A soft robotic gripper with neutrally buoyant jamming pads for gentle yet secure grasping of underwater objects

Cristian Enrico Capalbo, Damiano Tomaino, Fabio Bruno, Domenico Rizzo, Brennan Phillips, and Stephen Licht

Abstract

Delicate grasping of complex, diverse objects is a challenging task for underwater vehicles such as remotely operated vehicles (ROVs). A novel controllably compliant soft robotic underwater gripper is presented which uses two neutrally buoyant particle jamming pads to safely and securely grasp arbitrarily shaped objects, including fragile and/or massive targets. Antagonistic low-friction rolling diaphragm hydraulic cylinders are used to control the compliance of the jaw closure in order to passively limit the total force applied during approach; the antagonistic hydraulic cylinders also compensate for the volume reduction of the pads during the jamming process while still enabling rigid grasp during manipulation. Soft finger-like fiber-reinforced actuators are used to maintain the shape of pads without introducing rigid elements. Force limitation is demonstrated by the ability to pick up fragile objects without breakage, and to surround soft targets without excessive deformation of the object. We present the overall design, experimental setup, and in-water testing using a compact ROV-based hydraulic drive system. The resulting system has demonstrated capability for grasping a diverse range of objects that vary widely in terms of weight, size, and geometry, largely enabled by the hybrid design of soft grippers guiding jamming pads into optimal configurations.

Index Terms

Fiber-reinforced actuator, Jamming gripper, Low-friction hydraulic transmission, Remotely operated vehicle

I. Introduction

Robotic manipulators can already surpass human capabilities when tasks are well-defined and the environment is sufficiently controlled. However, safe and effective robotic manipulation of complex objects remains a difficult

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problem in unstructured environments. This problem is particular relevant to underwater applications, as remotely operated vehicles (ROVs) are often the only available technology for sampling objects during deep water archaeological, biological, and geologic sampling missions. The objects targeted may be positively, neutral, or negatively buoyant; flexible, brittle, or fragile; highly resilient or unable to sustain large point loading; rigid or highly deformable. The available grasp locations may be located far from the object center of mass and/or center of buoyancy on high aspect ratio or arbitrarily shaped objects. Furthermore, the operator of the gripper may not know the properties of the object prior to a grasping attempt.

The effort described in this paper is part of an emerging area of research focused on the radical redesign of underwater end effectors to introduce passively compliant and 'soft' components. The mechanical design of conventional deep sea manipulators is an area of robust commercial competition, and in the scientific literature there is increasing attention to autonomy and advanced sensing/control in manipulation tasks (see [1] for a recent overview). Among other advances, conventional manipulator and gripper hardware can be improved with advanced human-machine interaction to aid ROV pilots through augmented reality [2] and force and position feedback, e.g. as in [3].

Underwater soft robotic grippers have the potential to complement these improvements on conventional manipulator systems. As detailed in [4], research in soft robotic grippers in general has rapidly accelerated within the last decade, driven in part by the increased availability of rapid prototyping technologies for printing complex parts and molds. Two soft robotic technologies in particular have been previously demonstrated in deep water applications; particle jamming based grippers and fiber-reinforced fluidic elastomeric actuators (FEAs). Both technologies are driven by low pressure hydraulic actuation.

Particle jamming refers to the transition of a collection of granular particles from a deformable flowing mass to a hard conglomerate with the application of external pressure. A particle jamming gripper consists of a particle-filled flexible membrane which can conform to a target object in the soft state, and then effectuate the state transition in order to grasp it as a rigid tool [5]. Variations on this concept include the use of jamming elements on the contact points of mechanisms with moving links [6] and the use of jamming to stabilize soft arm mechanisms after large joint deformations are actuated [7]. Jamming grippers can be operated in the deep sea in ambient pressures exceeding one hundred atmospheres, installed on, and operated from, ROVs at depths in excess of 1000 m [8].

Since the particles are constrained only by the membrane until the gripper is jammed, large positive or negative weight leads to membrane deformation (either sagging downwards or ballooning upwards). Previous efforts with jamming grippers have generally mitigated the effect of this membrane deformation by grasping from above e.g. as in [9] or [5], or by using small pads such as finger tip pads [6], and using membranes that are slightly overfilled in order to maintain membrane shape. Overfilling to maintain shape is undesirable, however, as [8] suggests that underfilling a jamming gripper can significantly reduce object contact forces. However, approaching only from above severely limits the capabilities of the gripper in unstructured environments, and is not compatible with a pincer style grasp, motivating the need to identify readily available, pressure tolerant neutrally buoyant particles of sutiable geometry for use in jamming grippers.

Pioneering soft grippers in the 1990s were developed using FEAs, such as the four-fingered gripper developed by

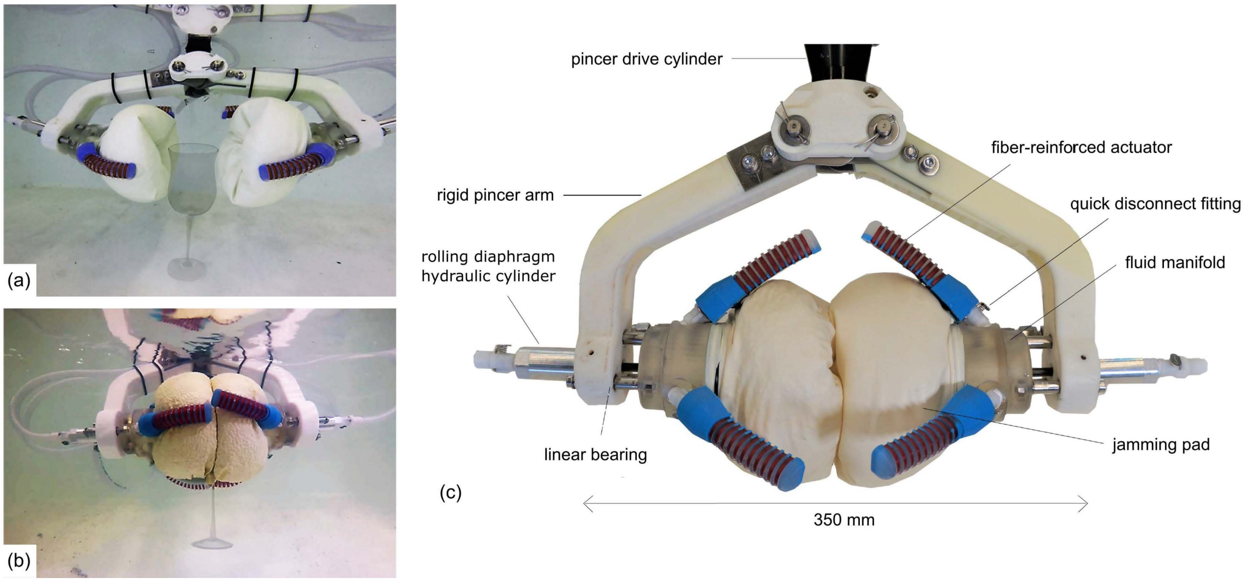

Fig. 1. Each half of the soft robotic gripper includes a neutrally buoyant jamming pad and three fiber reinforced fluidic elastomeric actuators mounted to a fluid manifold. (a) Unjammed pads during approach; (b) jammed pads for rigid grasp; (c) annotated image of gripper design

[10]. FEAs are actuated through pressure within a chamber constructed of deformable materials. Their structures are asymmetric and anisotropic, such that a volume change results in a bending or torquing of the whole actuator. 'Pneunets' bending FEAs fabricated using soft lithography have been successfully used to pick up a raw egg and even an anesthetized mouse ([11]). [16] presents the development of two types of FEA based underwater grippers to delicately manipulate and sample fragile species on a deep reef: a bellows-type soft actuator, and a boa-type fiber-reinforced actuator. The work was extended in [12] with a fully soft, fluid driven, multi-joint manipulator arm with a three finger hand deployed from a human piloted submarine.

This effort is a step towards our ultimate goal, which is to simplify the ROV operator's task when grasping complex, fragile or sensitive objects including biological samples and non-renewable cultural resources (i.e., artifacts). Critically, this approach does not add any additional control or sensing requirements, in order to avoid introducing new failure modes for deep-sea ROV manipulation systems.

II. Gripper Mechanism Requirements and Design Elements

The goal of this effort is to create an underwater gripper which can safely and securely grasp any object that fits within a jaw opening of approximately 25 cm. Controllable compliance through particle jamming is the underlying approach. The gripper prototype described in this paper (see Figure 1) further combines three fluid mechanical technologies to balance the competing requirements to first conform gently to arbitrary shapes, and then maintain strong rigid grasps with high strength during manipulation:

1) **A pair of neutrally buoyant 'jamming' pads are used to conform to arbitrarily shaped objects during jaw closure.** The use of neutrally buoyant particles eliminates deformation caused by gravity in the compliant (soft)

phase, regardless of how the gripper is oriented. This is a novel approach to jamming gripper construction, which we detail here in the literature for the first time.

2) **Antagonistic rolling diaphragm hydraulic cylinders are used to control the compliance of the jaw closure.** Low pressure hydraulics are used to transmit linear spring forces which press the pads on to the target as the jaw closes. Because a fluid transmission is used, it is possible to switch from series-elastic operation (i.e. with closing force proportional to jaw opening) and inelastic (i.e. rigid) operation simply by closing a fluid valve.
3) **Soft, finger-like, fiber-reinforced actuators replace rigid supports, reducing the risk of damage to fragile objects.** A variation of an open source design and manufacturing process is used to create six finger-like actuators to support the two jamming membranes without creating a pinch hazard, as would be the case with conventional jamming gripper supports.

A. *Neutrally buoyant jamming pads*

The main compliant elements of the underwater gripper are two jamming pads which act as the ‘palms’ of the gripper. The two gripper pads can be switched between soft (unjammed) and hard states (jammed) by moving water in and out of the membrane, which changes the pressure differential between the ambient external fluid and the interior of the membrane. In the unjammed state, the pads surround and conform to the object between them as the pincer jaws press them together. The jamming pads can then be jammed to ensure that the object is securely held in a rigid grasp.

The membranes are unmodified, uninflated latex balloons (Qualatex 30” Round). The neck of each balloon is stretched around the body of a cylindrical 3-D printed manifold. The neck is secured to the manifold with two Buna-N rings. The o-rings provide a pressure seal to separate the internal volume from the ambient external fluid. Water can flow in and out of the balloon from the manifold through a filter cut from stainless steel wire cloth with nominal 0.0015” square opening size (McMaster 85385T117) which covers the fluid port at end of the cylinder. The manifold was printed on a FormLabs Form2 stereolithography (SLA) printer, using proprietary FormLabs Clear Resin with 100% infill density to create an impermeable (at low pressure) part with fresh water and seawater resistance [13].

The ‘flattened sphere’ shape of the membrane is intended to provide a large contact area between the object and the gripper, while maximizing the gap between the jaws in the open position. The membrane shape is maintained by a small o-ring which is used as an elastic to hold the center of the balloon onto the end of a short piece of flexible rubber tubing. The rubber tubing is completely inside the membrane, with one end attached to a support at the center of the manifold filter. Rubber tubing is used rather than a rigid protrusion, which could make hard contact with the object to be grasped.

The media inside the jamming pads is a mixture of fresh water and 0.25 inch nominal diameter High Density Polyethylene (HDPE) pellets (Victory Pellets, Victory Plastic Inc.). The use of a liquid, rather than a gas, as the fluid media allows the operation of the gripper with a closed-loop fluid system; an incompressible fluid is necessary for

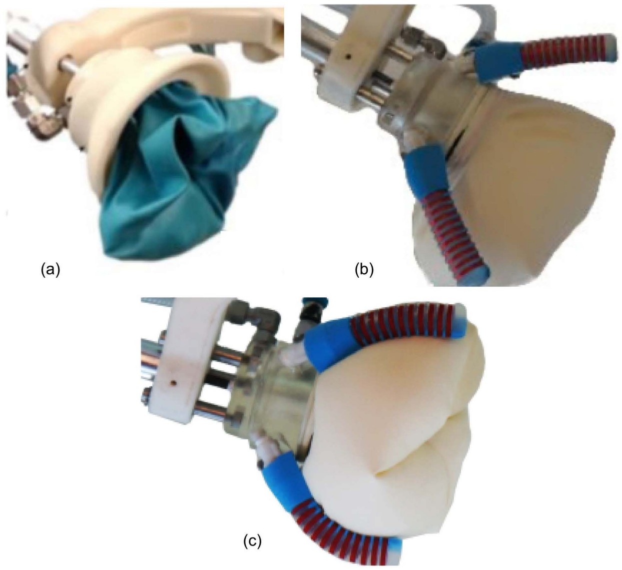

Fig. 2. Evolution of hybrid gripper design, comparing grippers with (a) rigid support cap, (b) deformation caused by negatively buoyant particles in unjammed state (c) neutrally buoyant particles in the unjammed state. The fiber reinforced actuators are pressurized in (c).

high-pressure applications since otherwise an extra reserve would be needed to compensate the volume reduction during operations at increasing water depths.

The HDPE beads are nearly neutrally buoyant in fresh water (within 5% of fluid density) which allows the gripper pads to maintain their desired shape even when the membrane is underfilled. The immediate benefit can be visualized by comparing the shape of the gripper in the water with near-neutral beads (Figure 2c) with a similar gripper morphology with negative particles (Figure 2b).

For this effort, the membrane is connected to one chamber of a water filled cylinder, which is actuated by a smaller bore cylinder driven by the hydraulic power unit that also drives the joints of the Hydrolek 5-DOF arm; for details of the fluid drive, which has also been used during at sea trials in water depths over 1000 m, see [8]. The overall gripper design is not sensitive to the means by which the low pressure water hydraulic system is powered, provided sufficient volume and pressure are available.

B. Antagonistic rolling diaphragms for passive application and limitation of compression force.

The pincer mechanism described here allows the two jamming pads to completely surround and even meet around the sides of target objects. However, when an underfilled jamming gripper transitions to the rigid state, the volume of the gripper can be significantly reduced. If the gripper support is stationary, the gripper pad will retract from the target object, and lose contact with the object. A continuous force on the pads is required to keep the gripper in contact. In vertical gripping tasks, a steady force on the pad can be supplied by the gripper's own weight, provided that the gripper is allowed to move freely on a vertical bearing [8]. In the pincer style grip, however, weight cannot be used as the driving force.

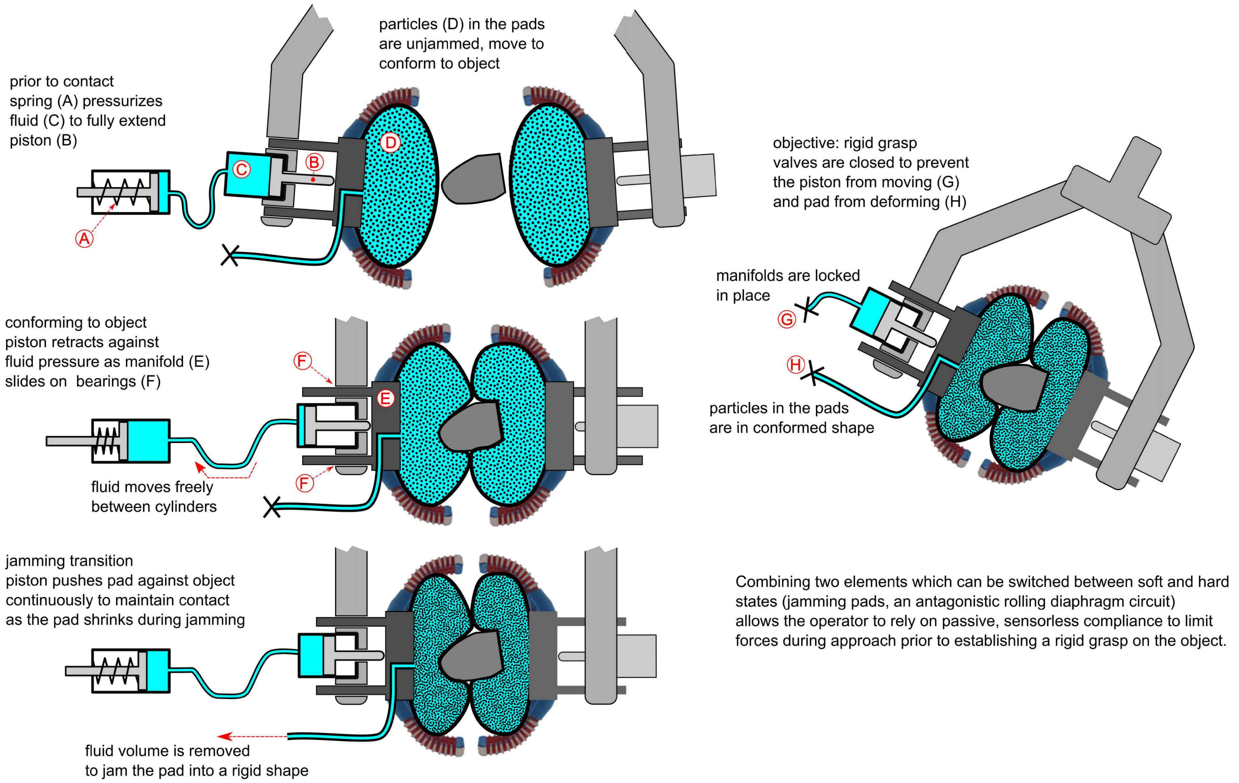

Fig. 3. Jamming pads and spring loaded antagonistic hydraulic cylinders combine to provide compliance during approach followed by rigid grasp.

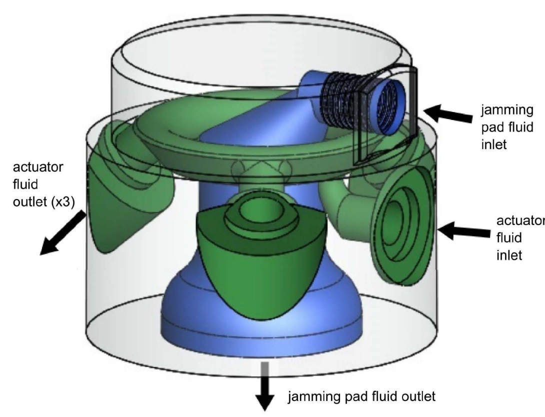

Fig. 4. The hydraulic manifold has two unconnected flow paths. The blue path directs water to the jamming pads. The green path directs water to all three actuators.

To supply a continuous inward force in arbitrary orientations, we implemented a lockable hydraulic spring system which uses pairs of antagonistic rolling diaphragm hydraulic cylinders. For each pad, two low-friction/zero-stiction rolling diaphragm hydraulic cylinders (ControlAir MiniMight 2) are used in a closed-circuit system filled with an incompressible fluid (fresh water), as in Figure 3. One of these cylinders is mounted on the end of each pincer, with the piston rod in contact with the back of the manifold. Extending this cylinder pushes the manifold inwards. The chamber of this cylinder is connected by way of a flexible tube to the chamber of a second cylinder, mounted in a convenient location away from the gripper apparatus. The second cylinder has an internal reaction spring which supplies a force on the piston in proportion to the piston position.

The pads can move relative to the pincer arms by sliding on linear rod bearings with a 2.5 cm range of motion. During approach and jamming, the pads are pushed towards one another (i.e. on to the target object) by the end of the piston rod. The cylinder is compressed, and the force exerted by the end of the piston rod results from fluid pressure within both cylinders. Both the fluid pressure and the resulting force are therefore proportional to the linear distance between the manifold and the pincer.

As the gripper pads shrink during jamming, the pistons extend, and the pads are continuously pressed together, thus maintaining contact with the object. Once the jamming process is complete, the fluid connection between in the antagonistic cylinders can be blocked by closing a valve. Blocking the flow between the cylinders locks the pistons and the two gripper pads in place. The low stiction of rolling diaphragm hydraulic cylinders makes then suitable for high fidelity transmission of forces at the scale of human grasping [14] [15] in the context of safe human-robot interactions and surgical robotics.

The use of antagonistic spring loaded hydraulic cylinders also introduces a passive force limitation mechanism into the system. Since the operator is able to visually monitor the travel of the manifolds on the linear bearings, they can guarantee that the total forces applied to the object is limited to the maximum spring compression force by ensuring that the hard stops on the piston position are not reached. This force limitation, which does not require additional sensing or control, is a significant secondary benefit; the soft fingers prevent direct contact between the object and rigid components around the periphery of the pads. However it is still possible for pinching between the rigid fluid manifolds to occur on objects that are wider than the minimum jaw separation, if the pistons are allowed to reach maximum travel (i.e to bottom out). Because the second piston can be located away from the gripper itself, the potential exists to measure position and applied force, and to apply additional controlled forces, without increasing the size or changing the shape of the end effector.

C. Finger-like soft actuators

Previous iterations of jamming grippers described in the literature for use both in air and underwater include a rigid cone as a backstop to force the gripper to conform to the objects of interest. While this approach could be used in a pincer style gripper (e.g. as in an earlier design iteration of this gripper seen in Figure 2a), it raises the possibility that the target object could be pinched between two hard components, negating one of the primary advantages of soft grippers.

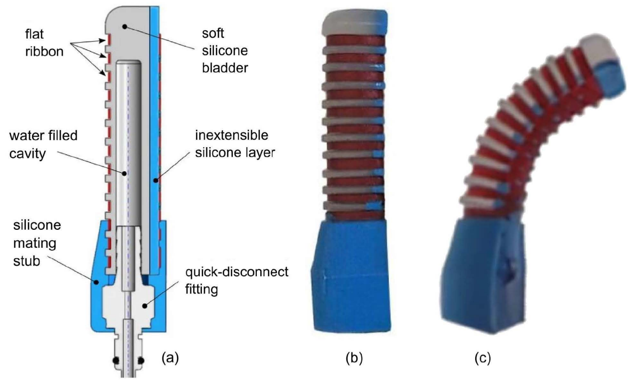

Fig. 5. The fiber-reinforced actuator bends as the volume of the internal water cavity increases when pressurized. (a) section view indicating cavity; (b) unpressurized; (c) internally pressurized, 70kPa above ambient

In this effort, we replaced the rigid cup with compliant, finger-like fiber-reinforced actuators. Fiber-reinforced actuators [4] consist of a flexible bladder with an inner cylindrical cavity. When the bladder is pressurized, it deforms in the axial and radial directions. An inextensible layer is applied on one side of the bladder in order to convert the axial deformation to bending. Radial deformation is limited by wrapping an inextensible fiber (in our case a flat ribbon) around the bladder. The manner in which the ribbon is wrapped dictates the bladder's bent shape when pressurized; a double coil of reinforcing ribbon promotes bending without twisting. These soft actuators were shown to be operable underwater in [16].

For the current effort, the fiber-reinforced actuators are used primarily as passive compliant elements which help to maintain the curved shape of the membrane. We anticipate future efforts in which the actuators will be used individually to actively shape the membranes to improve grasp quality, however in this effort they were always pressurized together to support the initially axisymmetric gripper shape. Three quick-disconnect fittings (self-closing on disconnect) are threaded into ports on the printed manifold. These ports are connected within the manifold; actuators can be connected or disconnected from the ports in any number or combination, but all connected actuators are either pressurized or depressurized at the same time.

The length of the actuators was chosen to enable the future use of half of the gripper as a modified universal gripper. In this mode of operation, a single pad could be pressed against an object resting in any orientation for conformal grapsing. For objects not resting on a sufficiently resilient substrate (e.g lying on or embedded in soft mud) the underfilled pad would be allow to conform to the object, and then be pressed against it from the sides by pressuring the fingers to make them curl inwards. As a result, the actuators were designed such that the ends would not extend past past the pads in the direction of the manifold axis even with the pads slightly compressed.

The soft actuator used in this effort (see detail in Figure 5) has a body made of two different silicone rubbers; the main body has a nominal Shore 40A hardness rating (Reynolds Advanced Materials Sorta-Clear 40), while the flat strain limiting layer which controls the actuator bending direction has a nominal Shore 50A hardness rating (Reynolds Advanced Materials Smooth-Sil 950) . A 1/8" wide cloth ribbon limits radial strain, both bulk (i.e. blowing up like a balloon) and concentrated (i.e. blowing out at a single point of failure). A male quick disconnect

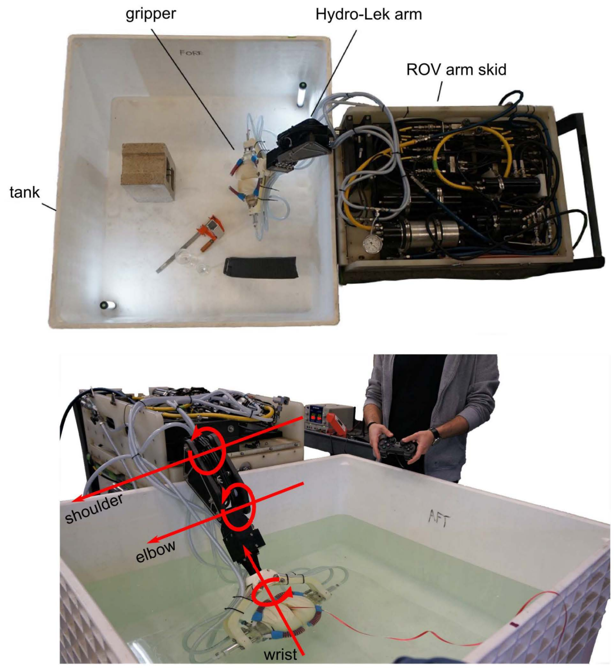

Fig. 6. Position of operator and ROV arm with respect to tank and targets. Rotational axes and direction of positive rotation of shoulder, elbow, and wrist joints are indicated.

connector (CPC PMCD 1/8" series) is embedded into a mating stub (Smooth-Sil 950, Shore 50A) at the open end of the actuator. Three matching female fittings are threaded into fluid ports on the gripper manifold (see Figure 4). Both male and female connectors include spring-loaded valves that shut off flow when the coupling is disconnected, allowing connection and disconnection of the actuator from the manifold without loss of fluid or introduction of air into the closed water hydraulic system.

D. Integration of jamming pads, actuated fingers, and fluid spring mechanism

A four valve solenoid acutated valve pack directs fluid transfer between the low pressure water hydraulic drive cylinder, the three fiber-reinforced actuators, and the jamming gripper pads. All flow is routed to the 3-D printed fluid manifold as shown in Figure 4. The first path directs fluid to the jamming membrane, and the second directs fluid to three soft finger actuators. Three evenly spaced fingers surround the membrane, inclined 40 degrees with respect to the manifold's axis.

III. Experimental Apparatus

We performed a series of qualitative in-water experiments to verify the range of objects that can be grasped using the actuated jamming approach described above. For testing purposes, we mounted the gripper apparatus to the end effector on a five-DOF hydraulic arm (Hydrolek HLK-43000) which is sized for integration with an inspection class ROV. The gripper jaws are driven by the short travel (28.8 mm) linear hydraulic cylinder on the end of the arm.

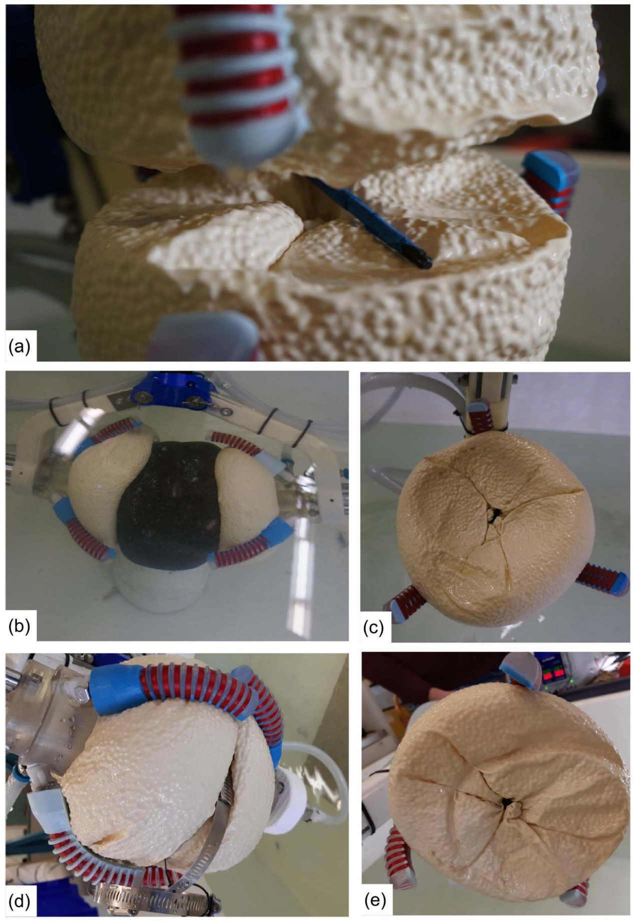

Fig. 7. Examples of grasping of objects with different shapes. (a) Gripper jaws opened after grasping a hex key tool. **Small** objects can be entirely surrounded by the gripper. **Heavy** objects can be lifted by the gripper in the jammed state. (b) 4.5kg solid rock lifted out of the water and held in air and (c) impression in the jammed gripper after jaw opening. The latex membrane is not inflated at any point, and hence is resistant to puncture by **sharp** objects. (d) Stainless steel hose clamp grasp and (e) impression left in jammed gripper.

The ROV arm was statically mounted to a platform next to 4’ square plastic shipping crate which was filled with fresh water to a depth of 1m. Thirteen objects with different geometries, materials, and in-water weights were manually placed inside the tank within the workspace of the manipulator, and in view of a submerged camera with a fish-eye lens (GoPro Hero Black).

The experimental apparatus and the operator control position are depicted in Figure 6. The operator controls individual joints, the main pincer, and the fluid flow to actuators and jamming pads through inputs to a hand-held video game controller while always having a clear view on the system; the speed of arm’s joints, jamming balloons and fingers are not proportionally controlled, i.e. all joint moves are on/off, with speed and acceleration determined by system pressure and preset fluid restrictor valves; unpredictable latencies of up to 250 ms exist. Given these limitations, the experimental approach was to control joint motion serially, rather than in parallel, i.e. all moves during grasping were accomplishing by moving one joint at a time until the desired position had been reached via visual inspection.

The objects were gripped and then moved using the following arm sequence: (a) elbow out rotation of up to 30 degrees in order to lift the object off the bottom of the tank; (b) wrist twist rotation to approximately +/-30 degrees from center, followed by a return to center, to demonstrate secure grasp under hydrodynamic and inertial forcing; (c) elbow out followed by shoulder out rotation until the arm is horizontal, in order to lift each object completely out of the tank and verify the gripping under the worst-case scenario of out-of-water weight of the objects. Maximum joint rates were set by manual adjustment of hydraulic limiting valves such that individual joint moves lasted less than 2 seconds for each rotation; joint rotational speed ranged between 150°/s and 180°/s. The gripper was then opened while still jammed to release the object. Joint and rotational axes are shown in Figure 6, and steps (a) and (b) are illustrated in Figure 9.

A wide range of objects with different dimensions, materials, strengths, and weights, were chosen for qualitative testing, as listed in Table I. The selection of target objects to allow comparison across different manipulators is a perennial problem in the soft robotics literature, as soft manipulators are generally intended to operate on arbitrary unstructured objects. In particular, there is no existing database of objects that spans the range of targets that might be encountered in an ocean exploration context. As a result, we attempted to select objects that span the widest range of interest in an ocean exploration context.

In particular we employed the gripper on objects smaller than the jamming pads, heavy and of similar size to the jamming pads, and with sharp points and metal edges which might be expected to puncture thin membranes (Figure 7); fragile enough to be destroyed by the hard pincers alone (Figure 8); slender and heavy, or bulky and irregular (Figure 9); easily deformable (Figure 10).

IV. Results

The operator was able to successfully grasp and recover each object included in Table I, provided that it was placed in a manner which afforded the pads the ability to close on them. Each object was lifted completely out of the water and held stationary such that the lowest point on the object cleared the water surface by up to 10 cm, as dictated by the limits of the arm actuators. While the altitude was not entirely uniform, this indicates that the gripper was able to support the full in-air weight. Small objects such as the hex key and the can be entirely surrounded and held inside the pads. Large round objects were cupped from either side by the pads, leaving distinct impressions in the jammed pads once the pincers were opened. Of note is the fact that, given a rock and a water balloon of similar sizes, the operator was able to execute different grasping strategies. It was possible to close the pincers completely on a heavy rock after jamming to maximize weight carrying capacity. By contrast, the pincers could be closed partially on the near-neutrally buoyant balloon, such that the compression force was limited to that provided by the springs in the antagonistic hydraulic cylinders. We note that the inclusion of an unusually large number of images in this work reflects our understanding that the primary contribution is in the qualitative assessment of the gripper capabilities.

In the grasping attempts illustrated here, the fiber-reinforced actuators were pressurized before approaching the object, essentially acting as a passive flexible limiter of the membrane movement. By observation, where the volume of the object sandwiched between the pads was relatively low, the three fingers were sufficient to preserve the axially

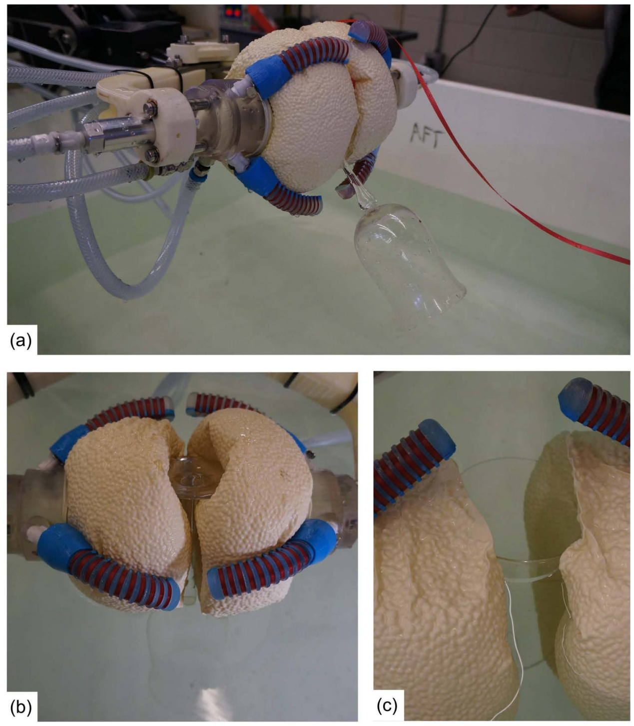

Fig. 8. **Fragile** objects can be grasped without force sensing or feedback. Wineglass, grasped by foot (a), stem (b) and bowl (c)

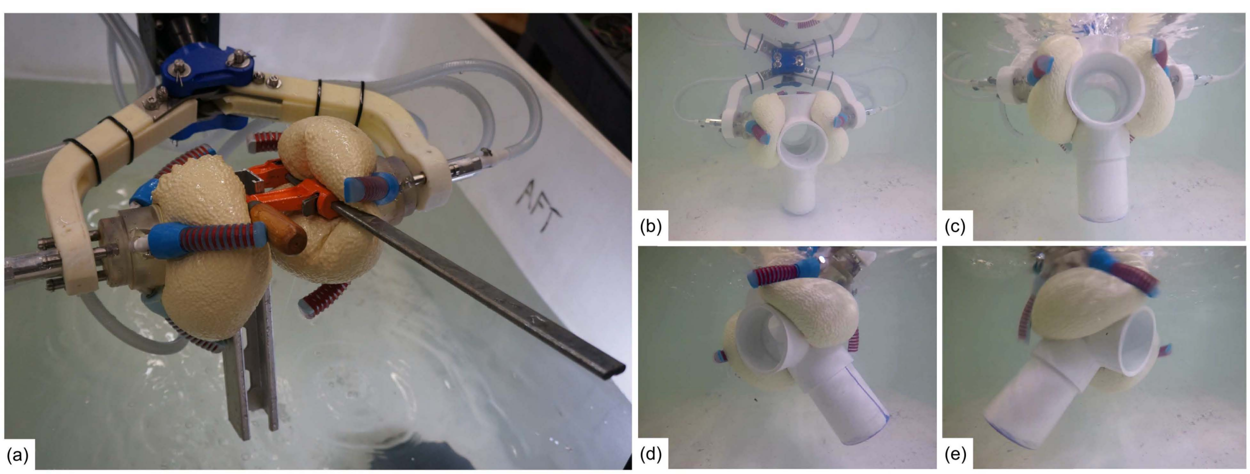

Fig. 9. (a) Large **irregular** objects can be grasped. Each object was grasped as in (b), lifted off the bottom (c), and rotated at least +/-30 degrees with the wrist (d)-(e) before being lifted out of the water.

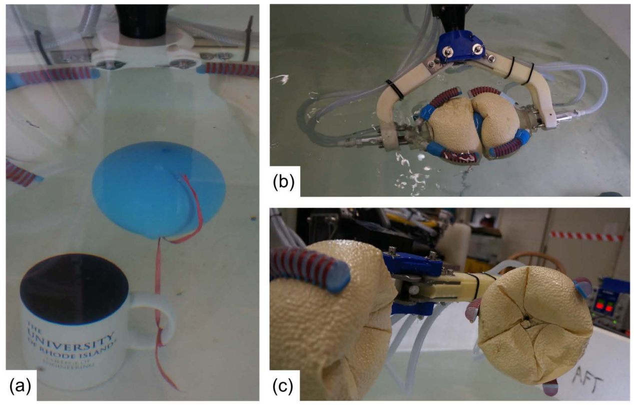

Fig. 10. The gripper can conform to **deformable** objects, and then support them in a rigid cradle; (a) water filled balloon, (b) lifted out of the water, and (c) the impression left in the gripper

TABLE I
TARGET OBJECT DETAILS

Object	Material	Weight	Dimensions	Image
wine glass	glass	100 g	20 cm long, 5 cm bowl diameter	Fig. 1,8
hose clamp	stainless steel	45 g	1 cm wide, 15 cm diameter	Fig. 7
round rock	stone	4500 g	20 cm diameter	Fig. 7
hex key	steel	5 g	8 cm long	Fig. 7
pipe coupling	PVC	2050 g	40 cm long, 13 cm diameter	Fig. 9
clamp/bar	steel	1725 g	12 cm width at grasp, 50 cm max length	Fig. 9
water balloon	latex (water filled)	525 g	10 cm diameter	Fig. 10

symmetric shape against both hydrodynamic and the limited hydrostatic (i.e. buoyancy) forces. For larger, more complex objects, the fingers had the effect of folding the membrane around the target, and served as an additional passively compliant element maintaining contact between the membrane and the target throughout the grasping process. Figures 9(b)-(e) provide an example of this effect, showing the gripper shaped around a large diameter PVC pipe coupling.

Quantitative assessment and verification of these effects will be a necessary component of any future actuator design and optimization efforts.

V. Conclusions and Future Work

In this paper, we describe a soft robotic gripper that combines neutrally buoyant jamming pads with passively compliant support structures.

The resulting system can securely grasp objects with a wide range of weights, sizes, and geometries. The grasps are achieved while passively limiting applied force, as demonstrated qualitatively by the ability to pick up fragile objects without breakage, and to surround soft targets without excessive deformation. Mechanical innovations that allow grasping of arbitrary unstructured targets include the use of neutrally buoyant particles in the jamming gripper pads; of pairs of low-friction rolling diaphragm hydraulic cylinders, which supply linear forces that can be switched between elastic and rigid modes; and of pressurized fiber-reinforced actuators to maintain the membrane shape in the unjammed state.

We believe the novel design has specific applications that are of value independent of its direct comparison of grip force with other soft actuation strategies, and that this effort provides significant qualitative design insights through extensive examples. However, it is important to note that further research efforts should include quantification of total force, and distribution of force, applied to the target objects,

Operational tests on ROVs, in both shallow and deep water, are required to demonstrate the applicability of the method in the field; the effect of partial view occlusion of gripper and target in particular must be tested in practical application. Mechanical improvements prior to these tests will include the development of more compact fluid manifolds to improve usability, and pincer arms with internal hydraulic lines to reduce the potential for snagging and increase robustness. Based on the prior success of the relevant technologies in underwater deployments, we believe that no fundamental design changes will be required in moving from tank to open water testing at ocean depths and in salt water.

We anticipate that gripper performance can be further improved, and possibly extended to grasp of objects resting on surfaces, through optimization of the 'finger' morphology which will enable the fiber-reinforced actuators to take a more active role in reshaping the membrane before and after contact with different targets.

Finally, we believe that the demonstration of effective particle jamming with neutrally buoyant particles has wider implications for soft robotics underwater, as it has the potential to enable much larger scale controllably compliant structures.

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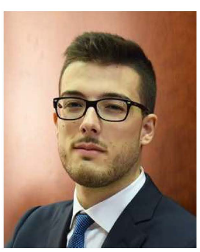

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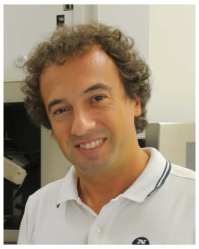

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