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A Bidirectional Soft Biomimetic Hand Driven by Water Hydraulic for Dexterous Underwater Grasping

Haihang Wang¹, He Xu¹, Fares J. Abu-Dakka², Ville Kyrki², Chen Yang¹, Xin Li¹, and Siqing Chen¹

Abstract—Soft robotics shows considerable promise for various underwater applications. Soft grippers as end-effectors are particularly useful for compliant and robust grasping compared to rigid mechanisms. In this work, we describe the design, fabrication and operation of a soft robotic hand driven by water hydraulics for underwater grasping. The proposed design has, in addition to the five fingers of a human hand, an extra soft thumb arranged symmetrically in an active soft palm. The soft fingers are designed with four chambers to enable bidirectional bending and deflection motions. We propose a novel elastic fiber reinforced structure to enhance and constrain the flexion movements of three palm actuators. The versatility of the underwater robotic hand is evaluated by implementing the human grasping gestures of the Feix taxonomy. Furthermore, we present a low-cost one-camera-multiple-mirrors imaging approach for capturing the grasps from multiple viewpoints simultaneously.

I. INTRODUCTION

Dexterity of the human hand is of tremendous importance for exploring and interacting with the world and a top design objective for robotic hands [1]. Collecting samples underwater is essential for ocean exploration but it is a challenging, dangerous and high-cost task for humans [2]. Considering the high risk and physical limitations the underwater environment poses for humans, underwater robots are in high demand. However, underwater end-effectors or grippers are typically made of simple but reliable rigid structures, which are often not suitable for robot-environment or human-robot interaction. On the other hand, soft robotics offers an alternative for underwater grasping [3].

Fluidic elastomer actuators provide particular advantages over rigid underwater actuators, owing to their flexibility, light weight, low cost, and waterproofing features inherently endowed by soft materials [4], [5]. Although soft robotics is a relatively young field, research on underwater soft grippers has recently obtained encouraging results [6], [7] and water hydraulic grippers have been proposed also for underwater robotic sample acquisition. Galloway *et al.* [8] developed two types of soft grippers for biological sampling on deep reefs and a soft manipulator actuated by water pressure [9]

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Fig. 1. Soft hand in underwater environment.

was proposed for underwater robotic sampling. However, the role of palm motions is commonly overlooked in the gripper design, which limits the gripper dexterity.

Bidirectional actuators that are capable of both inward and outward bending show potential on improving the grasping capability of grippers. Due to the challenging fabrication process of silicone-based actuators with high strength, manufacturing bidirectional actuators by 3D printing has been proposed [10], [11], [12]. However, this approach has the drawback that the elasticity and ductility of 3D printed materials are smaller than those of silicone rubber materials. Therefore, a 3D printed soft actuator generally requires a longer finger body to achieve a sufficient bending angle.

Human hand dexterity has provided numerous insights on design of robotic hands. Soft robotic hands with anthropomorphic design are emerging and being developed by researchers. Compared to joint-like bending motion with a small bend radius and a large bend range of human fingers, soft bending actuators lack the capability of controlling the angle of the fingertip. An opposable and flexible palm enables fingers with more grasping dexterity. To date, various designs of soft palms have been developed for dexterous grasping [13], [14], [15], [16]. However, compared with the multiple fingers cross/parallel design, the ring and little fingers in most existing anthropomorphic designs are usually redundant and unactuated during grasping. Furthermore, augmented functionality of human polydactyly [17] presents inspiration for the development of robotic hands with more than five fingers.

In this letter, we present a soft robotic hand that is

Fig. 2. (a) 3D drawings of the soft biomimetic hand (units in mm). (b) Biomimetic design inspired by human hands. (c) and (d) Soft hand conducting bidirectional grasping, which needs two human hands to achieve.

capable to simultaneously grasping objects both forwards and backwards in an underwater environment, as shown in Fig. 1. The proposed hand differs from our previous one [16] in e.g. bidirectional functionality, design and actuation (see Table I).

The main contributions of this paper are:

- A novel design of an underwater robotic hand for dexterous and bidirectional grasping.
- New modular designs of a soft robotic finger and a palm with high force capability.
- A new imaging method for observing the hand from multiple viewpoints simultaneously.

The hand comprises of six soft fingers and three palm actuators which all can be actuated independently. The underwater soft hand is driven by water hydraulics, which avoids compressibility difference between the outside and inside of the silicone body.

II. HAND DESIGN AND FABRICATION

A. Design of Soft Biomimetic Hand

The proposed soft hand in Fig. 2 is anthropomorphic in shape and size. Its dimensions are $193 \times 108 \times 28.5$ mm and weighs 0.612 kg. From the figure, the soft hand is capable of grasping two different objects bidirectionally, which would require two human hands to accomplish. The design extends the reachable volume and workspace of the hand.

The soft robotic hand is mainly made with silicone rubber material. The existing underwater soft grippers generally use a silicone with high hardness to resist high pressure and generate large output force, such as the bellows-type actuator [8] with Smooth-Sil 950 (Shore hardness of 50A) and the soft gripper [18] with Dragon Skin 30 (Shore hardness of 30A). However, their weakened performance on elongation at break (320% and 364%) causes an increased risk of damage. In this work, we propose to use Smooth-Sil 936 silicone (Smooth-On Inc.) with 36A Shore hardness and 500% elongation at break as a balanced choice.

B. Design of Bidirectional Fingers

The soft fingers use a symmetrical structure to achieve bidirectional bending. The fingers in Fig. 3 comprise four

chambers connected to four pressure inputs. The chambers can be divided to up and down actuator bladders, which cause bidirectional bending in normal and inverse direction. Moreover, the fingers can also achieve side-to-side deflection (perpendicular to the grasping axis) by actuating the same side chamber of up and down actuators. The deflection enables to grip a thin object between two adjacent fingers and to grip an object with a hole by inserting two fingers inside the hole.

The fingers use bellows-type bending actuators with a wall thickness of 2 mm, similar to the actuators presented in [8] and [19]. Compared to the bending actuators driven by the straining motion of the elastomer material, such as fiber-reinforced actuators developed in [20] and PneuFlex actuators used in RBO Hand 2 [13], the non-uniform inflation between neighboring bellow units of the bellows-type actuators generates smaller strain on the material and creates motions in volume instead of in length. They achieve the same bending angle at lower pressures. We use fiber-reinforcement to prevent excessive radial bulging of the elastomer chambers. This helps to improve the bending ability of the elastomer body. An auxiliary groove structure on the body surface of the finger guides the winding path of the fiber.

The fingers imitate the shape and size of human fingers, with short fingers as thumbs (Fig. 3(b)), medium length fingers as index and little fingers (top in Fig. 3(c)), and long fingers as middle and ring fingers (bottom in Fig. 3(c)). The finger lengths are respectively 79 mm, 85 mm and 93 mm. As shown in Fig. 3(c), the bidirectional finger consists of a modular fingertip, a silicone-based finger body, a rigid hub, inverted cone fittings and hard teflon tubes. To address the high working pressure of the fingers and the separate sealed chambers upon pressurization, the rigid hubs, 3D printed of nylon, are used for fluid connections, similar to the sealing strategy in [21]. Four threaded holes are tapped by a tap, and further fit with inverted cone fittings and hard teflon tubes.

C. Fabrication of Fingers

Figure 3(a) presents the fabrication process of the fingers. The molds were produced using 3D printer. A degassing process using a vacuum chamber and a pump is usually needed through the fabrication process. Fabrication techniques are based on the existing multi-stage molding for soft fingers [16]. The main novelty here is the new fabrication strategy on embedding the rigid hub within the soft body. Instead of inserting the hub into a prepared hole of silicone body, the rigid hub was firstly immersed in uncured liquid silicone. Then, the main finger body was inserted and placed upon the rigid hub. After fully cured, the rigid hub was integrated with the soft body. Nylon fishing line (red thread in the figure) was bound around the base of the finger to achieve the sealing connection. The yellow silicone markers in Fig. 3(b) are used for measuring the motion of the finger in action.

Fig. 3. Design and fabrication of the bidirectional fingers. (a) Fabrication steps. Step 1: Filling molds with liquid silicone. Step 2: Casting the bottom layer and winding the fiber reinforcements. Step 3: Integrating the two half bladders of the soft finger. A strain limiting layer (silkscreen fabric) is embedded between the two half bladders. Step 4: Inserting the end of the finger body into a mold with a rigid hub and filled with liquid silicone. Step 5: Demolding. Step 6: Fastening a sealing end and connecting the fingertip and markers. (b) Prototype of the soft finger. (c) Each soft finger is composed of a soft boy and fingertip, a rigid hub and inverted cone fittings.

Fig. 4. Design and prototypes of the soft palm. (a–b) Design of the soft active palm. (PA1: palm actuator 1; PA2: palm actuator 2; PA3: palm actuator 3.) (c) Using a crochet hook to knit the elastic fiber. (d) The major palm actuator module. (e) Modular palm actuator achieves palm bending and thumb abduction when pressurized.

D. Design of Palm

The proposed design uses fingers and palm collaboratively to achieve dexterous grasps, similar to a human hand. The soft palm consists of two parts (blue and red parts in Fig. 4(a) and (b)). The blue part is composed of two adjacent actuators (palm actuator 1 and 2), while palm actuator 3 (the

red part) is a smaller one. From the function perspective, the main novelty of the proposed hand design is the new bidirectional grasping function. Considering human palm movement, thumb opposition is the key movement of the human hand. Palm actuators 2 and 3, connected with the two thumbs, achieve bidirectional thumb opposition. In addition, palmar flexion, which decreases the angle between fingers and palm without bending the fingers, can help precision grasping. The flexion is achieved by Palm actuator 1 providing additional dexterity for the other four fingers. The soft palm has a biomimetic appearance. The lengths of the chambers are designed to be as long as possible to maximize the flexion performance. Pressure delivery strategy based on inverted cone fittings is also applied to the three palm actuators. The palm bending and thumb abduction motions are illustrated in Fig. 4(e).

To increase the strength of the compliant palm, we propose a novel actuation structure, called “elastic fiber reinforced structure”. Figure 5(a) shows the working principle of the proposed elastic fiber reinforced structure (in yellow) using a simplified model of the palm actuators. The elastic cord is made of outer high-quality fabric and an internal elastic core. Its diameter is 1 mm. When pressurized, the chambers are inflated, so that the elastic cord is also elongated. The elastic force F_E generated by the elastic cord will effectively counteract the radial extension of the chamber caused by pressure force F_P and cause negligible lateral bending. Simultaneously, the bulging of the chambers causes palm flexion as the strain of the bottom part is limited, while having only small impact on the cord elongation. By using the same fluid inside and outside the silicone chambers, the influence of the buoyancy can be ignored. Figure 5(b) presents the setups for testing the relationship between tensile length and elastic force. A bundle of elastic cords (7 cords with an original length of 30 mm) was tested using a universal testing machine. As shown in Fig. 5(c), the elastic force increases nonlinearly with increasing tensile length, with a relatively slow increase initially and a rapid increase

Fig. 5. Elastic fiber reinforced structure. (a) Working principle with a simplified model. (b) Test setup of the elasticity measurement of the cord and (c) its result.

after the tensile length exceeds 35 mm. The elongation of the elastic cord is limited by the outer fabric to avoid stretching it to more than twice of the original length. This characteristic is valuable as a safety measure to prevent unlimited inflation of the palm actuators. The cords were pre-tightened by 5–10 mm to obtain a suitable initial tension on the palm actuators.

E. Fabrication of Palm and Hand

The fabrication of the palm actuators and the assembly of the hand was guided by our previous fabrication process described in [16]. The blue and red parts of the soft palm were fabricated identically with each other. In addition to [16], the elastic fiber reinforcement was performed as follows: The elastic cords were arranged on the grid-shaped indentations on the palm surface, and shuttled through bottom layer as shown in Fig. 4(c) and (d). A crochet hook was used to help pull the cord. Then, the cords on the bottom were packaged inside silicone. Finally, the hand was assembled by attaching the modular fingers on the palm.

III. CHARACTERIZATION OF FINGERS AND HAND

A. Finger Characterization

The fingers achieve the bidirectional bending motion in the major grasping axis and bidirectional deflection in the side-to-side axis by applying actuation pressure to two adjacent chambers of the four actuator chambers. To measure the bending angle along the major grasping axis, the two upper chambers were actuated with identical pressure from 0 to 350 kPa. The resulting angle between the fingertip and finger base was measured from images. The results are shown in Fig. 6(a), which shows a linear relationship. As the pressure reaches 350 kPa, the bending angles are 248, 245 and 193 degrees, respectively. Burst pressures of the major grasping

Fig. 6. Characterization of finger bending performance. The variation of the (a) bending angle and (d) force generated by the long/middle/short fingers while applying pressure in grasping axis. The variation of the (b) bending angle and (e) force generated by the long/middle/short fingers while applying pressure in side-to-side deflection axis. (c) The experimental setup for force tests. The side deflection enables the underwater works of (f) gripping a metal spanner and (g) lifting a pipe adapter with a hole. (h) The force test of a ball grasped by index finger and thumb.

chambers were 380 kPa or higher, with variation due to deviations in the fabrication. Considering the results of the bending angle test and required grasping force, we chose 0 – 300 kPa as the nominal pressure range for experiments. The variation of bending angle and pressure for the three fingers with different lengths showed a similar increasing trend. The resulting average bending angle of deflection motion in Fig. 6(b) is around 90 degrees at the operating point of 300 kPa, which is sufficiently large for finger deflection.

Figure 6(c) shows the setups to evaluate the tip force exerted by the three soft fingers. The vertical force of blocked fingertips was measured while the chambers were actuated. During the test, water hydraulic pressure was increased from 0 to 350 kPa in steps of 25 kPa. The individual fingers

Fig. 7. Characterization of palm actuation performance. The palmar flexion is shown (a) at rest, (b) with actuation (200 kPa) in underwater. And the thumb opposition is shown (c) at rest, (d) with actuation (200 kPa) in underwater. The variation of the (e) flexion angle and (f) force generated by the palm actuators while applying pressure.

were fixed on a bench clamp, while one side clung to a rigid slab. The force on a fingertip was measured by a force meter. The results of the force along the grasping and side-to-side axes are shown in Fig. 6(d) and (e). The difference in the rising slopes between the three fingers is because the distance from the fingertips and the fixed base differs between the fingers. The maximum force in the grasping axis is 14.9 N with a pressure of 352 kPa, which is larger than the capability of most pneumatic actuators, due to the incompressibility of water. Compared with the finger flexion, both the bending angle and the output force of the deflection motion are smaller, which meets their design goals as main and auxiliary motions. The deflection motion of fingers enables some useful functions, as shown in Fig. 6(f) and (g). The gravitational forces after subtracting buoyant force were 1.1 N of the metal spanner and 2.1 N of the pipe adapter. Figure 6 presents the experimental setup, with a spherical object in grasp being pulled out from the hand by a force gauge. Under 250 kPa pressure, the maximum grasping force generated by the gripper assembly was 5.8 N (average over three trials).

B. Soft Palm Characterization

The human-inspired soft palm used in this study was tested to analyze its performance on palmar flexion and thumb abduction. As shown in Fig. 7, we recorded the change in angle as the pressure increases. The movements of both palmar flexion and thumb abduction by palm actuators 1 and 2 meet with the frequently-used bending range of human hand, while that of palm actuator 3 is relatively smaller. Benefiting from the elastic fiber reinforcement, the flexion rate decreases after the pressure reaches 150 kPa, whosing

TABLE I
COMPARISON OF THE RANGES OF MOTION (ROM) AND FORCE OF HUMAN HAND, THE NEW ROBOTIC HAND, AND THE PREVIOUS DESIGN ONE [16]

Finger		ROM [°]			Force [N]	
		Human	[16]	Proposed	[16]	Proposed
Thumb	IP		[0, 90]			
	MCP		[0, 70]	[0, 287]	1.23	14.9
	Abd/Add		[-40, 50]	[0, 37] [0, 35]/[0, 17]	2.90	12.8/7.1
Index	DIP		[0, 80]			
	PIP		[0, 120]	[0, 287]	1.23	10.4
	MCP		[0, 90]	[-245, 245]		
Middle	DIP		[0, 80]			
	PIP		[0, 120]	[0, 287]	1.23	8.9
	MCP		[0, 90]	[-248, 248]		
Ring	DIP		[0, 80]			
	PIP		[0, 120]	[0, 287]	1.23	8.9
	MCP		[0, 90]	[-248, 248]		
Little	DIP		[0, 80]			
	PIP		[0, 120]	[0, 287]	1.23	10.4
	MCP		[0, 90]	[-245, 245]		

that the actuator inflation is increasingly constrained in a safe and adequate range.

Fig. 8. Comparison of the 3D grasp workspace generated from fingertip trajectories during (a) normal, (b) bidirectional, and (c) contingency mode in failure grasps.

C. Comparison of Range of Motion and Force

In Table I, we summarize the ROM and force data of human hand¹, and the proposed hand recorded in the test of soft finger and palm above, as well as our previous design [16]. The proposed design can duplicate about 85% of the human hand ROMs. The maximum force generated

¹data from <https://www.verywellhealth.com/what-is-normal-range-of-motion-in-a-joint-3120361>

Fig. 9. The soft biomimetic hand successfully implemented all the 33 grasp types according to Feix taxonomy in underwater environment.

from each fingertip, as well as that of thumb adduction, is significantly higher compared to the earlier design. The results show that the proposed design has the potential to be used in various grasping tasks.

D. Analysis of Grasp Workspace

To analyze the grasp workspace, we consider the soft hand kinematics as consisting of constant curvature curves (soft bending sections) and lines (rigid parts) and compute the location of the fingertips in three-dimensional Cartesian space. A vector, $\mathbf{p}_{Fn}$, of the coordinates of the n^{th} fingertip is described in the base coordinate system at the origin of the hand, $\mathbf{p}_O$, as

$$\mathbf{p}_{Fi} = \mathbf{T}_{Fn} \mathbf{T}_{Pi} \mathbf{p}_O = \begin{bmatrix} \mathbf{R}_{Fn} & \mathbf{t}_{Fn} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R}_{Pi} & \mathbf{t}_{Pi} \\ 0 & 1 \end{bmatrix} \mathbf{p}_O \quad (1)$$

where $\mathbf{T}_{Pi}$ denotes the homogeneous transformation matrix from the base coordinate to the i^{th} palm actuator coordinates, and $\mathbf{T}_{Fn}$ denotes that from palm actuator coordinates to n^{th} fingertip coordinates. $\mathbf{R}$ is the rotation matrix and $\mathbf{t}$ is the translation vector. As a result, the workspace of the hand can be illustrated by the fingertip trajectories, as shown in Fig. 8, using the ROMs of the fingers and the palm from above.

Figure 8(a) shows the workspace resulting from finger and palm actuation in normal grasp, using five fingers. Actuating the secondary thumb and bending the ring and little fingers in reverse direction, the hand has a second workspace that enables grasping another object, as shown in Fig. 8(b). Compared to the normal grasp, the bidirectional grasp is an obvious extension to the single-direction workspace, although the palm actuator 1 is not actuated during reverse bending of fingers. As a contingency case, if some chambers of finger or palm are ruptured, the hand has an additional contingency grasp that is achieved by pressurizing the chambers on the other side of bidirectional fingers and palm actuator 3 to continue the task. The contingency grasp has a suitable

workspace (Fig. 8(c)) for most grasping tasks except some precision grasps.

IV. CHARACTERIZATION OF GRASPING PERFORMANCE

A. Experiment Setups

The water hydraulic pressure was driven by a universal water hydraulic system. In underwater settings, the hydraulic pressure needs to be matched with the ambient water pressure at the working depth, using e.g. a water compensation bladder. We focus on studying the grasping performance in laboratory environment such that the influence of buoyancy is negligible. Water flow into and out of the soft hand was controlled with the dedicated hydraulic valve console, with five proportional control valves and 27 solenoid valves. Five pressure sensors with a resolution of 0.1 kPa were used to measure the real-time pressure through five proportional valves.

B. Grasp Taxonomy

To evaluate the grasping performance of our soft biomimetic hand, we chose grasp types and objects based on the most comprehensive grasp taxonomy to date, the Feix taxonomy [22]. Feix taxonomy includes 33 grasp types, which is further developed based on the Cutkosky taxonomy [23]. It provides a common terminology to define and evaluate static grasps by human and robotic hands.

As shown in the results presented in Fig. 9, the soft hand successfully completed all 33 stationary grasp types based on Feix taxonomy benchmarks. The success was checked by gently moving the hand with object in water. The grasps were all stable and repeatable. Furthermore, the contingency grasp mode was also testified to implement both power grasp, such as larger diameter (#1) and power sphere (#11), and precision grasp, such as prismatic 2 finger (#8). The palmar flexion in the normal grasp mode enabled by the palm actuator 1 proves useful and essential role in achieving palmar pinch

Fig. 10. Using the bidirectional fingers and palm, our soft hand is able to implement bidirectional Feix grasps, in addition to the normal Feix grasps.

(#9), lateral (#16), extension type (#18). We achieved the inferior pincer (#33) with and without the help of the palm actuator 1 in both Fig. 9 and Fig. 10(e). The larger contact area with small ball in Fig. 9 benefits more stable grasping. The distal type (#19) is easy to accomplish the gesture which needs to statically hold a scissor. However, it is like a type of in-hand manipulation rather than grasping, and is challenging to employ the minor open and close motions by actuating the fingers in real tasks.

C. Bidirectional Grasps

We explored the utility of the bidirectional grasps by testing its performance on the gestures of Feix taxonomy using thumb and other one, two or three fingers. Fig. 10 presents four bidirectional grasping cases based on three normal Feix taxonomy as described above. Bidirectional Feix 31 + 31, 3 + 3, 33 + 33 and 14 + 33 grasps were achieved by actuating the fingers as the diagram. The blocks in red and blank in the diagram represent the corresponding chambers to be actuated. The palm actuator 2 and 3 were also pressurized to cooperate the thumb opposition. Beyond the four cases, there are more different actuation combinations for various objects and more potential applications in practice.

The images from front and side view cannot fully present the back condition of the bidirectional grasps. And the secondary thumb was blocked by the yellow bottle during the bidirectional grasps in Fig. 10(b) and (d). To comprehensively capture the hand motions during grasping task, we propose a novel imaging platform to capture the experimental images, which is developed from the one-camera-multiple-mirror imaging device in Ref. [24]. The major modification to the previous imaging method is that except for six side mirrors in previous method, one more mirror, noted as

Fig. 11. Capturing the bidirectional grasping motion using the one-camera-multiple-mirror imaging device (a) Setups. (b) Experimental images during bidirectional grasping experiment.

top mirror, was placed upon the observed the soft hand submerged in water tank to reflect the gesture in top view, as shown in Fig. 11(a). This transform the observation directions from two-dimensional plane into three-dimensional space. And the images from top view offer clear information of the bidirectional grasps. Using the reflection of the top and side mirrors placed around the observed space, the grasping videos from top, front, back, left and right views were collected by single camera. There is certainly no time difference, compared with the traditional method that applying five individual cameras or repeating the same works for five times. The imaging method using mirrors to replace cameras is a low-cost strategy, while getting totally synchronous hand motion videos.

The motion sequence of the bidirectional Feix 3+3 grasps was captured using the mirror system, as demonstrated in Fig. 12. The images were extracted from their original photographs, as the frame in Fig. 11(b). To avoid the object or human hand hide the fingers from view, the hand first finished the bidirectional grasp gesture without grasping object. Then, the two bottles were inserted and stably grasped by the hand.

V. CONCLUSIONS

In this letter, we reported a novel conceptional design of a soft robotic hand for bidirectional underwater grasping, using water hydraulic actuation, and providing compliant dexterity. The test results of the finger and palm actuators demonstrate their satisfactory ranges of motion and force capability, and the effectiveness of the novel type of elastic fiber reinforced structure. The extended workspace allows the hand to grasp an additional object and provides fault tolerance through the backward grasp in the case of faulty forward grasp. The hand successfully achieved all grasp type of the Feix taxonomy in underwater environment. The extra thumb and bidirectional fingers enable bidirectional grasping, as demonstrated by several typical bidirectional grasping cases. Additionally, we developed a one-camera-multiple-mirrors imaging system to measure the bidirectional grasping motions from multiple viewpoints simultaneously. This system offers great potential for applications that require capturing complex three-dimensional movements of soft robots.

Fig. 12. Experimental images of the underwater bidirectional grasps captured by one-camera-multiple-mirror imaging device. The full motion sequence can be found in the Supplementary Video.

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