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DESIGN OF A SOFT UNDERWATER GRIPPER WITH SMA ACTUATION

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ABSTRACT

Underwater robot tasks pose many challenges for conventional robotic systems. The current rigid robots are limited in their adaptability to the environment and the objects to be manipulated. Soft grasping of objects offers advantages due to the flexibility when dealing with, for example, living organisms, random shaped objects, and coral reefs. Additionally, conventional robotic systems face difficulties when exploring the planet's deep waters due to higher pressures and susceptibility of the often large amount of electronics to underwater conditions. Smart materials such as shape memory alloys can be more advantageous for the actuation of soft robotic underwater grippers because there is less need for complex electronic systems. Therefore, this project explores the use of smart materials for the actuation of a soft robotic underwater gripper. With this aim, three different gripper designs were made and evaluated. Various flexible materials, smart materials, 3D printing settings, numerous gripper configurations, and manufacturing methods are investigated. The gripper is intended to be a maintenance and inspection add-on for an underwater autonomous vehicle.

Keywords: Soft robotics, smart materials, shape memory alloys, compliant mechanisms, 3D printing

1 INTRODUCTION

Soft robotics is a growing paradigm of robotics that focuses on the design of flexible and adaptable robots so that their bodies can generate motions such as bending [1], elongation [2], and torsion [3] for actuation [4]. Soft robots use hyper elastic materials like polymer, rubber, and silicone for their primary body and moving parts [5]. This is in contrast to the traditional rigid materials used in conventional robotic systems, such as steel and aluminium. The differences in materials used and manufacturing methods also result in differences in protection and stability strategies. Soft robots do not require sophisticated protection or stability control algorithms, in contrast to conventional robots, because the materials used have shock-absorbing properties. Therefore, rigid robots are made to function in controlled environments, doing specific tasks, whereas soft robots are made to work in unstructured areas [6, 7]. Moreover, conventional rigid robotic systems make use of rigid hinges and connections that limit the robot's degrees of freedom. This leads to less adaptability to complex and changing surroundings. Soft robotics, on the other hand, make use of flexible hinges and connections to provide a broader range of motion and adaptability. When working with fragile objects or objects of random shape, these soft connections offer greater compliance. This simplifies tasks such as grasping and improves the manipulation of delicate objects [5]. The control architectures and strategies are also different for soft robotics. Rigid robotic systems usually follow their pre-programmed motion patterns. This has proven to be effective in static environments, such as in automated manufacturing processes. The rigidity of conventional systems supports these reoccurring motion patterns. In dynamic environments, however, like deep sea research and the interaction with randomly shaped or fragile objects, the interest in soft robotics is growing [7]. Furthermore, conventional robotic control strategies are based on mathematical models that require complex computational power to predict system behaviour and adapt the orientation of the gripper to the object to be grasped. Soft robotic systems can be more advantageous in these examples too, due to their increased adaptability and flexibility. Pick and place operations can be executed without precise positioning or accurate geometric models of the objects to be grasped [5, 8]. The need for complex control systems is compromised due to their adaptability. Due to their softness, they can grasp objects oriented in any direction without potentially damaging them. Soft grippers would need less complex computation power compared to a rigid robotic gripper that has to change its orientation based on sensors, cameras or other predictive control strategies. Rigid robotic systems often have limited degrees of freedom (DoF), whereas soft bodies have an infinite number of DoF due to their extra abilities in bending, contraction, extraction, and torsion. On the contrary, soft materials can show nonlinear material properties, making modeling and model-based techniques difficult [9]. This paper explores the possibilities for overcoming this characteristic by utilizing well controlled actuation and compliant mechanisms. In recent years, soft robotics has made significant progress. It started with pneumatic actuators and has evolved to include different kinds of sensors, smart materials, and control systems. These developments were used in several types of micro-robots [10] and reconfigurable robots [7, 11, 12].

The aim of this research is to contribute to the field of soft robotics by means of the development and testing of a soft robotic, compliant underwater gripper actuated by shape memory alloys (SMAs). This includes research on the characteristics and applications of different configurations and dimensions of SMAs. The development, fabrication, and testing of different 3D printed soft robotic gripper designs, based on the principles of compliant mechanisms is also part of this work. In this research, the advantages of using SMAs for actuation and soft materials over conventional rigid actuation methods and materials in underwater applications by means of flexibility and adaptability are investigated. This work functions as a feasibility study for SMA-actuated soft robotic gripping solutions in underwater environments. The results and conclusions drawn from this research can serve as a basis for future developments in underwater soft robotics, which have the potential to greatly improve the manipulation of objects and delicate organisms at sea. Moreover, as the underwater infrastructure becomes more and more dense, interaction with underwater objects of random shape is extremely beneficial for the offshore wind industry. The advantages of using SMAs in underwater gripping are related to their high flexibility, which allows for efficient adaptation to random shaped objects in complex underwater environments. Moreover, SMAs do not need complex electronic systems to operate in underwater applications. Their compactness allows them to be embedded in the structure or components of the underwater gripper. This allows for more compact and lightweight underwater grippers that facilitate maneuverability and minimize drag. The findings of this study can further be used to guide future research into the combination of smart materials with compliant mechanisms in underwater robotic systems.

First, the requirements for the gripper were specified. The soft robotic principles and smart materials followed from a thorough literature study. Different fabrication methods and settings have been tested on different soft robotic grippers designed with CAD software and 3D printers. Subsequently, the available smart materials in various dimensions and configurations were tested and programmed. The best smart material configuration was selected from this test. The smart material was then prepared for use in underwater conditions. The effects of these additions on the performance have been analyzed. All soft gripper designs have been evaluated based on the damage caused to objects and their manipulation dexterity. The final design was further tested on the actuation time to deform to the programmed shape, reliability and durability.

2 SMA INTEGRATION IN SOFT GRIPPING MECHANISM

SMAs possess properties in line with the principles of soft robotics and allow for adaptability in actuation. Soft gripping mechanisms can benefit from these properties. This section focuses on how SMA integration aligns with the soft robotic principles discussed in the introduction, for gripping mechanisms.

2.1 Actuation

Soft robots are designed to operate differently from conventional rigid robots. The main differences are in the actuation mechanisms, because of the use of flexible materials that can bend and deform to generate movements. They feature continuum deformation of the flexible body, resulting in high degrees of freedom (DOFs) [5, 13]. The actuation mechanisms need to be compatible with these added degrees of freedom. Furthermore, the mechanism should be able to withstand the pressure and flow in underwater environments. This is crucial for the gripping motion that enables the manipulation of objects.

SMAs are thermally responsive actuators operated by heat upon reaching their transition temperature. This can be achieved by direct joule heating, indirect heating using ultraviolet waves, or conductive heat transfer by putting them in a medium like hot water. By doing so, the molecular constitution of the material changes, reducing their elastic modulus or resulting in a deformation. SMAs allow for bidirectional deformation, which means that the molecules can move in two opposite directions [4]. As a result of the alloys' conductivity, thermal activation is achieved by direct joule heating without the use of an external heater. The most commonly used SMAs are nickel titanium alloys [14], also called nitinol. Their properties rely on their dynamic crystalline structure. The molecular structure is temperature- and stress-sensitive. SMAs have three distinct temperature phases: martensite, austenite, and annealing [15]. SMAs are in martensite phase when their temperatures are below the phase transition temperature, which varies depending on the exact composition of the alloy. In this state, they can deform due to external forces. Once heated above the transition temperature, the SMA enters the austenite phase. The deformations done in the earlier state will be eliminated and the material will turn back into the pre-programmed original shape [4]. In order to program a new memory shape, the temperature of the material should enter the annealing or high temperature phase. In this phase, the crystalline structure reorients to remember its present shape. For most compositions of nitinol, this phase is above 500 °C [15]. SMAs can be used in the form of tendons, coils, or sheets, depending on the desired actuation mechanism.

SMA actuation is advantageous in soft and compliant gripping mechanisms because it provides controllable and reversible shape changes. They can undergo large deformations and recover their original shape when the right stimulus is applied. The flexible structures of soft grippers allow for effective force and pressure distribution. SMAs can be integrated in the structure of soft grippers, due to their relative compactness and shapes. This integration allows the gripper to selectively change shape and enhances grasping capabilities. This property can be used for the grasping of objects of various shapes. The sensitivity of SMAs to temperature, in combination with the actuation times, can be used to adjust the gripping strength to conform to objects of different geometries and textures. This increases the manipulation dexterity of the gripping mechanism. SMA actuation in soft gripping mechanisms allow for controllable response and high reliability, providing efficient manipulation of objects. SMA actuation in combination with soft robotic principles is advantageous for underwater grippers that can adapt to changing surroundings, handle a variety of objects, and assure secure and delicate gripping.

3 INTEGRATION IN UNDERWATER ENVIRONMENT

This section elaborates on how soft robotics principles and smart materials were translated into an underwater gripper design. The soft underwater gripper needed to comply with a set of design requirements. The gripper needed to be able to grasp objects underwater, such as tools and debris. It should facilitate sampling and collection of underwater sediment or coral reefs; help in the deployment of scientific instruments; and be capable of object retrieval, such as retrieving lost items underwater. The gripper's performance was measured based on weight that can be held, damage caused to the object, adaptability to different object shapes and control accuracy, manipulation dexterity, resistance to corrosion, water resistance, and its reliability and durability.

In order to optimize the functionality and performance of the gripper, various design choices and options were organized in a morphological scheme. This was done in order to to break down this complex design problem into smaller components, because

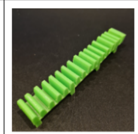
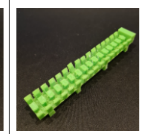
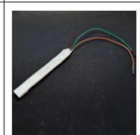
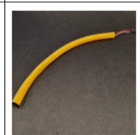
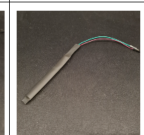
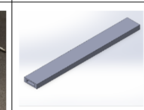
Function	Option 1	Option 2	Option 3	Option 4
Actuation	Pneumatic	SMA	SMP	DEA
Geometry				
Material	Silicone	3D printer filament	Foam	Soft mesh fabric
Manufacturing method	Molding	3D printing	Foam shaping	Suing
Power supply	Pressure pump	Conductive heat transfer	Power supply	Battery
Control system	Pressure valves	Power electronics control systems	Current limiter	Temperature controllers
Waterproofing	 Silicone	 Silicone tubing	 Heat-shrink	 3D printed case

FIGURE 1. Morphological scheme

of the large number of factors to be taken into account for optimization of the gripper's performance and functionality. The morphological scheme can be found in Fig. 1.

Based on a survey of previous underwater soft robotic grippers in the literature, the actuation method and manufacturing method for the soft robotic gripper were selected. SMAs were discovered to be the least used actuation technology in underwater soft robotics, making them a promising choice for this research to fill that gap as a contribution to the field. 3D printing was selected as the manufacturing method, because of its capability and flexibility to create complex geometries. These properties were considered vital for the creation of a soft robotic gripper for underwater applications. Like explained earlier, SMAs can be made to reach their activation temperatures via direct joule heating due to the alloy's conductivity without the need for other external heat sources. This was going to be achieved by using a power supply.

Three soft robotic finger geometries were designed using CAD software. These geometries can be found in Fig. 2. The geometries were designed and 3D printed to be hollow to increase their softness and manipulation dexterity, as shown on the left in Fig. 2. A soft TPU filament was chosen because of its distinct advantages over other filament types: being highly flexible, having high impact resistance, and high tensile strength for increased durability during grasping tasks. Furthermore, if printed using the correct settings, this filament also exhibits good layer adhesion, resulting in strong prints. These properties are ideal for printing soft and compliant fingers that adapt to objects with resilience. The complicated shape and the hollow geometries made 3D printing challenging, with the soft TPU. Various 3D printing settings were tested and evaluated for optimal use in the manufacturing process of soft robotic fingers. To determine their effect

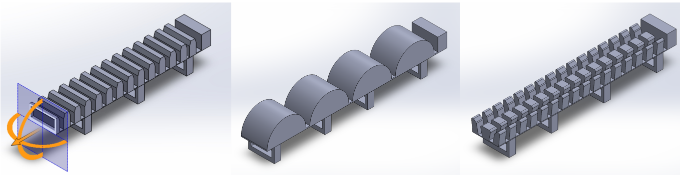


FIGURE 2. CAD designs of all three geometries. The first design (left) highlights a cut-through view, revealing the hollowness feature common to all three designs.

on the printed geometries, several combinations of layer height, print speed, infill density, and nozzle temperature were investigated. The layer heights and the flow rate affected the smoothness of the surfaces. Printing at lower layer heights affected the time it took for the print to finish significantly. The print speed and travel speeds were set to 20 mm/s for better print quality. The filament decomposition was more precise and the layer adhesion was improved. Print speeds below 20 mm/s resulted in oozing and overextrusion. This caused excess material to squish into a new area and negatively affected the print quality. The infill density affected the structural integrity of the fingers by a small margin, because the geometries were hollow, so the walls only consisted of 4 to 5 lines. The nozzle temperature affected the adhesion between the layers too. Higher temperatures caused stringing or oozing issues. Lower temperatures caused problems with layer adhesion. An optimum was found at 235 °C.

The SMA wires were chosen to be mounted below the fingers to offer additional protection against potential damage using slots. These slots offer advantages such as easy installation and replacement of the SMA wires as needed. This enhances flexibility in adapting the gripper's behaviour to fit for purpose.

These three compliant mechanisms consisted of flexible bodies that deformed in a desired way in response to the mechanical forces applied by the SMA. The links in between the different sections of the fingers are established by varying the material geometry in the areas where different stiffness is required, making them into a compliant joint, according to [16]. These joints allow for at least one relative motion between the links that is limited to a localized area. The joints are monolithic with the rest of the 3D printed geometry, hence their advantages over classical rotational joints: no friction losses, applicable in small-scale applications, no need for lubrication or maintenance, no hysteresis, and ease of fabrication [16]. These compliant links are marked red in Fig. 3, which shows the bending motion allowed by these compliant links. In order to prevent any contact between the nitinol wires and water, two waterproofing methods were tested. In the first method, the nitinol wires were encapsulated with a silicone material. A 3D printed PLA mold was treated with a release agent before placing the nitinol wires inside and filling it with silicone. The mechanical and chemical properties of three different silicones were compared to the properties of the flexible TPU. The silicone material needed to have a lower shore hardness, a greater elongation at break and be at least as water-resistant as the TPU material in order for it not to be a bottleneck in the performance of the soft robotic gripper. This was done because the primary function of the silicone was to make the SMA watertight, without affecting the performance of the 3D printed compliant finger. The encapsulated SMA can be seen in Fig. 7. Another method for waterproofing was to insert the SMA in a rubber tube (see Fig. 1). This tubing method was easier in terms of manufacturing and could therefore provide a better alternative for waterproofing as opposed to silicone encapsulation. Furthermore, the aim was to understand the difference in behaviour of the SMA in a constrained environment packed inside silicone versus a non-constrained environment in a hollow tube.

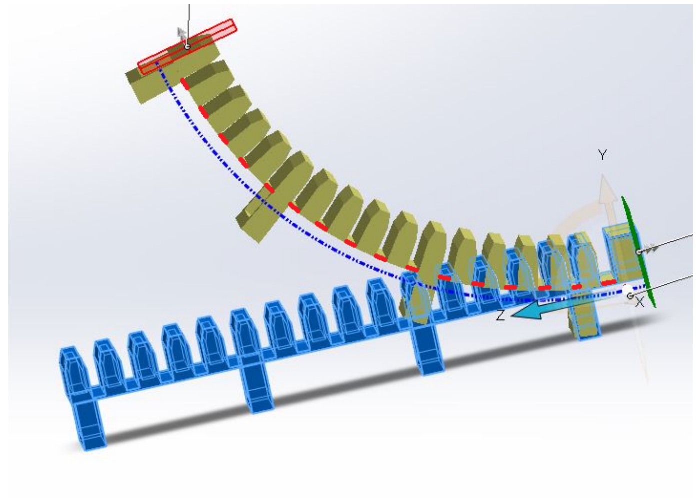


FIGURE 3. Bending allowed by compliant joints (marked red)

4 RESULTS AND DISCUSSION

In this section, the evaluation of the design choices is presented by means of material performances, actuation times, lifting capacities, and integrated designs. Subsequently, the final soft robotic underwater grippers grasping capabilities are illustrated.

4.1 Material testing

The 3D printed TPU material performed well in terms of durability to withstand the forces exerted by the actuated nitinol wires. After being submerged in water with a salt level of 3,5% for more than 1000 hours, no signs of wear or damage to the TPU material, nor to its bending performance were discovered.

The test setup from 4 was used to test the actuation time of the SMA wires, each having a length of 21 cm. The actuation

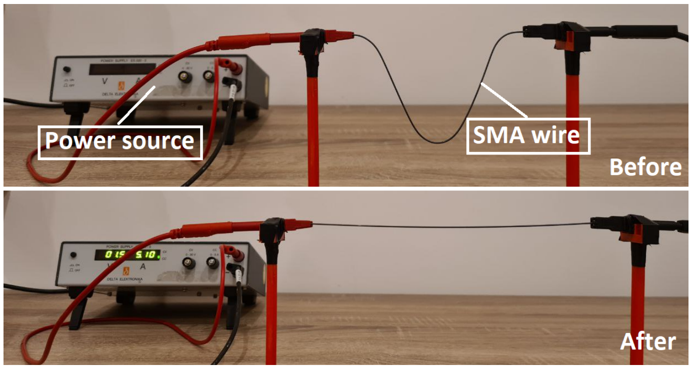


FIGURE 4. Test setup of a nitinol wire subjected to no load

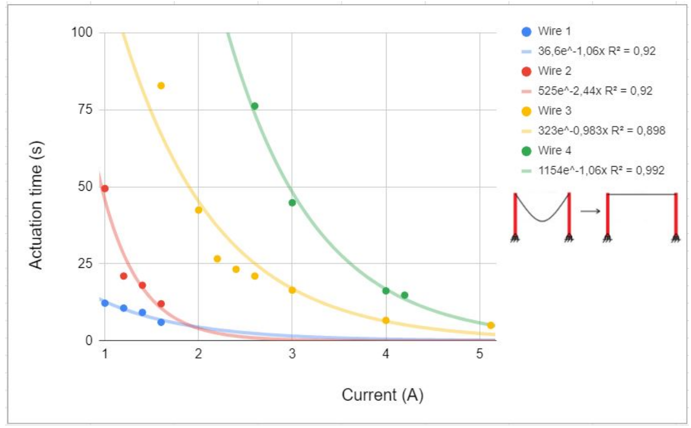


FIGURE 5. Results of the no load tests with all four wires

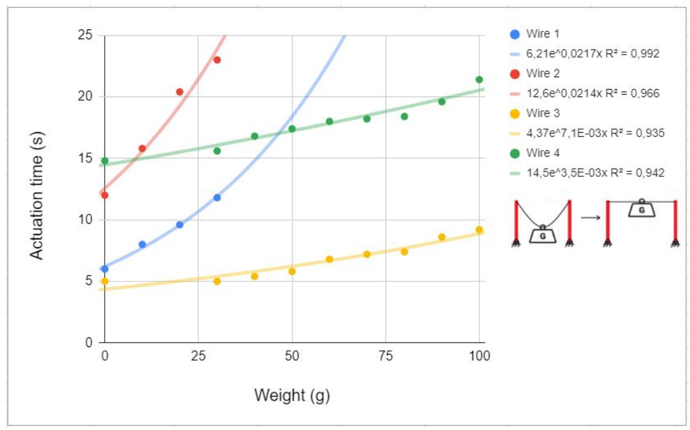


FIGURE 6. Results of the load tests with all four wires

time here refers to the duration for the nitinol wires to deform and reach the programmed shape after the electrical current is applied. For these tests, four different SMAs were used. The properties of each wire, including its diameter d and activation temperature T_{act} are listed below. The objective was to assess the performance of four different nitinol wires based on their activation temperature, diameter, and reaction times under varying loads.

- Wire 1: d=0.5 mm (0,0196 in), T_{act} = 40°C (104°F)
- Wire 2: d=0.5 mm (0,0196 in), T_{act} = 60°C (140°F)
- Wire 3: d=1.0 mm (0.0393 in), T_{act} = 40°C (104°F)
- Wire 4: d=1.0 mm (0.0393 in), T_{act} = 60°C (140°F)

A trendline formula was generated from the measured data, in order to model the SMA's behaviour. This can be used as a predictive tool for future research and optimization of SMA actuation in other soft robotic applications.

The first test as shown in Fig. 4 was repeated for all four wires. The results for this no load tests are shown in Fig. 5. This graph formed a good overview to compare the relationship between the diameter, activation temperatures, and behaviour in terms of actuation time for the different wires. The 1.0 mm wires showed comparable actuation times to the 0.5 mm wires, but required higher currents to achieve this.

Subsequently, all four wires were loaded with a weight varying from 10 to 100 grams using the same test setup in Fig. 4. The results of these maximum lifting capacity tests are presented in Fig. 6. Wires 1 and 2 reached a maximum lifting capacity of 30 grams. Beyond this point, the wires could hardly recover their fully straight shape. Wires 3 and 4 were more capable of lifting weights up to 100 grams. The slope of the 0.5 mm wires is also steeper, showing that the larger cross-sectional area of the 1.0 mm wires enables a more efficient phase transition process, leading to a shorter actuation time. This is the effect of a lower stiffness for the 0.5 mm wires, due to their smaller cross-sectional areas. These wires allowed for greater deformation under load, as noticed during the tests. This increased deformation and strain require more time for the wire to recover its original straight shape, resulting in a longer actuation time compared to the relatively stiffer 1.0 mm wires.

Ultimately, wire 3 showed the most favorable performance characteristics compared to wire 4. This wire exhibited a higher lifting capacity than wires 1 and 2, relatively stable actuation times, and lower actuation times than wire 4 due to its lower activation temperature.

4.2 Integrated Design Testing

SMA wire 3 was programmed to do a bending motion. Followingly, the actuation times for different scenarios were measured. From the results in Table 1, it can be seen that the programming of the wire has very little effect on the actuation time of the wire. This is due to the bending angle of the SMA wire. Because in the test with the factory settings, the 21 cm long nitinol wires were excited to go from a 45 degree angle to a 180 degree angle (see Fig. 4). This wire was then programmed to go

TABLE 1. Actuation Times for Different Testing Methods

Testing Method	Actuation Time
Wire (factory settings)	5.0 s
Programmed wire	6.4 s
Wire in tubing	9 s
Silicone encapsulated wire	9.6 s
Tubing + TPU Concept 1	11.2 s
Tubing + TPU Concept 2	12.0 s
Tubing + TPU Concept 3	11.0 s
Silicone + TPU Concept 1	11.6 s
Silicone + TPU Concept 2	12.4 s
Silicone + TPU Concept 3	10.8 s

from a straight to almost folding double to an angle of 170 degrees. The tubing and the silicone encapsulation solutions for the waterproofing showed similar effects on the actuation times. In comparison, the effects of the combination of the waterproofing methods with the soft TPU fingers were smaller. This can be related to the use of thin compliant hinges between the segments of the three concepts. These results show they proved their purpose. There is, however, a difference between the concepts which can be related to the distance between the compliant hinges. Concept 2 showed a slightly larger effect on the actuation time. This is because of the larger segments and thus the lesser hinge points. Concepts 1 and 3 have a higher density of compliant hinge points along their lengths. The distributed force applied by the bending nitinol wire is spread more evenly across these multiple hinge points and allows for a more uniform and coordinated bending motion. This results in quicker overall finger bending and thus a shorter actuation time for concepts 1 and 3.

In order to select the best waterproofing method, the soft robotic gripper with four TPU fingers, combined with the tubing solution was tested in multiple grasping tests. This method proved to be operational in water and passed the submersion test. However, the nitinol wires inside the tube became entangled during grasping tasks. This was due to the fact that the wires were not constrained to move in the x and y directions, allowing for potential twisting along their longitudinal axis. This entanglement led to a decrease in grasping performance. Encapsulating the nitinol wires in silicone with a shore hardness of 15 A, as shown in Fig. 7 solved this entanglement risk.

In order to select the best concept for the final design, a comparison of the most important performance metrics was made. This included tests on the manipulation dexterity. The manipulation dexterity of the three concepts was tested using objects of varying sizes, shapes, and weights. The results of these grasping tests can be found in Fig. 8. Concept 3 showed poor performance with the spherical objects, because the fingers twisted while grasping the objects. This was due to the lack of torsional stiffness of the TPU finger, due to the thin segments in between the 3 teeth on each row. This concept could potentially dam-

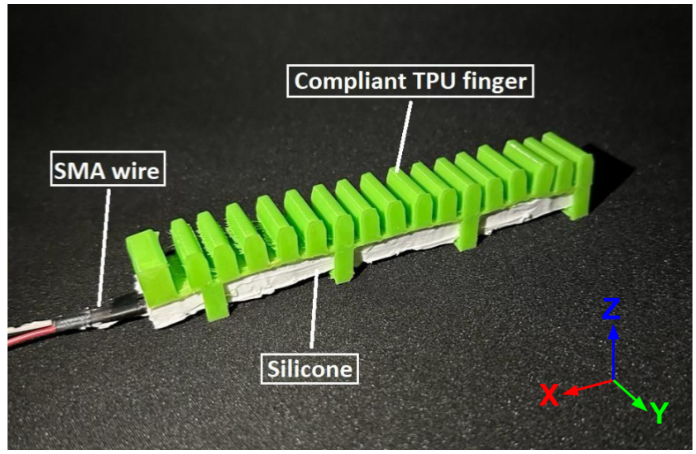


FIGURE 7. Encapsulated SMA combined with compliant TPU finger

Performance Metrics	Concept 1	Concept 2	Concept 3
Textured object - 3D printed rock	+	-	-
Elastic object - balloon	+	+	- (lack torsional stiffness)
Irregular-shaped object - springs	+	+	+
Mesh shaped object - nets	+	+	+
Bending angle	60 degrees	30 degrees	50 degrees
Post-actuation stability	+	-	+
Damage assessment rating	+	+	- (sharp edges cause pinching)
Consistency rating	+	+	+

FIGURE 8. A Comparison of Performance Metrics for Different Gripper Concepts

age delicate objects due to its relative sharper edges, allowing for pinching the object. This was also observed while grasping the balloon. Concept 2 showed good grasping performance on most of the objects due to the smaller density of compliant hinge points. The larger distance between these hinges allowed for greater torsional stiffness. But when picking up the smaller 3D printed rock shape, this concept performed poorly due to the lack of shear force, which depends on the friction between the object and the fingers. The smooth, rounded surface of this concept resulted in a reduced contact area with the smaller object. Moreover, this concept lacked indents for a secure grip, compared to the other concepts. Concept 1 showed the best performance for grasping different objects. The indents and the density of compliant hinge points demonstrated its effectiveness over the other concepts. Furthermore the bending angle of the three concepts was measured. The size of the segments of concept 2 limited its bending angle and grasping agility. Post-actuation stability was

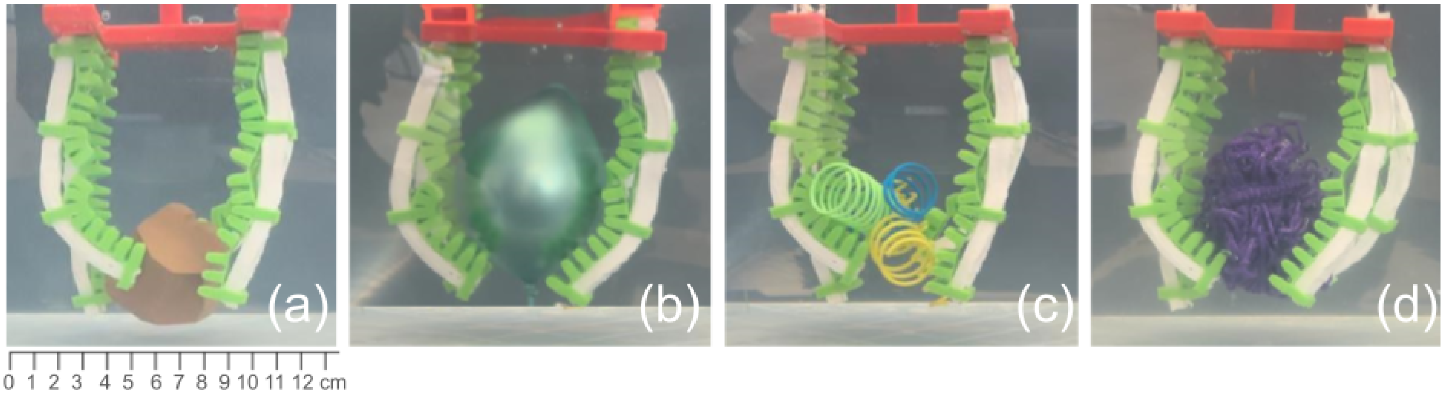


FIGURE 9. Soft underwater gripper design demonstrating its ability to grasp diverse objects: (a) 3D printed rock with a mass of 90 grams, (b) a balloon with a mass of 3 grams, (c) springs with a mass of 10 grams, and (d) nets with a mass of 60 grams.

measured to evaluate the ability to maintain a secure grip on objects after the power supply was cut off. The consistency rating was evaluated to provide an additional measure for reliability and repeatability in the evaluation process. Concept 1 was chosen for the final design of the gripper due to this performance metrics comparison. Despite repeated actuation of the SMA, with more than 100 test cycles, no signs of wear or damage to the SMA were discovered. The combined configuration was found reliable and showed consistent results when grasping objects of varying sizes and shapes. Fig. 9 shows the grasping of various objects underwater. The time required to grasp the objects was 12 seconds.

The actuation time of SMAs for application in soft grippers could be slower compared to actuation methods used in conventional grippers. However, it is crucial to acknowledge that the actuation time is heavily influenced by factors such as the applied current, the dimensions of the SMA, and their composition. Moreover, not all applications in underwater environments require time-critical actuation. Excessive fast gripper actuation underwater can cause hydrodynamic forces. As a result, disturbances due to turbulent flow or unwanted vibrations can affect overall control and stability during manipulation. Slower gripping movements enhance safety when human interaction, e.g., from divers, is involved. Fast gripping movements can cause damage or apply excessive forces when manipulating fragile objects underwater. In the context of this study and application, the actuation times of SMAs did not pose any issue when grasping objects underwater. This paper, aimed to show a systematic method for the selection process of a suitable SMA by providing an overview of different SMA behaviours and comparing differences in SMA properties. This led to the selection of the SMA with more favourable performance outputs in terms of lifting capacity (strength) and actuation time. The performance of the gripper was significantly affected by the choice of the SMA. Further investigation on more advanced feedback control systems could potentially improve actuation in underwater applications.

CONCLUSION

In this paper, a SMA-actuated soft robotic gripper was designed and prototyped. SMA actuation and manufacturing by 3D printing formed the foundation of this work. The performance of the SMAs has been researched in various conditions and combinations with components. Three different compliant finger designs were designed, 3D printed, and tested on their actuation time, manipulation dexterity, reliability, and durability. The benefits of using SMAs in underwater gripping are associated with their flexibility, which enables effective adaptation to a variety of randomly shaped objects in complex underwater conditions. Additionally, SMAs can function in underwater applications without the use of complex electronic systems. Because of their compactness, they can be embedded in the gripper frame or other components. This makes it feasible to create lightweight grippers and increase maneuverability by reducing drag in an underwater environment. The results of the tests on SMAs can be used as a predictive tool for future design and optimization of SMA actuation in other soft robotic applications. The performance in terms of manipulation dexterity and actuation time of the final design shows the strong potential of SMA-actuated underwater robotic applications. This paper's contribution is due to the study of the performance trade-offs of SMAs in soft gripper designs. It offered suggestions for developing and improving underwater actuation systems in accordance with particular application needs. The performance of soft robotic grippers could be further improved in future research by using feedback control systems. The deeper understanding of SMA-actuated soft robots in real-world settings provided by this paper enables the development of more advanced underwater grippers, further expanding the possibilities of underwater exploration and manipulation.

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