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Updated Review of Soft Robotic Grippers and Tactile Sensors for Underwater Robotics

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Abstract

Research in underwater robotics is rapidly advancing, with innovations in sensors, manipulators, and control systems for deep-sea exploration and specimen collection. Soft robotics is transforming the field by enabling more adaptable and flexible operation in unpredictable underwater environments. This paper presented a narrative review of recent developments in soft robotic grippers for underwater manipulation. It analyzed a range of grippers—including jamming grippers, origami-based polyhedral grippers, and biomimetic soft hands—and critically reviewed them based on factors such as design, mechanism, and sensing capabilities. The study also examined complementary tactile sensors. Through its discussion, the paper highlighted recent advances and trends, providing comparative information while underscoring the research gaps that must be addressed before large-scale deployment in real-world underwater missions. The key findings suggested that different types of grippers are better suited for delicate grasping compared to traditional grippers, and each gripper is better suited for specific applications (for instance, jamming grippers achieve higher payloads). Additionally, their integration with improved sensing technologies is crucial for enhancing object detection, force control, and autonomy. However, findings also show that most grippers have been validated only in laboratory conditions, highlighting the need for robust field testing and long-term durability studies.

Keywords: Underwater Robotics, Underwater End-Effector, Robotic Underwater Hands, Soft Robotic Grippers, Tactile Sensors

1. Introduction

The last few decades have witnessed that development and research in underwater (UW) robotics have received great attention (Yuh, 1995). Underwater robotics provides us with unique opportunities, and now, novel systems like Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), and Unmanned underwater vehicles (UUVs) are used for numerous tasks, from UW sample collection to bathymetric and magnetic field mapping (Yoerger et al., 2007). For example, autonomous underwater vehicles are now being used for autonomous inspection of seaweed farms, which is more cost-effective and sustainable than current methods centered on fossil fuel-consuming boats (Stenius et al., 2022); oceanographic exploration can also be carried out using AUVs (Barker et al., 2020; Whitcomb et al., 2000).

To allow interaction with the environment, underwater vehicles are equipped with manipulators (Sivčev et al., 2018). These underwater manipulators have various applications, from marine civil engineering to military uses, and are designed differently for different purposes. One of the most common uses of these manipulators is grippers for collecting scientific samples such as coral reefs, dead or alive organisms, and remains on the seabed (Mazzeo et al., 2022). Currently, aquatic grippers can vary in types, from jamming grippers (Licht et al., 2016; Licht et al., 2017) and suction grippers (Kumamoto et al., 2021) to soft robotic grippers. For example, Barbieri et al. (2018) have developed a three-fingered robotic arm that can be mounted on a small-sized remotely operated vehicle and is controlled using a

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master-slave approach.

Despite these innovations, collecting scientific samples underwater is very challenging. The rigid mechanics of most grippers result in limitations in the degree of freedom, mobility, and adaptability of the machine in an uncontrolled underwater environment with extreme and varying conditions. As a result, they cannot delicately interact with foreign objects without causing damage.

However, soft robots are made from deformable substances, making them more flexible, versatile, and adaptable while performing tasks. Integrating soft robotics and underwater robotics provides a solution to the challenges. It helps improve the functionality and capability of the systems to comply with discontinuities in a harsh environment (Laschi & Cianchetti, 2014; Iida & Laschi, 2011). So, the use of soft robotic grippers for object manipulation allows delicate and adaptive handling of objects underwater (Sinatra et al., 2019; Gong et al., 2019; Wu et al., 2022).

Underwater robots typically depend on acoustic sensors, electromagnetic sensors, bionic sensors, and cameras to detect their surroundings; however, each of these sensors has its drawbacks. For example, low visibility in the aquatic atmosphere diminishes the sensing capabilities of cameras (Y. Cong et al., 2021). One solution to this problem is tactile sensors and their integration with soft robotics (Muscolo & Cannata, 2015). For example, Wu et al. have developed a soft robotic gripper that is capable of compliant grasping of objects along with real-time object detection (2022).

2. Methodology

This paper presents a narrative review analyzing recent innovations in soft robotics and tactile sensors in order to highlight the implications of soft robotics grippers in the underwater regime.

Previously, soft robotic grippers and tactile sensors for underwater robotics have been discussed by Subad et al. (2021) in "Soft robotic hands and tactile sensors for underwater robotics" and Mazzeo et al. (2022) in "Marine robotics for deep-sea specimen collection: A systematic review of underwater grippers." However, these papers primarily focus on two-fingered, multi-fingered, and multi-joint soft robotic grippers and do not provide much detail about jamming pad grippers, origami-inspired grippers, and bio-inspired grippers. This paper is focused on the recent developments in the type of grippers mentioned above.

The reviewed studies were collected from Google Scholar, and the keywords used in the search included 'underwater soft robotic grippers', 'underwater tactile sensors', 'underwater end-effector', 'origami grippers' and 'bio-inspired soft robotic grippers'. In order to focus on recent developments, the selected studies were mainly published in or after 2022, with a few earlier works selected due to their continued relevance.

From the studies about grippers or hands, information regarding the designs of the grippers, their actuation mechanism, materials used, dimensions, gripping force, and sensing capabilities (if any) and has been presented in Section 5. Similarly, a descriptive review of tactile sensors, discussing their sensing mechanism, materials, and sensing capabilities has been presented in Section 6.

Section 7 presents a discussion of these technologies, where the implications of these technologies are critically reviewed, by making comparisons, synthesizing trends, identifying research gaps and considering real-world applications.

3. Soft Robotics

Robotic systems are usually made from rigid structures and materials that move using electric actuators or pressurized fluids. On the other hand, biological organisms rarely consist of rigid components; they are generally made from flexible and elastic materials. As a result of the difference in the mechanical properties, the control and actuation in the two types of systems are also very different. Inside a controlled and well-defined environment, hard robots can perform their tasks with great precision and consistency. However, they are generally non-compliant and cannot adapt autonomously to different tasks, conditions, and shapes. On the other hand, biological systems can outperform conventional robotic systems in many tasks. Therefore, taking inspiration from the biological physics that benefits biological systems, researchers try to mimic the design and mechanical features of these systems, mainly

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the flexible and elastic behavior, in their designs. This led to the emergence of the field of soft robotics (Iida & Laschi, 2011).

By taking advantage of the compliant nature of their elastomers, soft robots, despite their simple build, can conform autonomously to different conditions and discontinuities in the environment (Whitesides, 2018). For example, hard robotic grippers require specialized end effectors for varying sizes and shapes; on the other hand, soft robots can use whole-hand manipulation to maintain a tight grasp and lift objects of different sizes and shapes (Trivedi et al., 2008).

4. Soft Robotic Grippers

Compared to hard robots, soft robots can conform to unexpected and irregular shapes and sizes of objects. They are better equipped to perform in the ever-changing extreme conditions of an underwater environment. Their deformable structure allows more dexterous grasping of the objects while maintaining delicacy to prevent damage to the delicate objects. The soft materials used for these grippers also withstand sudden impacts and absorb vibrations from its surroundings. In addition, these materials are less dense compared to stiff ones; as a result, soft robotic systems are lighter and require small actuators (Trimmer, 2015). This section will discuss the designs of recent soft robotic underwater manipulators.

Many soft robotics grippers are made from particle jamming pads. Particle jamming pads consist of a flexible membrane filled with granular material. This material can move freely inside the membrane, but when the particles are jammed together by applying force or vacuuming air out of the membrane, the jamming pad becomes firm and can hold its shape. So, the material transitions between fluid-like and solid-like states. In jamming grippers, these pads are used to grasp objects: the robot presses the material in its unjammed state toward an object, allowing the particles to adjust to the object's shape, and then jams them, gripping the object (Stanley et al., 2013; Stanley & Okamura, 2015; Howard et al., 2022).

Capalbo et al. (2022) have developed a soft robotic gripper with neutrally buoyant jamming pads. (Figure 1). Made from a pair of jamming pads supported by six soft finger-like actuators, it is capable of gentle, secure, and compliant grasping. The design of a pincer-style gripper using jamming pads allows the grasping of objects of any shape that fits within its jaw opening of 25 cm. A continuous force on the jamming is maintained using antagonistic rolling diaphragm hydraulic cylinders; this keeps the jamming pads in contact with the object when they transition to their rigid state.

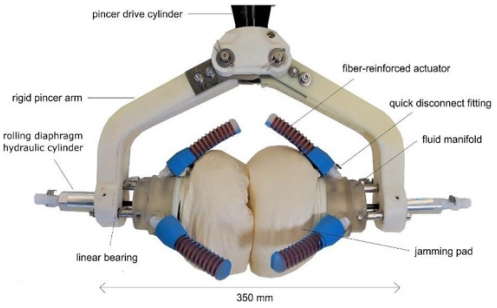

Figure 1. Jamming Pad Based Gripper by Capalbo et al. (2022)

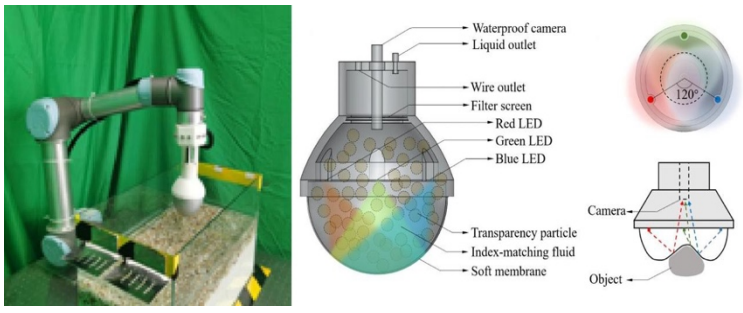

Figure 2. Tata gripper made by Li et al. (2022)

In 2022, Li et al. (2022) developed a jamming gripper capable of grasping irregular objects up to 2 kg (Figure 2). The design of this jamming pad gripper is similar to that of the jamming grippers made by John et al. (2012) and Licht et al. (2018). Li et al.'s gripper also has a vision-based tactile detection system, which its predecessors lacked. It can perform high-resolution object perception with the help of a camera and transparent glass jamming particles. Experiments on underwater gripping and pipe leak detection were conducted. The success rate of underwater object recognition and gripping was 96% , and the success rate of finding pipe leaks and closing valves was 95% .

Many soft robotic grippers take inspiration from origami. For example, Teoh et al. (2018) developed a self-folding polyhedral suitable for remote onboard underwater vehicles (Figure 3). Based on an axisymmetric dodecahedron net

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folded by external assembly linkage, it consists of five planar triangular segments with upward triangular tips folded using external assembly linkage that ensure the enclosure of the dodecahedron. This gripper is scalable, simple to operate, and designed to withstand and operate depths of up to 11 km. In addition, it was tested in deep-sea conditions and was made to collect organisms such as squid and jellyfish at depths of 500 to 700 m.

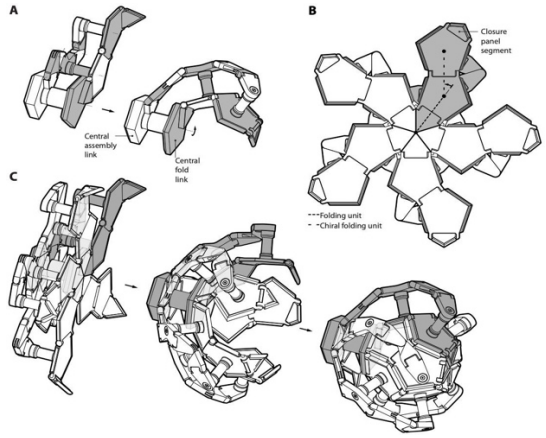

Figure 3. Self-Folding Polyhedral based gripper by Teoh et al. (Teoh et al., 2018)

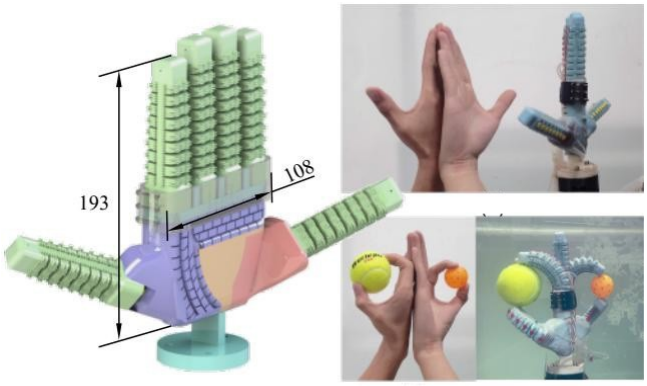

Figure 4. Bi-directional Biomimetic Gripper by Wang et al. (2022)

In 2022, Hung et al. (2022) developed a reconfigurable and proprioceptive soft origami gripper. The origami module uses a pleated fold pattern similar to the bellow design (Galloway et al., 2016). This design has a large compression and extension ratio, allowing better attachment of foldable sensors compared to more complex origami structures. The module has two basic movements: extension and bending. Extension is controlled using a pneumatic origami actuator, and bending is achieved through cable restriction of the module. The module also consists of a foldable sensor based on the self-inductance of multi-fold planar coils. Huang et al. have also proposed two gripper designs. First is an intelligent gripper with three origami modules capable of grasping force and target size measurements. The second is a jellyfish gripper assembled using five origami modules capable of buoyancy adjustment and underwater grasping. It is also capable of achieving forward movement.

While bio-inspiration is a common feature of soft robotics, some researchers have also mimicked human body parts. For example, Wang et al. (2022) have developed a soft robotic hand similar to a human hand. In addition to the five fingers of a human hand, it consists of an additional thumb attached symmetrically (Figure 4). The fingers use bellows-type actuators, which, compared to the straining motion of elastomer material, create smaller strain on the material and achieve the same bending angles at lower pressure, and are made up of four pressure chambers that allow bidirectional movement and side-to-side deflection. These fingers can bend up to an angle of 90 degrees and generate a maximum force of 5.8N. The soft palm of the gripper is also biomimetic and consists of two different soft actuators. These actuators facilitate bidirectional movement of the thumbs, enhance the dexterity of the gripper, and facilitate bending movement of the fingers.

Wu et al. (2022) developed a soft robotic gripper that is self-adaptive and has sensing abilities by taking inspiration from a glowing sucker octopus's grasping abilities. (Figure 5). The gripper is made from a silicone soft suction disc controlled using a tubular bellow actuator that makes the disc extend and retract to grasp an object. The surface of the disc has several suctorial mouth arrays attached to it. These arrays are connected to a pump that generates a suction force. The suction of these mouth arrays allows the grippers to grasp flat objects, which cannot be achieved by most of the other grippers. The disc can maintain a flat curve when suspended in air; it also has a certain degree of flexibility that allows adaptive grasping, as it can conform to different shapes, sizes, and types of surfaces. The suctorial mouths have fluid flowing through them; this flow gets affected when the mouths come in contact with an object. By monitoring the change in flow in real-time using a turbine flowmeter, it detects if the gripper comes in contact with an object. This sensor is also capable of identifying the dimensions of an object.

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Figure 5: Glowing Sucker Octopus Inspired Gripper by Wu et al (2022)(left) and Octopus Inspired Gripper made by Wu et al. (n.d.) (right)

Similarly, Wu et al. (n.d) developed another octopus-inspired disk-shaped gripper (Figure 5). Both of these grippers consist of a disk-shaped gripper surface with suction cups. However, instead of a bellow-type actuator extending and retracting the disk shape, this gripper consists of 6 arms that are embedded in the disk and bend to grasp an object. Furthermore, this gripper can detach from the robotic arm. Once detached, the six arms of the grippers allow it to perform underwater movements. As a result, the gripper can detach and move to access places underwater where the vehicle cannot go. However, this gripper cannot perform object detection, unlike the previous one.

Table 1. Characteristics of Soft Robotic Grippers Discussed.

Gripper	Actuation	Sensing	Gripping Force/ Object Weight	Weight	Diving Depth	Test Environment
Jamming Pad Grippers (Capalbo et al., 2022)	Closed Loop Fluid System	No	4500 g	-	-	Laboratory
Tata (Li et al., 2022)	Hydraulic Drive	Yes	2 kg	-	-	Laboratory
Self Folding Polyhedral Gripper (Teoh et al., 2018)	Motor Driven	No	-	-	11 km	Deep Sea Conditions
Glowing Sucker Octopus Inspired Gripper (Wu et al., 2022)	Pressurized Fluid	Yes	Suction - 100N/ Grasping Force - 30N	170 g	-	Laboratory
Octopus Inspired Gripper (Wu et al., n.d.)	Pressurised Fluid	No	3.8 N	1 kg	-	Laboratory (Tank)
Bidirectional Biomimetic Hand (H. Wang et al., 2022)	Pressurized Fluid	No	14.9 N	612 g	-	Laboratory
Modular Origami Soft Robot	Pressurized Fluid and Cable Driven (Huang et al., 2022)	Yes	320 g	-	-	Laboratory
Bellow or Boa Actuators (Galloway et al., 2016)	Pressurized Fluid	No	52.9 N	-	800 m	Sea Conditions
Wyss Ultragentle (Sinatra et al., 2019)	Pressurized Fluid	No	0.77 N	123 g	-	Laboratory

Table 1 presents the characteristics of the grippers discussed in this paper, including grasping force, actuation, weight, diving depth, and test environment. To provide a comparison, characteristics of the Bellow and Boa Actuators (Galloway et al., 2016) and Wyss Ultragentle gripper (Sinatra et al., 2019) have been provided. Data that was not available for certain grippers has been marked with a "-".

5. Tactile Sensors

While soft robotic end effectors offer higher compatibility with uncontrolled environments compared to conventional hard manipulators, oceanic exploration still has many challenges. Extreme underwater conditions, such as low camera vision, high pressure, moving water currents, and particulate dust, lead to decreased dimensional awareness and impede object recognition. As a result, precise control of soft robotic grippers is highly challenging. Tactile

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sensors can enhance sensing capabilities and dimensional awareness by providing a sense of touch to robots and delivering real-time feedback. This section will discuss various tactile sensing technologies, including triboelectric and iontronic tactile sensors.

Shahabi et al. (2023) developed an octopus-inspired suction cup with strain sensing for object recognition. The sensor morphologically resembles octopus suckers and is divided into two layers (Figure 6.1). The first layer consists of four microfluidic channels containing carbon grease. The second layer consists of a soft suction cup with radial grooves that help in adhesion. While the sensor can detect the direction and angle of contact, it cannot differentiate between different materials. The sensor can detect objects in both air and water; however, there is a difference between the trends of the data collected and analyzed by the machine learning model used because of the change in physical conditions in water.

One common principle on which several tactile sensors work is the piezoresistive effect. The piezoresistive effect is the change in electrical resistivity of a semiconductor because of mechanical deformation/ application of stress on the conductor (Hollander, Vick & Diesel, 1960). This effect is used to create various strain sensors and piezoresistive flex sensors. For example, Cross et al. (2022) created a waterproof multi-directional force sensor that uses piezoresistive flex sensors (Figure 6.2). The sensor consists of four Adafruit short flex sensors of length 17mm, placed inside a silicone-based hemisphere at an angle of 90 degrees from each other. The sensor can accurately detect forces up to 4N, produce repeatable data patterns, and estimate a localized force contact point. This sensor also showcases the successful use of low-cost components to create tactile force sensors capable of producing consistent and repeatable results.

Xu et al. (2022) have developed a triboelectric tactile sensor for underwater perception by mimicking a sea otter's leathery, granular textured palms (Figure 6.3). This tactile sensor is based on triboelectric nanogenerators and uses the linear relation between the output signal and parameters to sense the magnitude and contact area of the stimuli. This sensor comprises triboelectric sensing units, a flexible support, a fixed frame, an upper hatch cover, an O ring seal, and a flexible cover. The sensing surface consists of interlocked hills; these provide a localized and high-stress concentration near the receptors. As a result, the sensor can distinguish between normal and shear external loads and approximate the external simulation area (Xu et al., 2022).

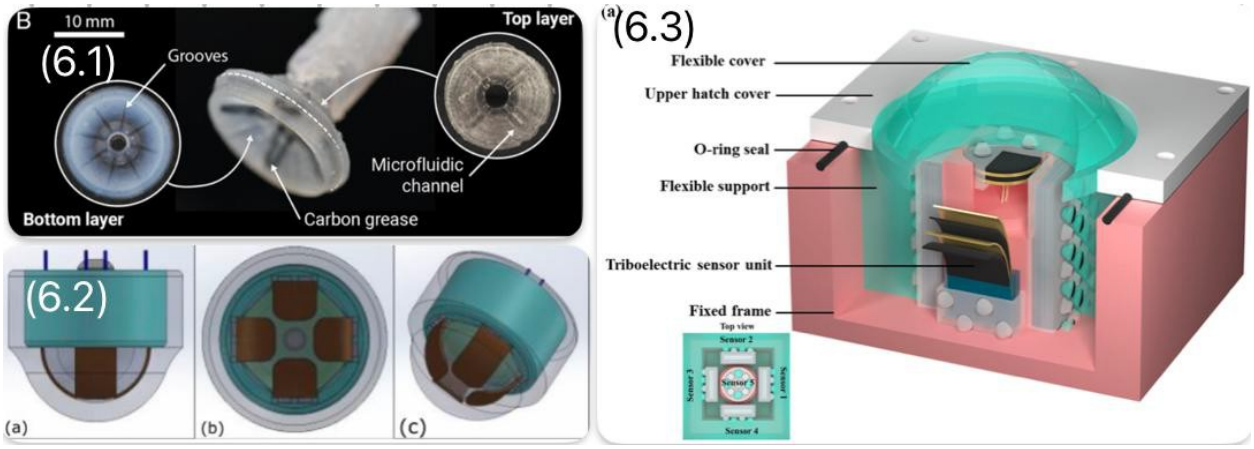

Figure 6. Tactile Sensors (Shahabi et al., 2023; Cross et al., 2022; Xu et al., 2022)

Many natural organisms use ionic carriers to sense their environments. Iontronic sensing, also known as supercar pacitive sensing, is a sensing mechanism that utilizes the supercapacitive nature of an electronic double layer (EDL) (Chang et al., 2021; Cheng et al., 2022). These iontronic skins offer high capacitive sensitivity and are used as alternatives to the technologies mentioned above. For example, Sun et al. have created a flexible, waterproof iontronic tactile sensor by taking inspiration from the bio-structure of a lotus (Sun et al., 2023). The tactile sensor has three layers: upper and lower layers made from fabric electrodes, and the middle layer consists of an ionogel electrolyte. In addition to these, it also consists of hydrophobic stearic acid micro-sheets on its outer surface. As a result of the super capacitive mechanism of the iontronic sensor, the tactile sensor has very high sensitivity. Testing done on the

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sensor shows that it can measure pressure up to 33kPa. Additionally, it is stable in a broad range of humidity, and its performance is not influenced by external temperature changes from 30-100 degrees Celsius.

6. Discussion

The grippers discussed earlier, like the jamming pad grippers (Li et al., 2022; Capalbo et al., 2022), the self-folding polyhedral gripper (Teoh et al., 2018), and the glowing sucker-inspired gripper (Wu et al., 2022), have simpler designs and actuation than previously developed grippers; this reduces grippers' complexity and makes their control easier; for example, the self-folding polyhedral gripper only uses one rotatory actuator.

Additionally, if the object's size is small enough, the self-folding polyhedral gripper can completely enclose the object (Teoh et al., 2018). This makes the gripper particularly suited for grasping extremely delicate samples of organisms such as jellyfish, squid, and coral polyps, as it can gently fold around the sample, shielding it from damage while being transported from the ocean floor to the surface for testing. Furthermore, this gripper enables a better grasp of granular objects compared to most other grippers reviewed in this study.

According to data in Table 1, the Jamming Pad gripper by Capalbo et al. (2022) and the Tata gripper (Li et al., 2022) can lift heavier objects compared to other grippers, indicating that the jamming pad allows higher grasping force and object weight. This makes them particularly useful for collecting heavier samples, such as rocks on the ocean bed or ceramic artifacts from shipwrecks.

However, these grippers cannot grasp multiple objects, unlike the bidirectional biomimetic gripper, whose fingers are bidirectional and capable of grasping objects on both sides, allowing the gripper to grasp multiple objects simultaneously (H. Wang et al., 2022). This capability can potentially reduce the resources required for collecting underwater samples, as multiple samples can be retrieved in a single trip of the underwater vehicle. For example, it can be used to collect fauna and sediment from the seabed simultaneously reducing the number of dives needed for multi-sample retrieval.

In grippers, such as the glowing sucker octopus-inspired gripper (Wu et al., 2022) and the Tata gripper created by Li et al. (2022), a trend has emerged of integrating sensing capabilities and force perception, enabling more precise actuation and control. Additionally, the tactile sensor in the Tata jamming pad gripper is also capable of object recognition, a feature lacking in the tactile sensors discussed in Section 6 of this review. This ability makes this gripper useful for applications such as leak detection in underwater pipes and valves. However, the payload volume of this gripper is lower than its alternatives, such as the Jamming pad gripper by Capalbo et al. (2022), which, with the help of its pincer-like design, can grasp any object that fits within its jaw opening of 25 cm.

The second octopus-inspired disk-shaped gripper (Wu et al., n.d.), which can detach from the robotic arm, allowing the gripper to access areas where the underwater vehicle cannot fit. For example, this could be beneficial when reaching into narrow crevices, coral reefs, or underwater cave systems to collect biological samples. Hence, while the gripper offers added mobility and range when detached, navigation and object detection become more challenging. Without precise localization and feedback, its control becomes challenging as it may struggle to identify objects and navigate while avoiding damage, reducing the utility of this mobility. Additionally, feedback helps in force control and delicate handling as grip force measure in real-time would allow firm gripping of samples like delicate jellyfish without crushing them.

Some tactile sensors, like the multidirection force sensors by Cross et al. (2022) and the octopus-inspired sensor by Shahabi et al. (2023), are capable of sensing the direction of the force or strain applied to them by the object, allowing for localization and mapping of objects for improved control. Their precision may be enhanced through fusion with technologies such as acoustic sensors. Additional scope for improvement may involve 3D mapping of objects and discerning the physical properties of materials (stiffness or hardness).

As bio-inspiration becomes an increasingly prevalent trend in grippers and sensors, the bio-inspired sensors discussed above, like the octopus-inspired suction cup strain sensor (Shahabi et al., 2023), the sea otter-inspired triboelectric sensor (Xu et al., 2022), and the lotus-inspired iontronic skin (Sun et al., 2023), provide scope for integration with soft robotic grippers that are also bio-inspired. For instance, the octopus-inspired suction cup strain sensor by Shahabi et al. is a promising candidate for future integration with artificial arms inspired by octopuses,

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such as the glowing sucker octopus-inspired soft robotic gripper by Wu et al. (2022).

While the studies discussed have some key advantages, several limitations exist, necessitating further development before these soft robotic grippers and tactile sensors can be applied on a large scale in real-life settings.

One limitation of several soft robots, like the origami modular gripper by Huang et al. (2022) and the octopus-inspired gripper by Wu et al. (n.d.), is that they are tethered. Tether tubes are small-sized fluidic tubes that power the pumps for pressurized deformation of the actuators. These tubes and valves often interfere with the robots and impact their actuation, especially during movements, and, hence, restrict the applications of the robot. Furthermore, these tubes can get damaged during application in an underwater environment because of various reasons, such as interactions with living organisms. Using untethered actuation systems can help increase the soft gripper's range of applications.

With the exception of a few grippers, such as the self-folding gripper by Teoh et al. (2018), most soft robotic grippers actuate with air or pressurized fluid controls. For example, the jamming pad grippers require vacuuming the air inside them to transition from a fluid-like state to a solid-like state (Li et al., 2022; Capalbo et al., 2022; Stanley, Gwilliam & Okamura, 2013), and fingered grippers like bellow and boa type actuators, soft origami gripper by Huang et al., and biomimetic soft robotic hand by Wang et al. use a pressurized fluid input (H. Wang et al., 2022; Huang et al., 2022; Galloway et al., 2016). Since these grippers are made from soft materials like silicone, they can be susceptible to cuts or other forms of environmental damage, which can lead to pressure leaks, reducing the gripper's functionality.

Soft robotic grippers and tactile sensors can be used for compliant, adaptive, and delicate grasping of objects underwater with precision. However, many of the grippers and sensors have not yet reached the stage for implementation in real life. They are not scalable due to their complex and difficult manufacturing processes, and require further development and testing before they can be used in extreme conditions at high depths underwater. As shown in Table 1, other than Self-Folding Polyhedral (Teoh et al., 2018) and bellow or boa actuators (Galloway et al., 2016), which were tested in sea conditions, most of the grippers discussed haven't only been tested in laboratory conditions; as a result, there is a need for further testing in conditions such as deep-sea environments to obtain a better evaluation of their functionality. For example, extreme pressure at high depths may limit actuation in grippers that use pressurized fluid and may also affect the sensing capabilities of tactile sensors. Hence, there is a need for further research, particularly experimentation, in order to gain insights such as the durability of the soft materials, their long-term performance in sea conditions, and compatibility with sensors. This would allow further development in the field to enhance their functionality and improve their implementation in real-life applications.

7. Conclusion

This review revealed that underwater soft robotic grippers are rapidly diversifying in both form and function, indicating a shift towards bio-inspired, modular, and sensor-integrated designs. Soft robotic grippers have various designs, ranging from jamming grippers (Capalbo et al., 2022; Li et al., 2022) to bidirectional biomimetic fingers (H. Wang et al., 2022) and polyhedral origami structures (Teoh et al., 2018). Each of which offers distinct advantages: for instance, the polyhedral gripper excels in enclosing delicate objects like jellyfish or coral polyps, the jamming-based grippers demonstrate superior strength for lifting heavier items from the ocean floor, and the octopus-inspired gripper is capable of grasping flat objects (Wu et al., 2022). Integration with tactile and force sensors—such as triboelectric, strain, and iontronic skins—would enhance their capabilities, allowing for more responsive and precise control in unpredictable aquatic conditions.

Real-world applications are beginning to emerge; However, real-life implementation still faces several limitations. Sensor-gripper integration often remains experimental, and while many designs show promise in isolated lab conditions or simulation, few studies evaluate their performance during extended underwater missions. This gap between prototype innovation and reliable real-world use represents a critical barrier.

Future research should emphasize robust field validation, not only to test system performance, but also to uncover more challenges and inform more effective, application-specific solutions

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