figure 1c). Finally, at a depth of 1190m in the deep sea, the soft robotic gripper successfully achieved the release of a 5kg ballast sandbag from the manned deep-sea submersible, contributing to the buoyancy adjustment of the submersible (Figure 1d).



**Fig. 1. The nitinol-embedded soft robotic gripper capable of assisting manned deep-sea submersibles in performing deep-sea operations.** (a) The nitinol-embedded soft robotic gripper is installed on the rigid gripper of the Deep Sea Warrior manned deep-sea submersible. (b) Operate fragile porcelain at a depth of 2582m and 1410m in the deep sea. (c) Operate a deep-sea precision instrument at a depth of 3600m in the deep sea. (d) Discard a 5kg ballast sandbag at a depth of 1190m in the deep sea. The demonstration of the experiments is available in the supplementary video.

This paper presents the design, simulation, and fabrication of the nitinol-embedded soft gripper (II), a series of laboratory experiments (III), a series of in-situ deep-sea experiments (IV), and discussions (V). Conclusions on the findings are conducted in Section (VI).

## II. DESIGN, SIMULATION AND FABRICATION

To complete the design of the nitinol-embedded soft robotic gripper efficiently, a modular design approach was employed, involving an in-situ wearable mechanism module and a deep-sea soft gripper module.

The specific design requirements for the in-situ wearable mechanism module are as follows:

- 1) The connection points should ensure shape consistency with the surface of the rigid gripper on the manned deep-sea submersible.
- 2) During use, the overall structure should not detach due to excessive loading.
- 3) Easy for the operators to operate.

On the other hand, the specific design requirements for the deep-sea soft gripper are as follows:

- 1) Ensure safe grasping of fragile objects.
- 2) Provide sufficiently large underwater gripping force to grasp heavy objects.
- 3) The materials or structures used should be able to withstand the extreme environment of low temperature and high pressure in the deep sea.

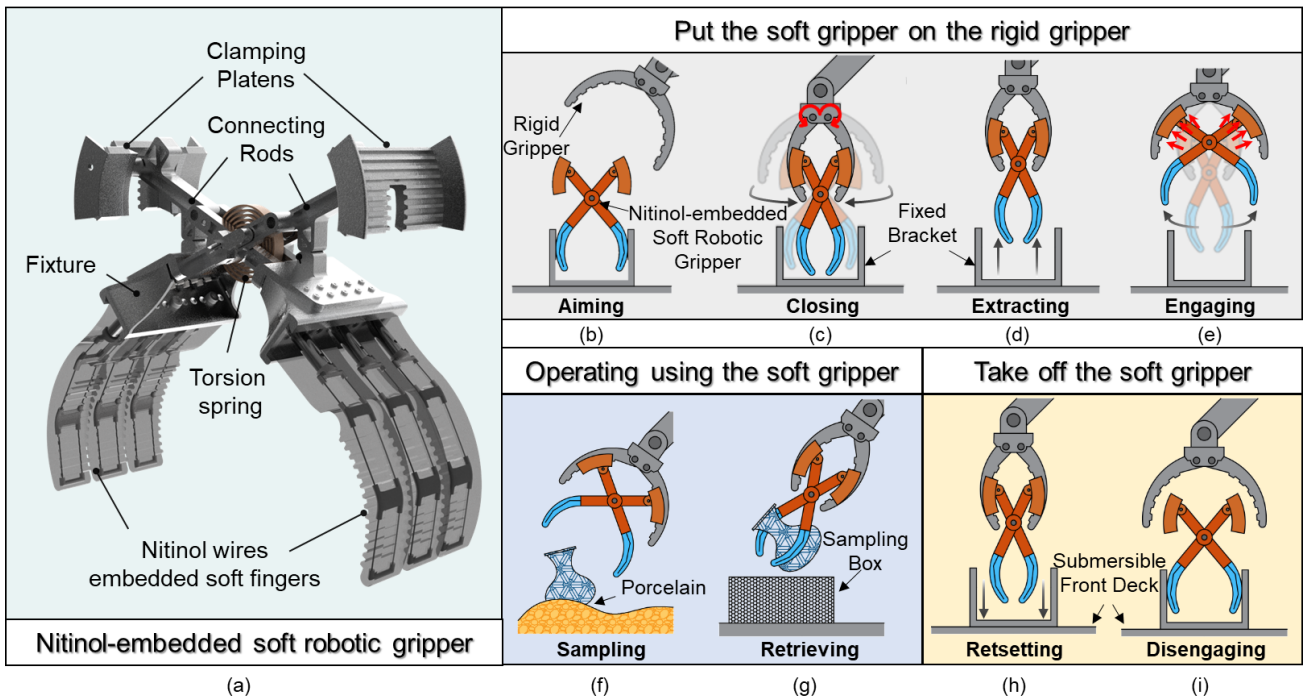
### A. The nitinol-embedded soft robotic gripper and in-situ wearable mechanism design

Following the design requirements mentioned above, the nitinol-embedded soft robotic gripper is composed of two parts: the in-situ wearable mechanism that can help the rigid gripper connect in situ and the nitinol wires embedded soft fingers that can safely collect heavy cultural relics (Figure 2a). The in-situ wearable mechanism is composed of two connecting rods, two clamping platens, a torsion spring, and their fasteners. They are respectively utilized for motion transmission from the rigid gripper to the soft gripper, as well as establishing a fixed connection between the rigid

gripper and the in-situ wearable mechanism. This arrangement enables the in-situ wearability of the nitinol-embedded soft robotic gripper without detachment in the deep-sea. The deep-sea soft gripper module is composed of six nitinol wires embedded in soft fingers with a low austenite-finish temperature. This design not only enables adaptive and non-destructive grasping but also enhances the grasp success rate.

We show the process of the manned deep-sea submersible mounting a nitinol-embedded soft robotic gripper on its rigid gripper (Figure 2b-e). The soft robotic gripper is placed inside a fixed bracket on the front deck of the Deep Sea Warrior manned deep-sea submersible before the submersible dives. When a safe gripping task is required, the operator of the manned deep-sea submersible operates the rigid mechanical gripper to align with the nitinol-embedded soft robotic gripper. The rigid gripper is operated to close, pulling the nitinol-embedded soft robotic gripper out of the fixed bracket by engaging with the clamping platens of its in-situ wearable mechanism. The torsion spring on the in-situ wearable mechanism provides a certain counterforce, ensuring that the grooves on the clamping platens tightly engage with the teeth of the rigid gripper, preventing loose coupling or the nitinol-embedded soft robotic gripper detachment.

Then, we show the process of the nitinol-embedded soft robotic gripper cooperating with manned deep-sea submersible to perform safe sampling tasks (Figure 2f-g). During the sampling process, the closure motion of the nitinol-embedded soft robotic gripper is achieved through the coordination of the connecting rods and the torsion spring. The superelasticity and flexibility of the nitinol-embedded soft finger allow it to adapt to the shape of objects, enabling the gripping of fragile items without damaging their surface texture information.



**Fig. 2. The composition and operating principles of the nitinol-embedded soft robotic gripper.** (a) The nitinol-embedded soft robotic gripper is composed of six nitinol-embedded soft fingers and an in-situ wearable mechanism. (b)-(e) Mounting the nitinol-embedded soft robotic gripper on the rigid gripper. (f)-(g) Sampling and retrieving the porcelain via the nitinol-embedded soft robotic gripper. (h)-(i) Disengaging the nitinol-embedded soft robotic gripper from the rigid gripper.

Finally, we show the process of the submersible taking off the nitinol-embedded soft robotic gripper (Figure 2h-i). After the completion of a sampling task, the rigid gripper closes and places the nitinol-embedded soft robotic gripper back into the fixed bracket. Due to the constraint of the fixed bracket, the rigid mechanical gripper can disengage from the clamping platens, allowing the nitinol-embedded soft robotic gripper to be inserted back into its original position.

This new method allows the human operator to put on or take off the soft gripper from the rigid gripper in the deep sea at will, enhancing the manipulation capabilities of manned deep-sea submersibles during a single underwater mission. It also enables the safe lifting of fragile objects with notable weight without damaging the surface texture in the deep sea.

### B. Fabrication of the nitinol-embedded soft robotic gripper

The fabrication of a nitinol-embedded soft robotic gripper can be divided into two parts: the assembly of the in-situ wearable mechanism and the integrated manufacturing and assembly of the nitinol wires embedded soft fingers.

The assembly process of the in-situ wearable mechanism is illustrated in Figure 3a. Firstly, the connecting rod A and the connecting rod B are placed crosswise. Then, a 3mm diameter cylindrical shaft is inserted into the hole reserved in the connecting rod B to secure the end of the torsion spring. Next, the torsion spring is placed into the gap between the connecting rods A and B. The torsion spring pin is inserted successively into the connecting rod A, connecting rod B, and the torsion spring. Finally, the torsion spring is tightened clockwise to provide a certain opposite force to the connecting rods and subsequently secured with the fastener. The two clamping platens, A and B, that engage with the rigid mechanical gripper are connected to the connecting rods A and B, respectively, through a 4mm diameter cylindrical shaft. The connecting rod A and B,

clamping platen A and B, torsion spring pin, and fastener mentioned above are all made of stainless steel through 3D printing.

We show the manufacturing process of the nitinol wires embedded in soft finger (Figure 3b-d). Due to the difficulty of traditional welding connection between the nitinol wires and stainless steel, a mechanical bending method has been adopted in this step. Two 15mm long nitinol wires are bent using two pre-set angled connectors. They are then tightened with several M3 bolts and locking nuts (Figure 3b). The nitinol skeleton that has been mechanically bent and shaped is placed into the mold, and fixed with an M6 bolt at the end (Figure 3c). The release agent is sprayed on the mold's interior surface. The Elastosil-m4641 liquid silicone rubber is properly mixed at a ratio of 10:1, vacuumed and poured into the gap between the nitinol skeleton and the mold (Figure 3d). After 24 hours of curing time, the nitinol-embedded soft finger is removed from the mold (Figure 3e).

Six nitinol-embedded soft fingers are manufactured in the same way, and connected to the in-situ wearable mechanism using M6 bolts to create a nitinol-embedded soft robotic gripper. All the mentioned connecting components are made of stainless steel through 3D printing.

### C. Principle composition and finite element simulation of the nitinol-embedded soft finger

Attempts have made to use rigid grippers on deep-sea submersibles to grasp fragile porcelain, but ensuring safety during the gripping process has proven difficult. There are two main reasons:

- 1) Traditional rigid grippers are typically designed with a focus on stability and robustness. The existing rigid grippers on the Deep Sea Warrior manned submersible do not have integrated sensors, thus they cannot provide real-time feedback on the gripping force. Therefore, submersible operators can only control the opening and closing of the mechanical grippers based on visual observation. However, for grasping fragile

objects, they are too rigid and inflexible so that excessive pressure or friction is easily generated during the gripping process, provoking scratches, abrasion, or even damage to the porcelain surface and corresponding value loss.

- 2) Rigid grippers have difficulty achieving uniform distribution of contact forces when gripping hard objects. In particular, the gripping of fragile porcelain can be approximated as a point contact, resulting in extremely high local pressure on the porcelain surface, often leading to breakage at that point.

Using soft grippers made of silicone material can improve the safety of gripping from these two aspects. Firstly, there is an upper limit to the contact force between the soft fingers and the object. During the closing process

driven by the rigid gripper, the soft fingers deform upon contact with the artifact, and the contact force initially increases and then tends to remain constant. By choosing the appropriate material, we can preset this upper limit of contact force to enhance safety. Secondly, flexible materials undergo compression deformation at the contact point, which can be considered as surface contact. The contact area expands with increasing pressure, leading to dramatically lower contact pressure compared to point contact.

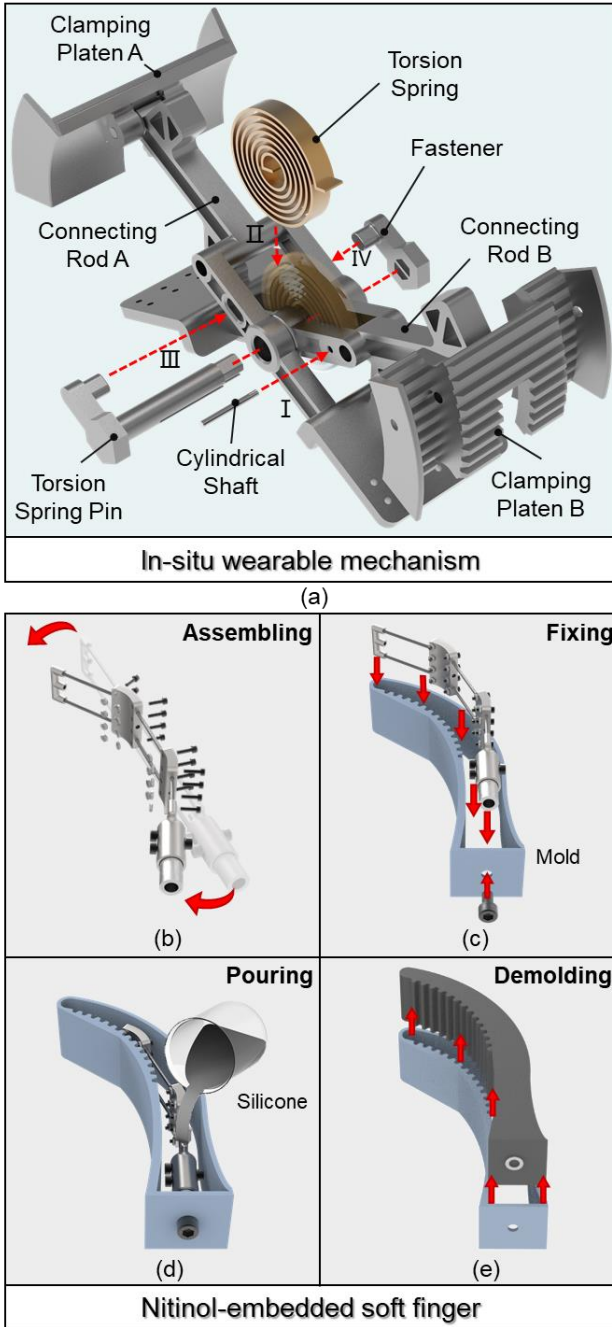
However, using only silicone material in the gripper makes it difficult to achieve a large output force. Researchers often use some smart materials as enhancements for soft materials to improve the overall performance of soft grippers [17]. In our research, a material with superelasticity is needed as an internal skeletal support to enhance its ability to grasp heavy objects. Nitinol wire exhibits this superelasticity when the environmental temperature is higher than  $A_f$  (austenite-finish-temperature) [18]. At this stage, the nitinol wire is in the austenite. Applying a load to the nitinol wire induces a martensite transformation, transforming it into non-twinned martensite. When the load is released, a martensite reverse transformation occurs, meaning that the nitinol wire can return to its original shape without external stimulation and plastic deformation (Figure 4a).

Since the water temperature in the deep sea is between 0-4°C, in order to effectively exert the superelastic properties of the nitinol wire, we use the nitinol wires with an  $A_f = -15^\circ\text{C}$ . In order to increase the overall stiffness of the soft gripper and prevent lateral torsion, the skeleton is formed by bending two 15mm long nitinol wires (nickel-titanium: 55%-45%) through two positioning connectors, shaped into the form of a traditional rigid gripper (Figure 4b). This design also aligns with the operational habits of submersible operators. The length, number, and diameter of the nitinol wire, as well as the elastic modulus and hardness of the silicone material, can be customized according to the specific weight capacity requirements of the task at will.

We first investigated numerically, via FE (Finite Element) simulations, the properties of nitinol-embedded soft fingers, focusing on the effect of the nitinol wire diameter on the contact force in two directions when extracting a bowl-shaped object. Specifically, all of our soft robotic fingers have the same external shape but five different diameter parameters for the internal nitinol wires, ranging from 0 to 4mm. We have made certain simplifications to the FE model. We simplified the internal nitinol wires of the soft robotic finger to a nitinol sheet model and used the shell model provided by ABAQUS (ABAQUS/Standard, SIMULIA, France) for its modeling. Due to the primary form of deformation in the soft robotic finger being bent, we first consider the equivalent bending capabilities of the nitinol wires and nitinol sheet. When constructing the model, we ensure that the bending section modulus of both the wires and sheet are equal. This can be represented by the equation:

$$N \times \frac{\pi \times d^4}{64} = \frac{b^3 \times h}{12} \quad (1.1)$$

where  $N$  represents the number of the nitinol wires,  $d$  represents the diameter of the nitinol wire,  $b$  represents the thickness of the nitinol sheet, and  $h$  represents the width of the nitinol sheet. The left side of the equation represents the bending section modulus of the nitinol wires, and the right side represents the bending section modulus of the nitinol sheet. By setting these equal, we achieve an equivalent



**Fig. 3. The fabrication process of the nitinol-embedded soft robotic gripper.** In-situ wearable mechanism: (a) The assembly process of the rigid connecting components. Nitinol-embedded soft finger: (b) Nitinol wires are assembled into finger shape. (c) The finger-shaped nitinol wires are fixed in the mold. (d) Silicone is poured into the mold. (e) The nitinol-embedded soft finger is demolded.

bending capability between these two models.

In our simulation model, we used a bowl-shaped model with a diameter of 120mm to simulate our target. Since the bowl-shaped model has a stiffness much higher than that of silicone, its deformation is much smaller compared with that of silicone. Therefore, we treated the target object as a rigid body and ignored its deformation. For the silicone material of the nitinol-embedded soft robotic finger, we employed a third-order Yeoh model. As for the nitinol material, we used a linear model. Frictional surface contact (with a coefficient of friction of 0.5) was implemented between the soft robotic finger and the target object. Using ABAQUS/Standard, a dynamic nonlinear simulation was performed. In this simulation, the base section of the soft robotic finger, embedded with a nitinol sheet, was fixed, and the target object was moved from 0 to 100mm to simulate its detachment from the fingertip. As the bowl-

shape object compressed the soft robotic finger along the axial direction, it induced bending. We recorded the axial and horizontal contact forces experienced by the target object during this process.

We first validated our numerical simulations by comparing the numerical results with the experimental results of soft robotic fingers embedded with nitinol wires ( $N=2$ ,  $d=2\text{mm}$ ;  $N=2$ ,  $d=1\text{mm}$ ) wrapped in Elastosil-m4641 silicone rubber (Figure 4c-f). Since we found an excellent agreement between two sets of data during the bowl-shaped target object extraction, we subsequently conducted a more extensive exploration of the diameter of the nitinol wires using FE simulation. We began the numerical study to investigate the influence of the diameter of the nitinol wires on the axial and horizontal forces during the extraction of a bowl-shaped object. It can be observed that the forces in both directions during the extraction process depended highly on the diameter of the nitinol wires (Figure 4g-h). Specifically, the force  $F$  increased as the diameter of the nitinol wires  $d$  increased. For instance, the forces multiplied by over threefold by increasing the diameter of the nitinol wires from  $d=3\text{mm}$  to  $d=4\text{mm}$ .

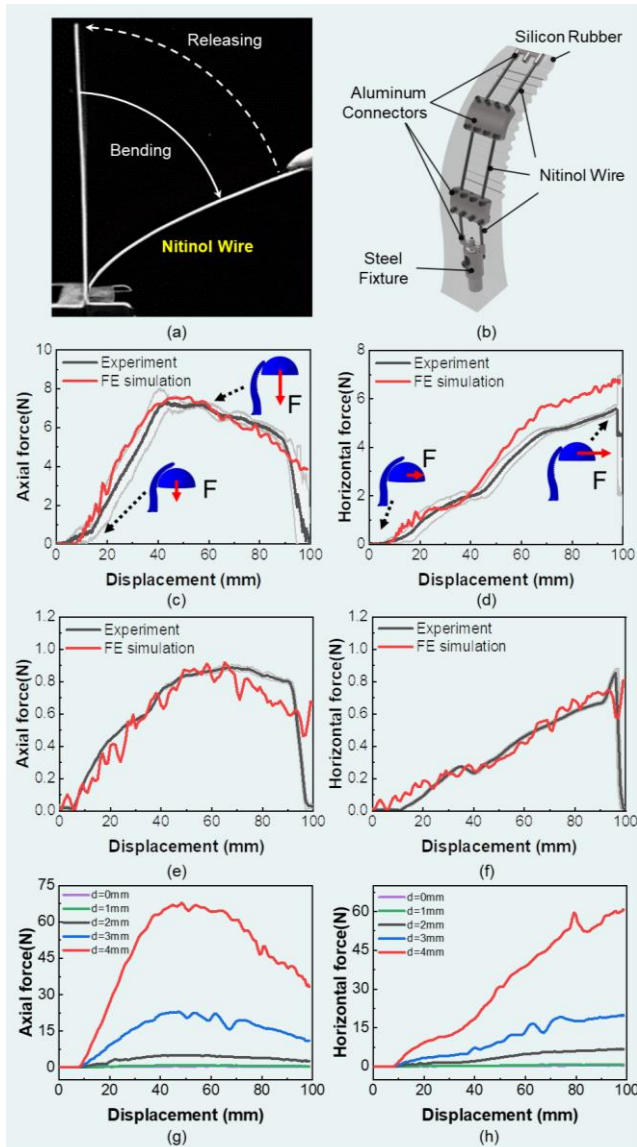
### III. LABORATORY EXPERIMENTS

It is crucial to choose different grasping strategies for the nitinol-embedded soft robotic gripper when grasping fragile porcelain according to the shape and size of the object. For jars with a large curvature, three fingers on the same side can be inserted inside to lift the object. For objects with a small curvature, such as bowls and plates, a gripping method can be used. Here, we characterized the mechanical performance of three different stiffness nitinol-embedded soft grippers for both gripping strategies, including a soft gripper without nitinol wires embedment, a soft gripper embedded with two 1.5mm diameter nitinol alloy wires, and a soft gripper embedded with two 2.2mm diameter nitinol alloy wires. At last, we conducted a gripping demonstration in the laboratory environment. All tests were repeated at least 5 times.

#### A. Single-finger force test

For lifting large curvature jars, we designed a single-finger force test to investigate the relationship between the normal contact and the displacement of the fingertip for three different stiffness fingers. The experimental setup was constructed (Figure 5a), where the soft fingers were laterally fixed on the experimental platform using a fixture. A linear motor and an ATI (Mini 40, ATI Industrial Automation, USA) force sensor were connected, with the force sensor contacting the soft fingers through an extended rod. The height of the linear motor was adjusted to ensure that the rod made normal contact with the fingers. Images of the finger deformation were captured from the top.

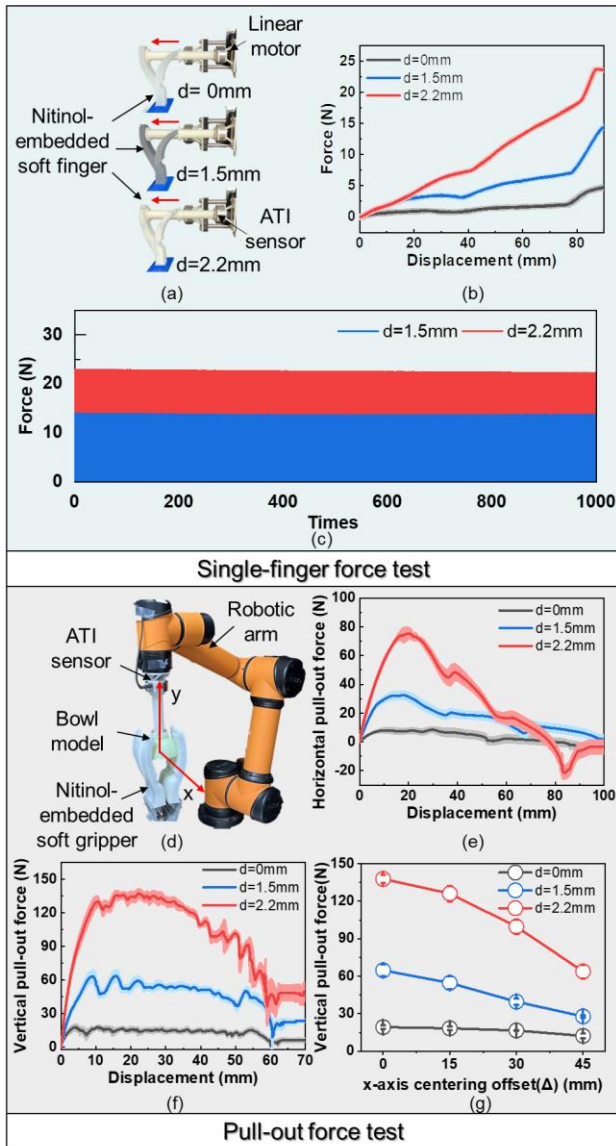
It can be seen from the experiment that the nitinol wires embedded in the soft finger still retains the advantage of the large deformation capacity of the soft material while improving the stiffness. The relationship between the normal contact force of the soft finger and the fingertip displacement is shown in Figure 5b. Based on the experimental results, it can be observed that the normal contact of the nitinol-embedded soft finger is positively correlated with the displacement of the fingertip and the diameter of the embedded nitinol wires. Among them, the normal contact of the finger without nitinol embedment, the finger embedded with two 1.5mm nitinol wires, and the finger embedded with two 2.2mm nitinol wires within a



**Fig. 4. The structure and simulation of the nitinol-embedded soft finger.** (a) The superelasticity of nitinol. (b) A schematic of the components of the nitinol-embedded soft finger. (c)-(d) Comparison of axial force and horizontal force between finite element simulation and experimental results of soft finger embedded with 2mm nitinol wires when pulling out the bowl model. (e)-(f) Comparison of axial force and horizontal force between finite element simulation and experimental results of soft finger embedded with 1mm nitinol wires when pulling out the bowl model. (g)-(h) Numerical results illustrating the axial and horizontal forces as a function of the diameter of nitinol wires when pulling out a bowl-shaped model.

90mm fingertip displacement are 4.8N, 14.5N, and 23.7N, respectively. By using soft robotic fingers embedded with nitinol wires of 1.5mm and 2.2mm, the normal contact is increased by 302% and 494%, respectively, compared to the fingers without embedment. If we install these three fingers side by side on the in-situ wearable mechanism, the maximum load capacity can be lifted up to 7 kilograms, which is more than enough to lift a heavy jar.

We also conducted a life test for the nitinol-embedded soft finger. The results in Figure 5c show that after 1000 fingertip contact tests with a 90mm displacement, the contact force of the fingers embedded with 2.2mm diameter nitinol wires decreased by less than 3%. The fingers embedded with 1.5mm diameter nitinol wires showed a contact force decrease of less than 2.5%. This meets the needs in actual deep-sea applications.



**Fig. 5. Laboratory test of nitinol-embedded soft finger and gripper.** (a) The setup of the single-finger force test with a soft finger embedded with nitinol wires of three diameters. (b) The variation of the normal contact while the fingertip displacement changes. (c) The variation of the contact force of the nitinol-embedded soft finger in life test. (d) The setup of the pull-out force test. (e) The variation of the horizontal pull-out force with the object displacement changing. (f) The variation of the vertical pull-out force with the object displacement changing. (g) The variation of the vertical pull-out force with the change of the x-axis centering offset ( $\Delta$ ).

## B. Pull-out force test

For gripping small curvature objects such as bowls, we designed pull-out force tests to investigate the vertical and horizontal pull-out forces of the soft robotic gripper embedded with nitinol wires of three different diameters. These two tests respectively correspond to the scene where the target object escapes from the horizontal and vertical directions in the actual grasping in the deep sea.

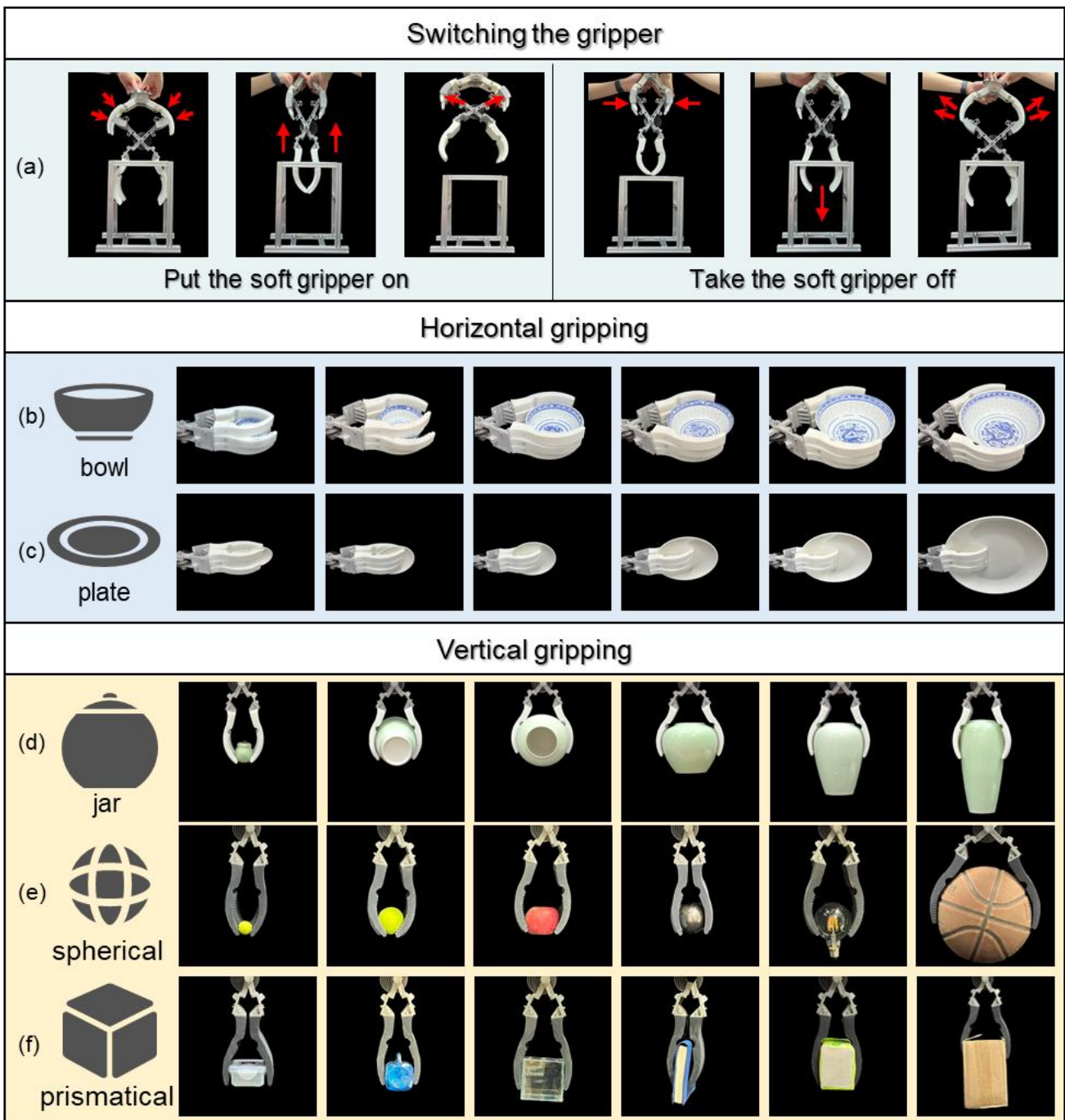
The experimental setup was constructed as shown in Figure 5d, where the soft robotic gripper was completely closed and vertically secured on the fixture. The ATI sensor was connected to the robotic arm to pull the 10cm bowl model out of the nitinol-embedded soft robotic gripper. The model bowl was placed in the center of the nitinol-embedded soft robotic gripper by adjusting the terminal position and orientation of the robotic arm. Then, we separately controlled the robotic arm to pull out the model bowl along the x-axis (horizontal direction) and y-axis (vertical direction), and recorded the force sensor data.

The variation of the nitinol-embedded soft robotic gripper's horizontal pull-out force of a 10cm bowl is shown in Figure 5e. It requires a force of 32.5N and 75.5N at least, respectively, to horizontally pull out the target from the soft robotic gripper embedded with 1.5mm and 2.2mm nitinol wires. The horizontal pull-out force has increased by 382% and 888% respectively, compared with the soft gripper without nitinol embedment. The variation of the nitinol-embedded soft robotic gripper's vertical pull-out force of a 10cm bowl model is shown in Figure 5f. Due to the anti-slip design of the soft fingertips, there will be fluctuations in the pull-out force. Compared with the horizontal pull-out forces, the vertical pull-out forces have been increased, which is attributed to the shape and the install direction of the internal nitinol wires. It can be observed that it requires a force of 63.4N and 135.7N at least, respectively, to vertically pull out the target from the soft robotic gripper embedded with 1.5mm and 2.2mm nitinol wires. The vertical pull-out force has increased by 391% and 840% compared with the soft gripper without nitinol embedment respectively.

In practical deep-sea operations, it is challenging to ensure that the target is positioned exactly at the center of the nitinol-embedded soft robotic gripper. Therefore, we have also explored the relationship between the vertical pull-out force and the target's offset ( $\Delta$ ) relative to the center of the soft robotic gripper. The test was conducted with an offset ( $\Delta$ ) gradient of 15mm as shown in Figure 5g. When the offset exceeds 45mm, the soft robotic gripper has only half of a finger in contact with the bowl model, which can be considered as unable to securely hold. The experimental results indicate that under conditions when  $\Delta = 45$ mm, it requires a force of 27.8N and 63.8N at least, respectively, to vertically pull out the bowl model from the soft robotic gripper embedded with 1.5mm and 2.2mm nitinol wires. As the offset ( $\Delta$ ) increases, the vertical pull-out force of the soft gripper on the bowl model gradually decreases. However, even with this decrease, it is still sufficient to grip small curvature objects in deep-sea environments.

## C. Grasping demonstration

Before the deep-sea in-situ test, the nitinol-embedded soft robotic gripper was demonstrated in the laboratory, including switching the soft robotic gripper on the rigid grippers and gripping in different strategies, in order to better manifest the expected performance of the soft gripper and its reliability in actual use.

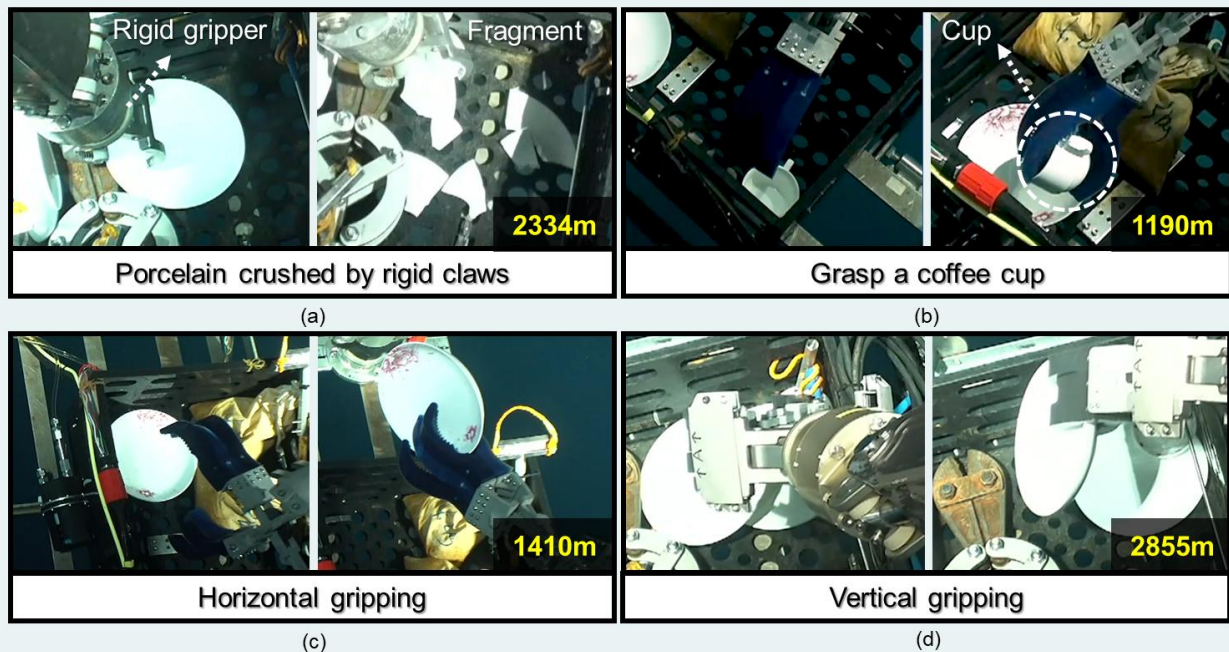


**Fig. 6. Laboratory demonstration of nitinol-embedded soft robotic grippers.** (a) Switching the nitinol-embedded soft robotic gripper on the rigid grippers. (b)-(c) Nitinol-embedded soft robotic gripper demonstrates horizontal gripping of porcelain bowls and plates of 6 different sizes. (d)-(f) Nitinol-embedded soft robotic gripper demonstrates vertical gripping of porcelain jars, spherical targets and prismatical targets of 6 different sizes.

We demonstrate the switching test of the nitinol-embedded soft robotic gripper conducted in the laboratory (Figure 6a). A rigid gripper, produced from a photosensitive resin in a 1:1 ratio, was used to put on the nitinol-embedded soft robotic gripper from a framework constructed with aluminum square tubes. The torque provided by the torsion spring easily secured the clamping platens of the soft robotic gripper onto the rigid gripper. The nitinol-embedded soft robotic gripper did not detach when opening and closing. Finally, when returned to the fixed framework, the rigid gripper could be easily released.

The static adaptive grasping capability of the nitinol-embedded soft robotic gripper was tested by grasping fragile porcelains with a wide range of shapes and weights. When using a nitinol-embedded soft robotic gripper, the primary goal is to be able to grab porcelains with different

shapes, sizes and weights regardless of their exact position, enabling the use in deep seabed environments. The gripper was tested in a horizontal position because it presents a lower pull-out force, making it more challenging to securely grasp objects. The tested objects included porcelain items of two different shapes, bowl-like and plate-like, with varying sizes and weights ranging from 73.5 to 2100 grams (Figure 6b-c). Also, the gripper was tested for a wide range of objects in a vertical position (Figure 6d-f). The heaviest and largest porcelain held by the gripper in these tests is a 40mm plate which was able to be grasped both in the vertical and horizontal position. Both of the two gripping strategies are capable of successfully grasping ceramic objects of any shape which indicates the reliability and versatility of the nitinol-embedded soft robotic gripper.



**Fig. 7. Deep-sea demonstration of a nitinol-enhanced soft robotic gripper gripping fragile porcelain.** (a) Porcelain broke when gripped by rigid gripper (b) Nitinol-embedded soft robotic gripper grasping a coffee cup at a depth of 1190m. (c)-(d) Nitinol-embedded soft robotic gripper demonstrating horizontal gripping and vertical gripping at depths of 1410m and 2855m respectively.

#### IV. IN SITU DEEP-SEA EXPERIMENTS

After undergoing testing in the laboratory, our nitinol-embedded soft robotic gripper was subjected to numerous tests during the expedition organized by the Institute of Deep Sea Science and Engineering, Chinese Academy of Sciences. During three deep-sea dive trials, the nitinol-embedded soft robotic gripper was used to grasp different types and sizes of fragile porcelain objects. It was also used to manipulate precision instruments and heavy objects. The demonstration of the experiments is available in the supplementary video.

##### A. Fragile porcelain grasping

Figure 7 illustrates the nitinol-embedded soft robotic gripper being worn by the Deep Sea Warrior manned deep-sea submersible and undergoing in-situ grasping tests of fragile porcelain in the deep sea. Before testing the nitinol-embedded soft robotic gripper, the rigid gripper was used to try to grasp the porcelain plate at a depth of 2334m. Due to the rigid gripper's hard surface, stress concentration occurred on the surface of the porcelain plate, resulting in its breakage (Figure 7a). Indeed, this serves as a clear demonstration of the limitations of using a rigid gripper for the collection of precious artifacts and emphasizes the necessity of utilizing the nitinol-embedded soft robotic gripper.

Then, we successfully grasped a coffee cup with an external diameter of about 7cm at a depth of 1190m (Figure 7b). It can be observed from the figure that the nitinol-embedded soft robotic gripper is fully closed, firmly gripping the coffee cup by leveraging the superelasticity of the nitinol wires and the adaptive deformation of the silicone rubber material. To validate the stability of the soft robotic gripper in the horizontal and vertical grasping of the target object under extreme deep-sea conditions, tests were conducted on a 25cm diameter porcelain plate at a depth of 1410m and 2855m respectively (Figure 7c-d). Indeed, the results demonstrate that the nitinol-embedded soft robotic

gripper can effectively and safely grasp the porcelain plate from different orientations. Also, even after vigorous shaking, the ceramic plate remains securely gripped by the nitinol-embedded soft robotic gripper without any slippage.

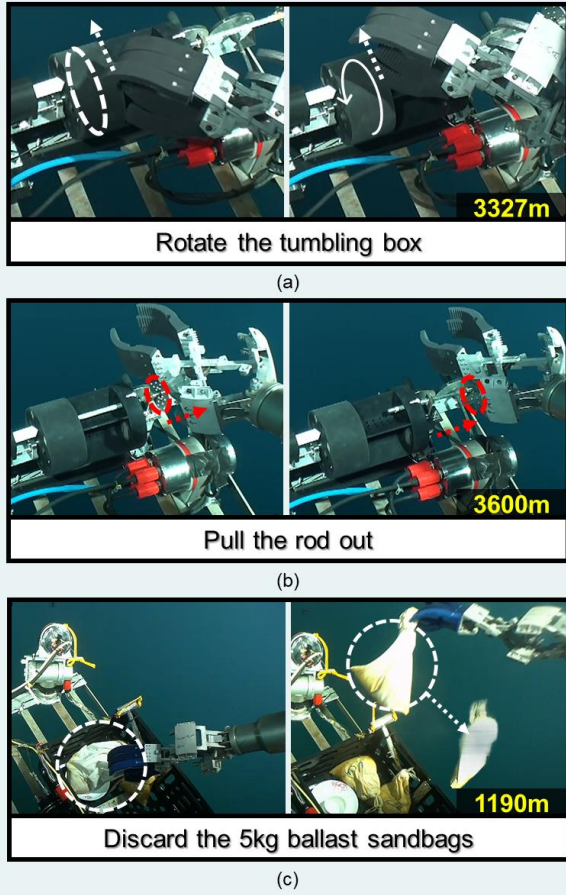
In summary, the nitinol-embedded soft robotic gripper provides a safer, more stable, and reliable solution for grasping fragile porcelain due to its outstanding adaptability, softness, and high output force capabilities.

##### B. Precision instruments and ballast sandbags operation

Additional operations of the nitinol-embedded soft robotic gripper in assisting the manned deep-sea submersible in exploring the deep sea are shown in Figure 8.

Due to the complex shapes and fragile structures of specialized precision instruments in the deep sea, using rigid mechanical grippers to manipulate them often leads to vibrations and impacts that can affect the performance and accuracy of the instruments, and even cause damage to their internal structures. However, using the nitinol-embedded soft robotic gripper to manipulate precision instruments can effectively compensate for these shortcomings. By conducting operations such as rotating the tumbling box of a precision instrument around its pivot axis (Figure 8a) and repeatedly pulling and pushing a metal rod (Figure 8b) at a depth of 3327m and 3600m, respectively, we have demonstrated the capability of the soft robotic gripper to perform complex tasks without compromising the precision of the instrument. Finally, we have also demonstrated the gripping ability of the nitinol-embedded soft robotic gripper when it comes to handling large and heavy objects. We successfully operated the soft robotic gripper at a depth of 1190 m to release several 5kg ballast sandbags from the front deck of the Deep Sea Warrior manned deep-sea submersible (Figure 8c). The release of the ballast bags reduced the overall weight of the submersible, boosting its ascent speed. In effect, this reveals that the nitinol-embedded soft robotic gripper is effective not only in deep-sea specialized operations but also in performing general tasks. Its

versatility and practicality have shown significant improvements compared to traditional soft grippers.



**Fig. 8. Deep-sea demonstration of a nitinol-enhanced soft robotic gripper operating precision instruments and heavy objects.** (a)-(b) Nitinol-embedded soft robotic gripper operating a precision instrument at a depth of 3327m and 3600m. (c) Nitinol-embedded soft robotic gripper discarding a 5kg ballast sandbags at a depth of 1190m.

## V. DISCUSSION

Our study investigates the performance of nitinol-embedded soft robotic grippers in realistic deep-sea environments. In this section, we discuss the experimental results of deep-sea manipulation and compare it with the Wyss Boa, Wyss Bellow, Universal jamming gripper, Wyss Bellow v2, and JPL-Nautilus deep-sea soft robotic grippers that have been reported and tested with diving depths exceeding 100m.

It can be seen from Table 1 that in the past, hydraulic actuation was generally used for driving deep-sea soft robotic grippers, which often leads to challenges such as seal leakage prevention and deep-sea pressure compensation. In contrast, our nitinol-embedded soft robotic gripper utilizes the superelasticity of the nitinol wires, enabling passive deformation for adaptive grasping of target objects. It is almost unaffected by deep-sea pressure, resulting in higher robustness compared to other aforementioned grippers. Evidently, our soft robotic gripper possesses the deepest tested depth (>3600 m), and presents a tremendously larger output force as well. Therefore, our gripper is particularly suitable for grasping heavy deep-sea porcelain artifacts, making it highly practical.

Although there are important discoveries revealed by research, several limitations still exist. Firstly, unlike the aforementioned grippers that can control the hydraulic flow

to precisely regulate the opening and closing of the soft fingers, our gripper's opening and closing range is controlled by rigid grippers connected to the Deep Sea Warrior manned deep-sea submersible. Due to the limitations in the operational precision of these rigid grippers, we cannot achieve extremely precise control over the opening and closing extent of the nitinol-embedded soft robotic grippers. Nevertheless, the passive deformation capability of the nitinol wires compensates for this

Gripper	Technology	Depth	Force	Application
Wyss Boa	Soft	170m	40N	Biocollection
Wyss Bellow	Soft	170m	15N	Biocollection
Universal Jamming gripper	Mixed	1200m	34N	General operation
Wyss Bellow v2	Soft	2440m	96N	Biocollection
JPL-Nautilus	Rigid	2000m	-	Geological collection
<b>Nitinol-embedded soft gripper</b>	<b>Mixed</b>	<b>&gt;3600m</b>	<b>136N</b>	<b>Archaeological sampling, Precision instrument operation, Discard sandbags for buoyancy control</b>

deficiency.

**Table 1. Comparison of the nitinol-embedded soft gripper with reported deep-sea soft grippers.**

Secondly, the previous hydraulic-driven deep-sea soft robotic grippers could infer the pull-out force at the soft finger through suction flow, thereby determining whether the target object was securely grasped. This allowed the operator in the submersible to have more intuitive control over the opening and closing extent based on the numerical feedback from sensors, thus ensuring the protection of the target object [19]. And that is also one direction we are currently striving for: embedding tactile and bending sensors within the nitinol-embedded soft fingers to achieve closed-loop control of the entire gripper.

## VI. CONCLUSION

This paper describes a soft robotic gripper embedded with the superelasticity of nitinol and successfully performed real-world underwater mission experiments in the deep sea. We quantitatively examined the grasping performance of the soft robotic gripper in all directions in a laboratory setting. We found that the gripping performance can be notably enhanced by adding nitinol wires (with an appropriate diameter) in the soft finger. The soft robotic gripper can safely grasp the fragile porcelain in the deep sea and perform operations on precision instruments. Meanwhile, the soft robotic gripper could discard heavy ballast sandbags for buoyancy regulation. The soft robotic gripper can also be worn and removed in situ by the human-crewed deep submersible, notably improving the efficiency of engineering operations. In the future, we aim to develop a soft robotic gripper with sensing capabilities and enable human operator-robot interaction in the deep sea.

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