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For safe and compliant interaction: an outlook of soft underwater manipulators

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Abstract
As underwater missions become more and more complex, novel underwater manipulators with better performance are demanding. Soft underwater manipulators are judged to be the development direction and expected to have better performance in safe and compliant interaction with the target in underwater operations such as biological sampling. This paper provides an overview on the state-of-the-art of both hard and soft underwater manipulators to give a prospect for soft underwater manipulators. Key technologies in the design of soft underwater manipulators are identified, including the configuration design, actuator design and stiffening design of them.

Keywords
Underwater manipulators, soft robots, bionic design, underwater mission, configuration design, actuator design, stiffening design

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Introduction

For decades, manipulators have been taken as the executors of Underwater Vehicle Manipulation System (UVMS) to conduct the interactions between underwater vehicles and the marine environment. They are utilized in many underwater tasks, including pipe inspection and rope cutting, opening and closing valves,[1] biological and geological sampling.[2]

Usually underwater manipulators are similar to the onland manipulators which are an arm-like mechanism capable of grasping and moving objects with a number of degrees of freedom (DOF). They are driven by hydraulic oil or electricity and controlled by the telecontrollers in the underwater vehicles. They meet the requirements of basic oceanic exploration tasks, but as the underwater missions become more and more complex, the functions of current manipulators are not adequate enough. Some problems of current manipulators are pointed out in an review article, including the low control capabilities, the lack of automation, the risk of collision.[3] However, most of the drawbacks are concluded from the perspective of the control and based on the current hard underwater manipulators. Meanwhile, many researches try to build manipulators which behave like or consist of continuum soft materials in the last decade.[4] The advantages of soft underwater manipulators can be categorized into "safe" and "compliance" interaction.

- Safe reflects on two aspects. On one hand, the underwater biological sampling task using soft manipulators is safer to samples. The task can be executed without destroying the shape of some fragile objects like corals or killing the living creatures. On the other hand, the collisions which may break down the hard underwater manipulators can hardly bring damage to the soft manipulators because of its high resistance to impact.
- The compliance brings about the high adaption of the soft underwater manipulators. The theoretically infinite degrees of freedoms ensure the manipulators have better performance in unstructured environments and grasp objects with different shapes.

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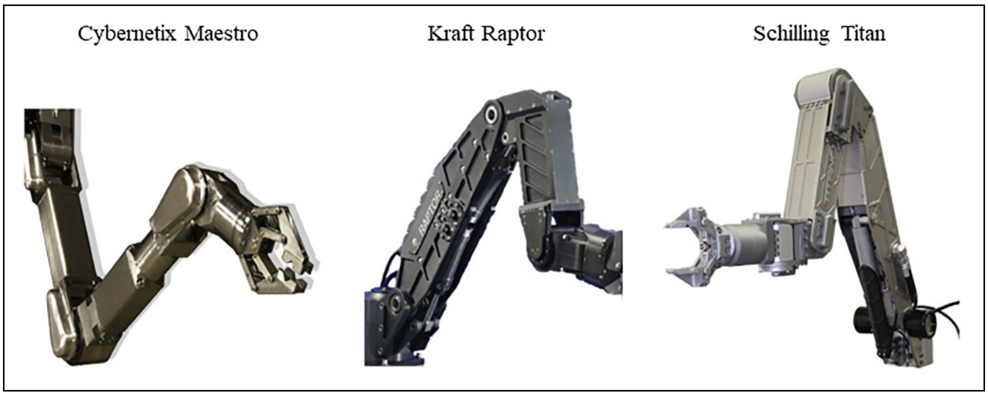


Figure 1. Some hydraulic underwater manipulators.

Therefore, this paper aims to provide an overview on the state-of-art technology of underwater manipulators and discuss some key problems in the design process of soft ones. The rest of paper is organized as follows. Sections 2 and 3 introduce the state-of-the-art of the design of hard and soft underwater manipulators respectively; section 4 presents the outlook of soft underwater manipulators, and section 5 draws some conclusions from this work.

State-of-the-art of the design of hard underwater manipulators

In 1959, the first manipulator (industry robot) was developed by Engelberger, and 1 year later, the first underwater manipulator was presented by Anderson in his paper.[5] It is called Remote Underwater Manipulator (RUM) and its goal was to conduct oceanographic researches. This manipulator was mainly made of metal materials and therefore this type of manipulators is called hard manipulator in differentiation with the manipulators made of soft materials. There are many developments since the first underwater manipulator. Early underwater manipulators were mostly hydraulic, but there were also some seawater-driven actuators for underwater manipulators.[6,7] The advantages of them are low viscosity, high power density, incombustibility, and no pollution,[8] while this approach was abandoned gradually for its salient disadvantages including corrosion, lubrication and sealing issues, and unsuitable working temperature, etc. The current hard underwater manipulators are mostly hydraulic or electric.

Hard hydraulic underwater manipulators

Hydraulic actuation is adopted by most commercial underwater manipulators because of the following reasons:

- High efficiency and high power-to-size ratio;
- Greater load-carrying capacity;
- No mechanical linkage (gears or reduction) is needed;
- Less seawater ingress problem because the internal pressure is higher than ambient pressure.

Figure 1 shows some commercial hydraulic underwater manipulators. In spite of the above advantages, there are also some drawbacks of hydraulic underwater manipulators. They have poor position accuracy and are hard for them to control the contact force during the operation.[9] These limitations make it difficult to realize the automation of hydraulic underwater manipulators. Another problem needs to be solved is the leakage of pressure oils. It brings out demands for the highest quality standards and materials for the manufacturing of components, making the whole system more expensive.[3]

Hard electric underwater manipulators

The developments of hard electric manipulators can be overviewed by several projects. The first project was the AMADEUS (Advanced MAnipulation for DEep Underwater Sampling) Project (1997), aimed at the dexterous underwater manipulations.[10] Two 7-DOF electrical underwater manipulators were designed in the project for cooperative operations. It has been proved that a 6-DOF underwater manipulator can reach any position with any orientation in its workplace, so a 7-DOF underwater manipulator is inherently redundant, but it is important for the autonomous manipulation because the redundancy can be exploited for a secondary objective such as obstacle avoidance. What's more, to execute more dexterous operations, an advanced gripper mechanism was developed in this project.

The second project was the SAUVIM (Semi-Autonomous Underwater Vehicle for Intervention Missions) project (1998). The manipulator equipped to AUV in this project was a 6-DOF manipulator called "MARIS 7080," and this manipulator was also utilized in the Maris project (2018).[11,12]

The third project was SAMURAI (Subsea Arctic Manipulator for Underwater Retrieval and

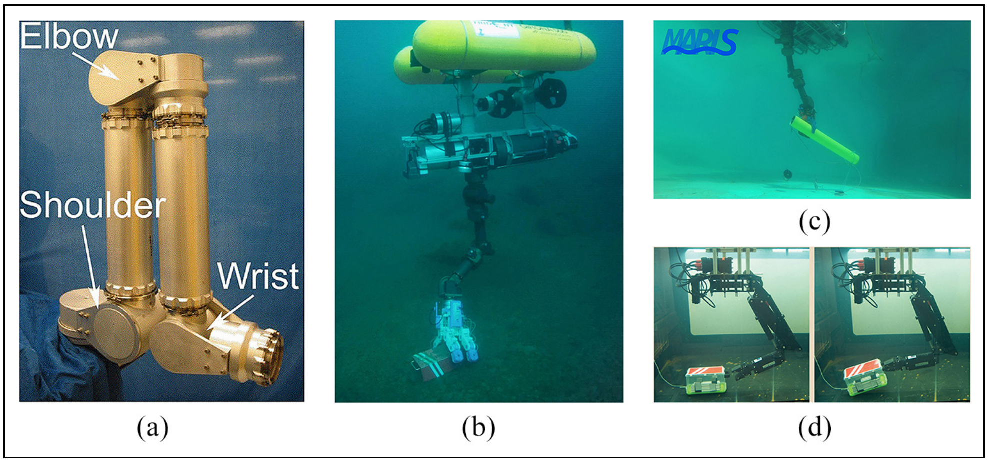


Figure 2. The electric underwater manipulators: (a) the underwater manipulator used in SAMURAI project[13]; (b) the underwater manipulator used in TRIDENT project[14]; (c) the underwater manipulator used in MARIS project;[11] and (d) the ARM 5 E underwater manipulator.[15].

Autonomous Interventions) project (2003), as shown in Figure 2(a). This underwater manipulator was designed to equip to the AUV working at the harsh and deep subsea environment and submerge to 6000 m below sea level, collecting specimens, and depositing them in sample containers before returning to the surface.[13]

The fourth project was TRIDENT (2013), whose aim was to perform underwater missions involving manipulations in a completely autonomous way, so a redundant manipulator was needed. Also, just similar to the AMADEUS project, the TRIDENT project designed a dexterous end effector called UNIBO gripper to execute more advanced operations. Last but not least, in this project, the first underwater modular arm was designed, and different modules can be combined to produce different arm configurations.[14] Figure 2(b) shows the underwater grasping task of it.

The fifth project was the MARIS project (2018), and the manipulator developed in this project is shown in Figure 2(c). It is the extension of the TRIDENT project, and it used the same manipulator as SAUVIM project-Maris 7080, but designed a more dexterous hand with a smaller size.[11]

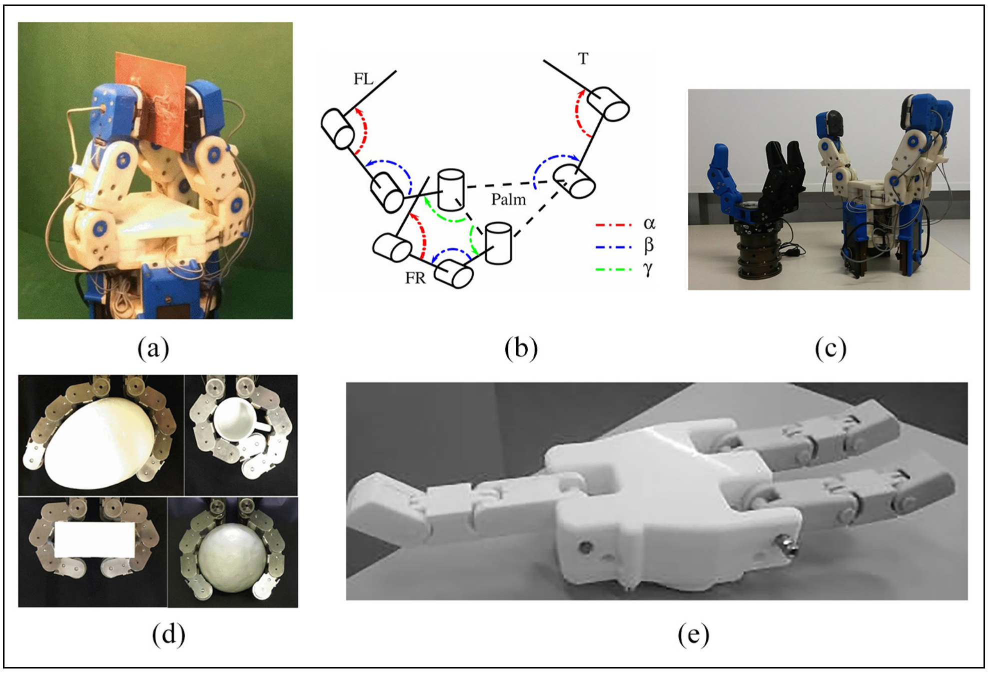
Besides, the manipulator (ARM 5 E) presented in Figure 2(d) was equipped to the AUV for shallow-water intervention, and this manipulator is commercially available.[15]

Compared to hydraulic actuation, the electric actuation has a higher position accuracy, so it is more suitable for the manipulators which need to execute complex operations and the trajectories are strictly restricted. Besides, it is inherently similar to the industrial robots, so many control schemes used in industrial robots can be transplanted into the control of underwater manipulators. Therefore, although in most cases the electric underwater manipulators can't meet the speed, reliability and strength or force requirements,[16] they are still used as research prototypes by many researchers.

Effectors

Underwater manipulators can be equipped with different end effectors to execute various operations. The most common end effectors used in subsea interventions are jaws, which are easy to be actuated but the grasping force and accuracy are hard to ensure. Also, jaws are often designed for certain purposes, and it is nearly impossible for them to act with dexterousness, so the dexterous underwater grippers are designed, and the researchers' ambitions were not stopped here. How to grasp irregular objects and keep the biological samples alive has been the problem troubling researchers. The soft robot technology has the potential to solve this problem, so some soft underwater grippers are proposed.

Mechanical jaws and crawls are the commonest end effectors of underwater manipulators, and there are many commercial products that can be selected according to the task. In the near future, a rapid increase in underwater applications is expected for exploration, industrial activities and scientific purposes,[17] but the current commercial grippers' motions are too simple, so some complex underwater operations must be conducted by divers. Hence, the TRIDENT project designed a dexterous three-finger grippers (Figure 3(a)) which has 8-DOF, actuated by DC brushless motors. Figure 3(b) shows its kinematic structure.[17] The afterward project MARIS improved this gripper. With kinematic structure unchanged, the project reduces the overall size and weight, modularizes the actuator components, and places a camera in the gripper palm, as shown in Figure 3(c).[11] Takeuchi et al. developed a multi-joint gripper (MJG) (Figure 3(d)).[18] The stiffness of the joints was controlled by using the Differential Gear Mechanism (DGM) chain. It made the gripper able to grasp objects regardless of their shape and softness. Figure 3(e) shows another dexterous gripper with



(a) (b) (c)

(d) (e)

Figure 3. Dexterous grippers: (a) the dexterous gripper designed by TRIDENT[17]; (b) the dexterous gripper designed by TRIDENT'S kinematic design[17]; (c) the comparison between dexterous gripper designed by MARIS (left) and that designed by TRIDENT (right)[11]; (d) a multi-joint gripper[18]; (e) an 8 DOF dexterous gripper.[19]

three fingers actuated by servomotors through hybrid transmission, tendons and gearing.[19]

State-of-the-art of the design of soft underwater manipulators

In the broad sense, the manipulator includes a robotic arm and its end effector, and in most cases, the end effectors are grippers. However, in some literature, the manipulator refers to the robotic arm or its end effector only. In this paper, the former definition is taken and the state-of-art of soft robotic grippers and arms are introduced respectively.

State-of -the-art of soft underwater grippers

According to the configuration, the soft underwater grippers can be divided into the multi-finger grippers, variable-stiffness ball grippers and tube-based grippers.[20] According to the grasp method, they are grippers grasping by actuation, controlled stiffness and controlled adhesion.[21] Classified by the driven methods, they are driven by fluid and grippers driven by the functional materials. In this section, driven methods are considered as the classification criterion because of its importance in the design of soft robots.

Fluid-driven grippers. Just as the name implies, the fluid-driven grippers are driven by hydraulic oil or pressured air. According to their configuration, most of them can be divided into two groups: the Fiber Reinforcement Actuators (FRA) and the Pneunet actuators (PA). Inherently, the different motions are realized by the structure anisotropy of the actuators. The structure can either achieved by the additional constraints (FRA) or the combination of materials with different stiffness (PA). Pneumatic artificial muscle is a typical kind of FRA. When air is input into the muscle, the rubber tube expands along the radial direction and contracts along the axial direction.[22] The different enwinding way of reinforcement fiber can bring about different motions, including contracting, extending, bending, and twisting. PA has synthetic elastomer layers and deforms when the embedded channels are filled with pressurized liquid or air. Unlike FRA, the various motions of PA, such as bending, twisting[23] and helical motion,[24] are achieved by the different channel shapes and their arrangement.

Hao et al. did some experiments about the performance of soft grippers with PA structure in amphibious environments.[25] The results showed that soft grippers were capable of grasping objects with different sizes and shapes successfully in both onland and underwater environment (Figure 4(a)). However, the experiments were conducted in the shallow water (in the tank which has a height of 330 mm). Therefore, the water pressure which should be a challenging problem in underwater equipment design was ignored. Galloway et al. designed a soft gripper for biological sampling on deep reefs and conducted in-situ testing at mesophotic depths, as shown in Figure 4(b).[2] The soft grippers combined two above-mentioned configurations: the FRA with bending and twisting motions for grasping tube-like objects

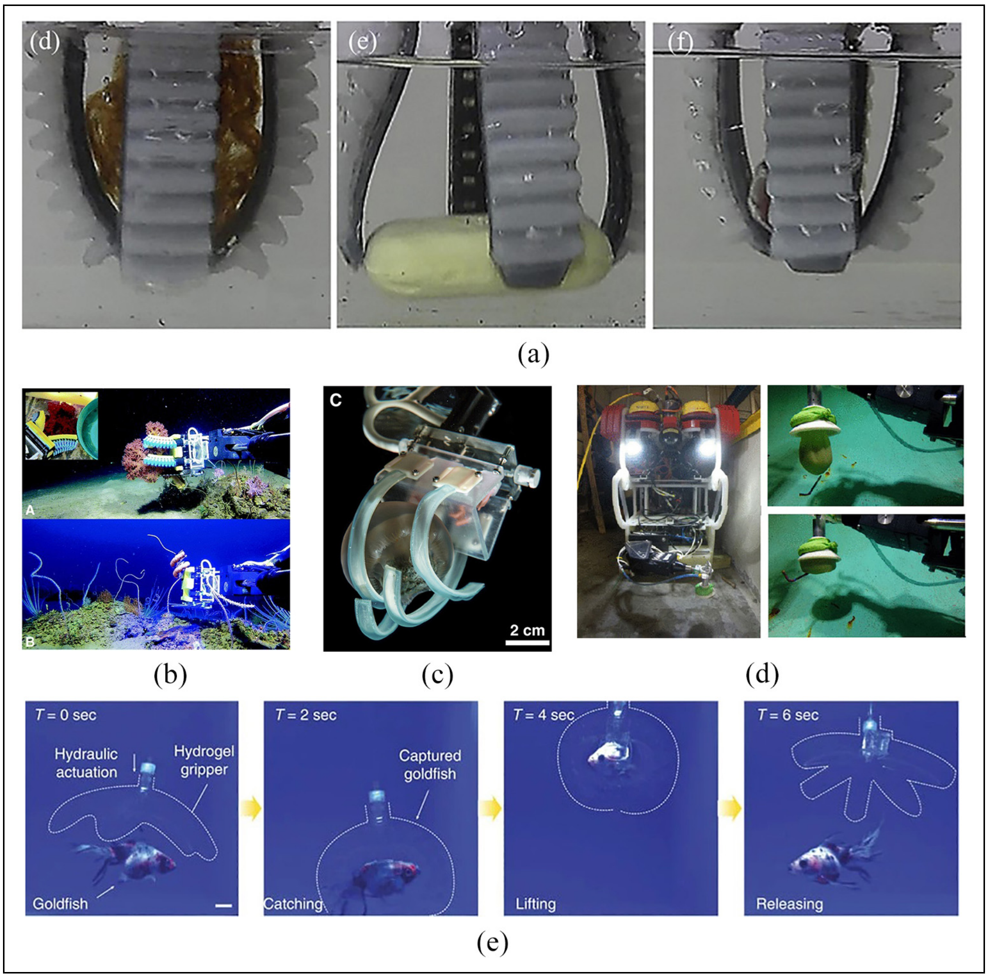


Figure 4. Fluid-driven soft underwater grippers: (a) the pneumatic gripper with PA structure[25]; (b) the hydraulic soft grippers with PA (up) and FRA (down) structure[2]; (c) the gripper with "ultragentle" manipulation[27]; (d) the universal soft grippers using jamming effect[29]; and (e) a soft hydraulic gripper using hydrogel as the body material.[28]

and four PAs with bending motions arranged as a four-finger gripper for others. Vogt at al. equipped the soft gripper with PA configuration to a ROV and finished the sampling task in the Phoenix Islands Protected Area.[26] Besides the better performance in grasping, the sample fabrication method is also an important advantage in oceanic investigation. To further improve the grasping performance, Sinatra at al. designed an underwater gripper driven by pressure air featuring "ultragentle" manipulation, which is shown in Figure 4(c).[27] To decrease the contact pressure, the nanofiber was used to reinforce the soft actuator, and as a result of it, the jellyfish can be grasped by the grippers. All the above grippers using silicone elastomer for its compliance and easy manufacturability. Yuk at al. used hydrogel as the body material to catch the fish underwater, and the process is shown in Figure 4(e).[28] Apart from FRA and PA, there is another type of fluid driven universal underwater gripper shown in Figure 4(d) which uses "jamming" phenomenon to grasp objects.[29] Jamming occurs when vacuum is applied to rubber bladder filled with particles and fluids having the same pressure of the surrounding environment. The particles can move with little fraction at normal conditions, so the gripper can change its shape to envelope any object. When the fluid is removed, the fraction arises so the gripper can hold the shape to finish the grasp task. The gripper features the outstanding adaptability and grasping robustness.

Smart material driven grippers. The smart material means the materials which can perform sense, control, and actuation.[30] Specific to the soft robots, the commonly used smart materials are shape memory alloys (SMAs), electroactive polymers (EAPs) and some other materials. However, the grippers made by these other materials are in a quite small scale,[31,32] so they will not be discussed here.

SMA can deform and return to the original shape when heated and it has been used for actuation. Shape memory materials can be embedded into soft materials to grasp objects.[33] Engeberg et al. designed an anthropomorphic finger (Figure 5(a)) antagonistically actuated by SMA plates which is easy to control.[34]

Electroactive polymers (EAPs) will undergo a significant amount of deformation in a proper electric field.

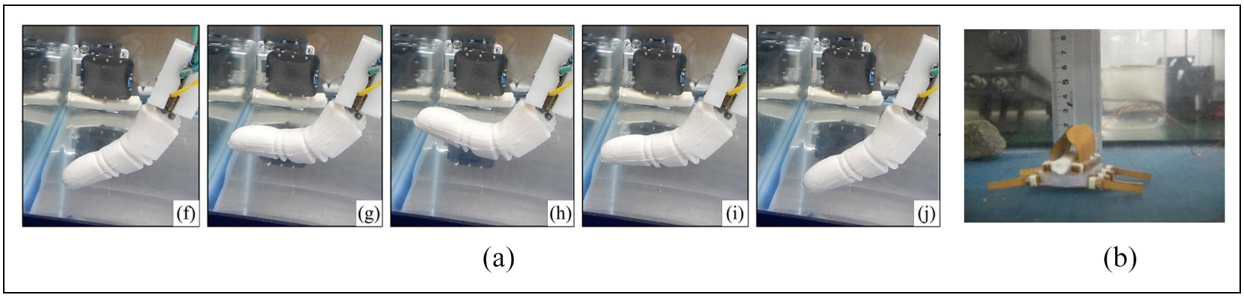


Figure 5. Soft underwater grippers driven by smart materials: (a) the finger working in the underwater environment driven by SMA[34] and (b) the IPMC driving Venus Flytrap.[45]

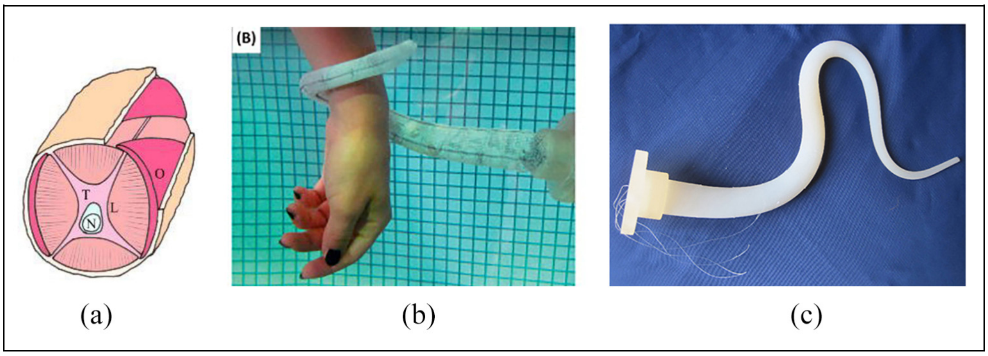


Figure 6. Soft underwater arms inspired by the octopus: (a) the muscle structure of the octopus arm[51]; (b) the robotic octopus arm driven by tendon and SMA[52]; (c) the soft robotic arm driven by tendon only.[49]

This property allows them to act as actuators. There are two types of EAPs, which are Dielectric elastomers (DE) and Ionic Polymer-Metal Composites (IPMC). Although DE is widely used in underwater robots[35–39] and grippers,[40–44] few examples can be found in the literature about the application of it in the underwater grippers. As presented in Figure 5(b), Shi et al. designed a robotic Venus Flytrap with IPMC actuators for grasping.[45]

State-of-the-art of soft underwater arms

Compared to the soft underwater grippers, the demands of the soft underwater arm are higher. They need larger displacement to expand the working space and stronger output force to carry the load. Therefore, the current soft underwater arms are mostly driven by either fluids or the cable.

Octopus has inspired engineers to design some soft underwater arms. As shown in Figure 6(a), in the arm of octopus there are three kinds of muscles: transverse, longitudinal and obliquely orientated groups, and different motions can be realized by the contraction of the muscles.[46] Laschi at al. designed a robot octopus inspired soft arms for underwater locomotion and manipulation which utilized the UHMWPE synthetic fibers as the longitudinal muscles and the SMA as the transverse muscles, respectively, as presented in Figure 6(b).[47] Some other soft actuators can also work as the muscles. Guglielmino et al. used PAMs to mimic the motion of the octopus's arm.[48] To reduce the difficulty in fabrication and control, some researchers gave up the transverse muscles and used cable to drive the soft arm.[49,50]

Elephant trunk is another source of inspirations. In the arm of elephant trunk, there are two kinds of muscles, which are rectus muscles and longitudinal muscles. Bending motion can be realized by the contraction of longitudinal muscle on one side, and the longitudinal compressional force, tending to shorten the entire organ or body, is resisted by the rectus muscle. Gong et al. designed a soft underwater robotic arm which with inner chambers and PDMS core.[53] The chamber worked as the longitudinal muscle in the elephant trunk while the PDMS core as the rectus muscle. Figure 7(b) presents its prototype. The difference is that the elephant trunk contracts the longitudinal muscle to bend while the soft arm extends the chamber.

Apart from the above achievements, some other soft underwater robots can also be viewed as soft underwater manipulators. Kim et al. designed a pelican eel inspired pneumatic origami structure (dual-morphing M-ori) which will experience two-step morphing process including unfolding and stretching.[54] The large range of the underwater motion makes it possible to be adapted in the design of soft underwater arms.

Outlook of soft underwater manipulators

To design a practical soft underwater manipulator, some key problems should be addressed including the configuration, actuation, stiffness adjustment. Since there are only a few successful soft underwater manipulation systems, some inspirations can be obtained from the soft manipulation systems in the air.

Configuration

If the soft arm and gripper together is considered as a system, it should have two basic system configurations. One is the combination of a hard arm and a soft gripper. The traditional hard robot arm has the advantages of wide reach, large carrying capability and high position accuracy, and the soft grippers are better at grasping delicate objects. In such a combination, the soft gripper is a kind of end effector which could be equipped when needed. The other configuration is to replace the hard arm with soft one. The soft arm features small mass inertia, low collision risk and better performance in unstructured environment. However, the compliance of soft arm means the lack of stiffness which has an important effect on the carrying ability. Therefore, stiffness adjustment is necessary which will be discussed in section 4.3.

If the arm is taken into consideration separately, there are some possible configurations. In section 3.2, some soft arms are introduced, and their configuration can be defined as the multi-directional bending configuration. The soft arm consists of some segments which can bend to several directions connected in a series. It is the commonest configuration and has been used in medical surgery, onland and underwater grasping. However, the reach space of this kind of soft arm is limited because of the discrete of bending directions. There is another kind of configuration which can be called as the multi-joint configuration. It is similar to current hard soft arms, and the key technology is to replace the hard joint with soft ones. Currently, the actuators with contraction or extension motions can work as the prismatic joints, while the actuators with bend or twisting motions can take place of revolute joints. Figure 8(a) shows a 6-DOF soft robot KAA, and each joint can rotate about certain axis.[55] Actually, it is a bionic manipulator getting its inspiration from the human's arm. Figure 8(b) shows another example. Two vacuum driven twisting actuators act as the manipulator joint and gripper joint as shown in Figure 8(c).[56] The soft underwater arm in Figure 8(d) combines the bending and elongation segments and has been equipped to an AUV to grasp delicate objects in the shallow water.[57] Figure 8(e) shows the soft arms with bending and rotary modules which consists of two FRA with different fiber enwinding method.[58]

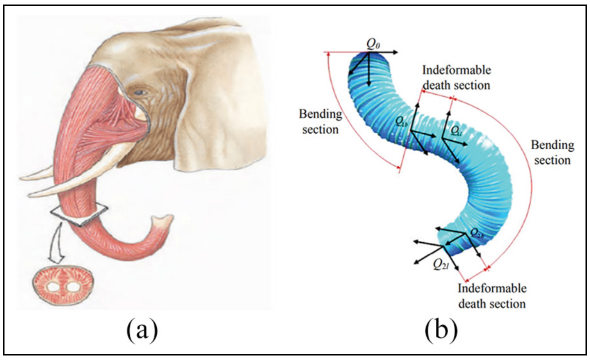


Figure 7. Soft underwater arms inspired by the elephant trunk: (a) the muscle of the trunk and (b) the prototype of the soft underwater arm inspired by elephant trunk.[53]

Actuation

To achieve better underwater performance, actuators with higher energy density, higher efficiency and large output is needed. Table 1 shows comparison between five typical actuation methods.

From the comparison, the feasibility of each actuation method can be analyzed.

- Hydraulic: It is commonly used in the current underwater systems. It has the advantages of large output and easy integration with onboard energy systems of underwater vehicles. However, the weight could be a problem if the manipulator is equipped to a small underwater vehicle.
- Pneumatic: Because of the easy design process and availability, the pneumatic driven method is widely used in the soft manipulators in the air. But when applied in the water, the pressure of the underwater environment can be a challenge. What's more, the overall weight of the system is also a problem.
- Tendon-driven: There are many underactuated rigid grippers, such as the underwater gripper used in the TRIDENT and Maris projects.[17] There are also some cable driven underwater robotic arms replacing the joint motors with guiding wheel, tensioners and cables to reduce the self-weight.[59] However, the tendon-driven soft manipulators discussed here refer to grippers or arms built by soft materials. The replacement of the rigid parts with soft ones will bring more compliance to the manipulators, thus making the interaction safer and gentler. Compared to other actuators, tendon-driven methods have advantages of the large output, quick speed and the controllability making it suitable for underwater manipulation. However, the design of tendon guiding structure in soft materials is more complicated than that in rigids ones. If tendons are embedded, those tendons are risky to bring damage to the soft materials.

Table 1. Comparison between typical actuation methods.

Property	Hydraulic	Pneumatic	Tendon-Driven	SMA	EAP
Displacement	Large	Medium	Large	Small	Small
force	Large	Medium	Large	Small	Small
Actuation speed	Quick	Quick	Quick	Medium	Quick
Overall weight	Heavy	Heavy	Medium	Light	Light
Energy consumption	High	High	Medium	High	Low

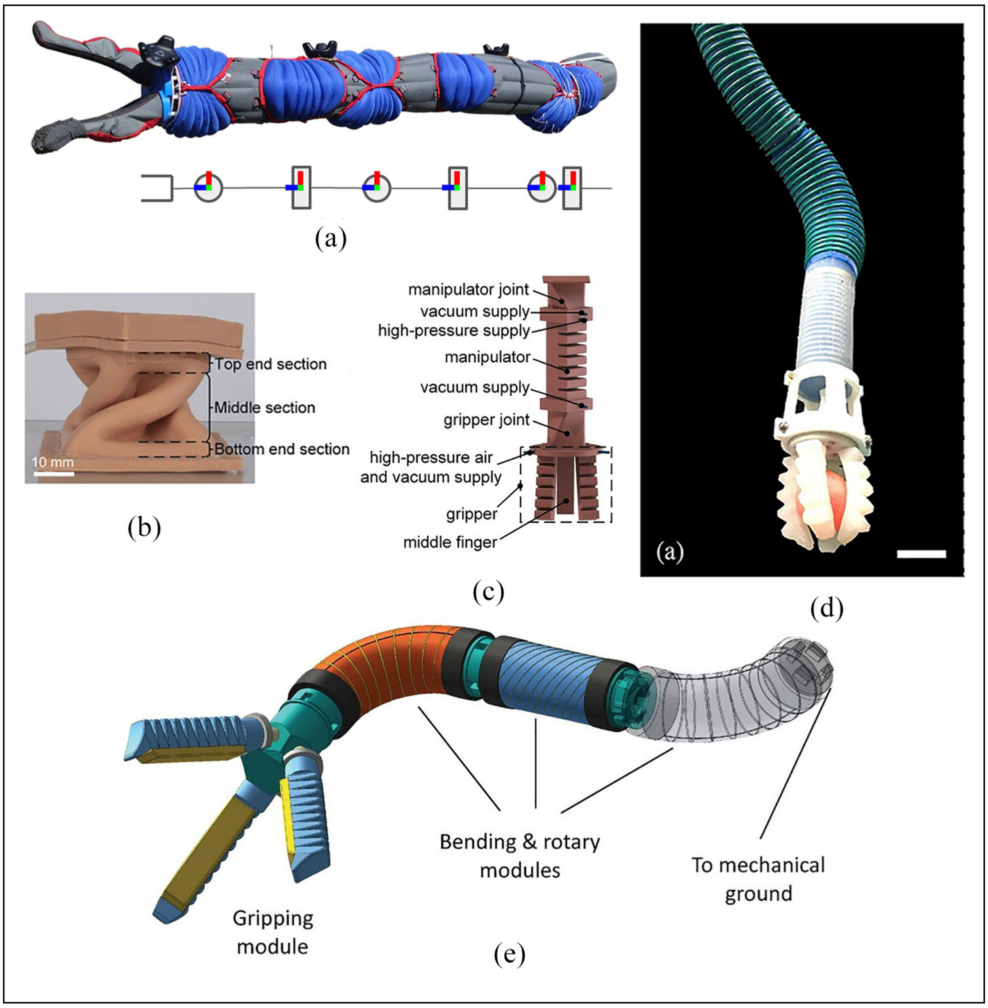


Figure 8. (a) Six-DOF soft robot KAA. The frames are assigned at each joint in the zero configuration with red, green, and blue (RGB) axes corresponding to the XYZ axes, respectively[55]; (b) the twisting actuator driven by vacuum[56]; (c) the manipulator with two twisting joints and one bending segment[56]; (d) the manipulator with two bending segments, one extension segment and a soft pneumatic gripper[57]; and (e) the manipulator with bending and rotary modules.[58]

- SMA: Although the low temperature of the underwater environment accelerates the cooling process of SMA, the slow recovery speed and output are still hard problems to solve.
- EAP: As illustrated above, DE material is hardly used in the underwater manipulators. The small output displacement of it is one of the reasons. Acome et al. utilized liquid DE materials to amplified output, and it is a possible actuator to soft manipulators.[60] Compare to DE, IPMC is more suitable for underwater manipulation for that it can work in water directly without embedding it into some other soft materials.[61]

Stiffness adjustment

For soft robots, inherent softness enables dexterity and safe interactions, and stiffening is needed for better force transformation when necessary. This is important for soft underwater manipulators, especially those

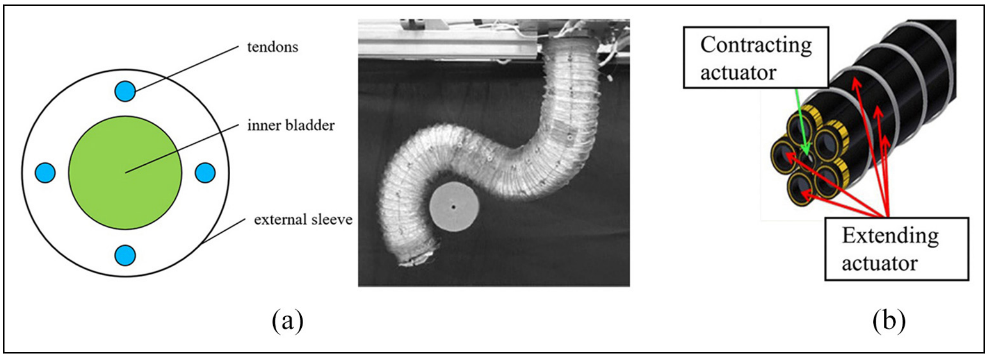


Figure 9. (a) Air Octor with antagonist actuator structure[63] and (b) varies stiffness actuator with extensible and contractile PAMs.[64].

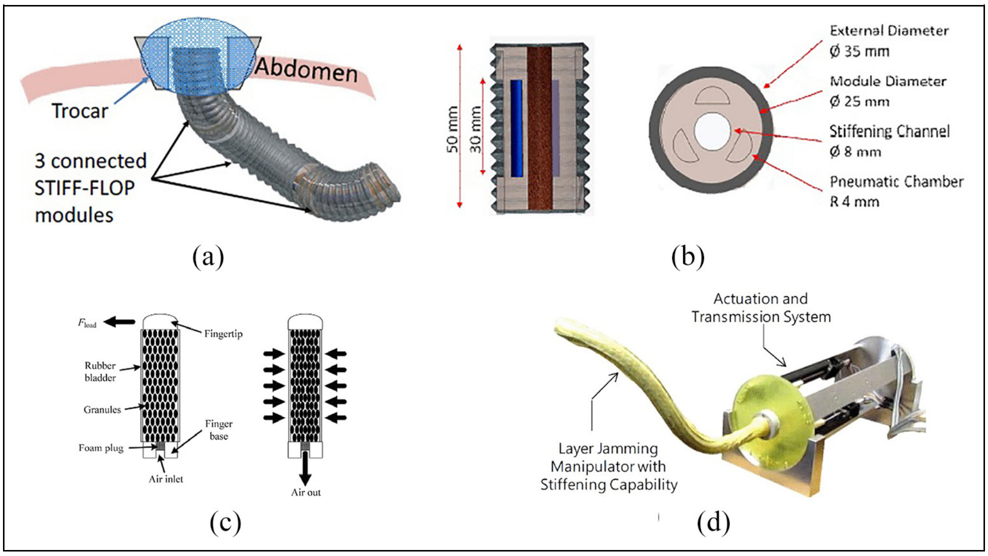


Figure 10. (a) The soft arm using jamming to change its stiffness; (b) CAD model of each module of the soft arm in Figure 10(a)[65]; (c) the soft finger utilizing granular jamming[71]; and (d) the soft manipulator with layer jamming structure.[70]

working at flowing water. Stiffening technology is widely used in the design of soft manipulators for surgery, because once the end effector is placed to the certain place, the robotic arm should keep their position in case of injuring other tissues or organs by accident.

The stiffening methods in general can be divided into three types, active method, semi-active method and passive method, but in current literature, only first two types have been studied.[62] The active method is to arrange different actuators (FEA or cable-driven methods) in an antagonist design. Figure 9(a) shows an Air Octor with an internal extensible bladder and an external sleeve designed by McMahan et al.[63] The inner pneumatic chamber tends to elongate the arm while the cables shorten it, and it brings about an antagonistic effect, thus realizing the stiffening. Figure 9(b) shows another variable stiffness soft arm consists of one central extendible PAM and three contractile PAMs. The stiffness can be adjusted by adjusting the inflating pressure of the extensible PAM and the contractile PAMs simultaneously.[64]

The semi-active method is realized by jamming, including granular jamming or layer jamming. The method has been explained in section 2.1. Figure 10(a) and (b) show the STIFF-FLOP soft robotic arm and its CAD model of one module. It has a silicon tube with three fluid actuators for 3D motion and a central granular jamming tube for stiffening.[65] More similar structure can be found in surgery robot manipulators.[66–69] Figure 10(c) shows a finger utilizing jamming to change stiffness.[44] Figure 10(d) is a soft manipulator using layer jamming inspired by the snake.[70]

Summary and conclusions

Hard underwater manipulators are well developed in the last few decades, but in further improving their performances, soft manipulators are judged to be the direction. To facilitate developments of soft underwater manipulators, many basic designs can follow the existing designs in hard underwater manipulators and soft onland manipulators. So, in this paper, the state-of-the-art of hard underwater manipulators and soft manipulators are introduced respectively. Then an outlook of soft underwater manipulators covering three design problems is presented. Through this overview, the following two conclusions can be drawn:

(1) Soft underwater manipulators are expected to solve the problem of collision avoidance and safe grasping without the damage to the samples in the underwater manipulators. Attention should be paid to the configuration design, actuation design and stiffening design if a soft underwater manipulator is to be designed.
(2) The developments of soft underwater manipulators are promising and achievable. The development from the traditional rigid underwater manipulators to soft manipulators has a number of key advantages. Soft underwater manipulators demonstrate the compliance required for underwater interaction in unstructured environments. Some prototypes have been designed in recent years, and it is believed that more soft underwater manipulators will be designed in the near future.

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