applied sciences

MDPI

Article

Soft Gripper Design and Fabrication for Underwater Grasping

David Herrero-Pérez [1] **and Humberto Martínez-Barberá** [2,*]

[1] Technical School of Industrial Engineering, Technical University of Cartagena, 30202 Cartagena, Spain
[2] Faculty of Computer Science, University of Murcia, 30100 Murcia, Spain
* Correspondence: humberto@um.es

Abstract: Underwater manipulation with current robotics technology is a challenging task with significant limits in versatility and robustness terms. Such functionality has tremendous potential covering a broad spectrum of applications, mainly replacing divers performing hazardous jobs. Soft robotics provides an efficient solution for operating in these scenarios and adapting to uncertain environmental conditions. This paper presents the design and fabrication of a simple, low-cost, and easily deployable soft gripper for underwater manipulation. We use modelling and simulation techniques for designing the soft fluidic elastomer actuators that compose the soft gripper and additive manufacturing techniques for rapid test cycles and validation. These techniques allow for a fast redesign depending on the application requirements. The proposal combines materials and fabrication techniques to take advantage of their strengths. We validate the feasibility and ability of the proposed soft gripper in a challenging underwater scenario using a subaquatic vehicle.

Keywords: soft gripper; underwater grasping; additive manufacturing; Remote Operated Vehicles (ROVs)

Citation: Herrero-Pérez, D.; Martínez-Barberá, H. Soft Gripper Design and Fabrication for Underwater Grasping. *Appl. Sci.* **2022**, *12*, 10694. https://doi.org/10.3390/app122110694

Academic Editors: Vladan Papić and Josip Musić

Received: 26 September 2022
Accepted: 11 October 2022
Published: 22 October 2022

1. Introduction

Current underwater technology permits accessing traditionally dangerous environments for divers using Atmospheric Diving Suits (ADSs), Remotely Operated Vehicles (ROVs), and Autonomous Underwater Vehicles (AUVs) [1,2]. However, underwater manipulation using these systems has shown limited manipulation abilities in versatility and robustness terms, principally operating with soft or fragile objects and organisms. Using rigid claw-like end-effectors [3,4] is quite common for performing easy and heavy mechanical works, such as wrist-rotation movements in construction or pipeline maintenance.

Most advanced end-effectors use sophisticated force/torque sensors [5–8] to close the control loop, minimizing damage and stabilizing the grasping operation. However, these end-effectors may not be suitable for complex underwater manipulation with different sources of uncertainty, such as currents in seawater, soft materials with large deformations, and delicate objects that require adapting to the geometry in the manipulation by distributing the grasping forces. Some examples of challenging underwater manipulation are underwater archeological recovery, biological sampling [1], and removal of dead fish in fish farms, to name but a few.

Using soft materials rather than conventional metallic ones and strong polymers permits us to mimic the behavior of natural systems. The compliance of soft actuators adapts them to a diversity of shapes with simple control schemes, avoiding the need for modeling and controlling such soft nonlinear continuum actuators. This fact provides a key advantage over stiff systems in grasping and manipulating unknown objects. Since the early work of Suzumori et al. [9,10] designing a soft gripper composed of fingers with elastomeric chambers hydraulically actuated and permitting bending with multiple degrees of freedom, several soft devices for grasping and manipulation purposes have been developed. Soft robotics hands [11,12] and grippers [13–15] allow us to manipulate delicate and complex objects by conforming to the object's shape and distributing the forces in the grasping operation. This adaptation allows us to perform such tasks without precise positioning or using accurate geometric models of the object to grasp [16]. These soft devices must even interact with humans using materials with a module similar, in terms of rigidity, to that of soft biological materials [17].

Underactuated adaptive soft actuators and transmissions [18] and robotic hands [1] have shown to be effective in underwater grasping operations by load-sharing passively among combinations of soft actuators inspired by phalanges and fingers. However, manipulating complex objects and organisms often requires modifying or redesigning the soft actuator [19]. For this reason, we need suitable tools to accelerate the design and fabrication cycle. Additive manufacturing and Computer-Aided Design (CAD) tools allow us to accelerate such cycles. Another crucial aspect of underwater manipulation systems is the power source, which can restrict the feasibility and autonomy in certain conditions. Submarine manipulation systems using soft fluidic elastomer actuators [20] usually require a hydraulic system to operate in a wide depth working range [21,22].

In this work, we present the design and fabrication of a simple, low-cost, and easily deployable soft gripper for underwater manipulation, which can be deployed in a small underwater vehicle, with little buoyancy reserve. This implies that the additional weight that can be carried from bottom to surface is relatively small. The target application is the recollection of small objects or living organisms (coral, seaweed, mollusks, etc.). The proposal combines materials in the design and fabrication of the soft fluidic actuators composing the soft gripper. The underlying idea is to combine flexible thermoplastics with a softer material. The former allows us to exploit the rapid prototyping techniques provided by additive manufacturing, whereas the latter permits us to increase the compliance and adaptability for manipulating unknown objects in uncertain conditions. This combination aims to take advantage of the strengths of both materials. Softer materials increase the underactuation in the manipulation, whereas hardened materials allow us to increment the force applied by the soft actuator and often show more robust mechanical properties. We also deal with the design and control of the power source for actuating the soft gripper, which can restrict the feasibility and autonomy of the underwater vehicles incorporating this device.

We organize the manuscript as follows. We devote Section 2 to reviewing and discussing the materials and the fabrication process used for developing soft fluidic actuators. Section 3 presents the modeling and simulation techniques employed for designing and developing soft fluidic actuators. It also describes the fabrication process used for manufacturing such actuator devices. Section 4 presents the proposed low-cost and easily deployable soft gripper, including the control system for manipulating delicate objects in underwater environments. Section 5 shows the experimental results validating the proposal, and finally, Section 6 presents the conclusion.

2. Materials and Fabrication Process

The use of flexible materials in the actuator design allows us to create underactuated devices which are highly adaptive for interactions. We usually do this by exploiting the adaptability and compliance of soft structures, allowing safe interaction with delicate objects and the environment. However, using materials with excessive softness can compromise other crucial skills, such as precision and the ability to apply significant forces. We also should consider some constraints and challenges using soft materials, such as non-linear response, fatigue performance, and potential manufacturing limits, to name but a few. There is a continuous spectrum of choices between soft and rigid materials, and the optimum selection along this scale will allow us to achieve the desired functionality of the specific application. Hence, the selection of material, actuation method, and manufacturing technique are of paramount importance in the design and development of soft manipulators, compromising the functionalities of the final design [23].

Figure 1 shows an overview of four quantitative properties according to the choice of materials in the gripper design. It shows the conflicting relationship between such quantitative properties. In particular, we reduce the ability to apply forces by increasing compliance.

In addition, we reduce the accuracy of the grasping maneuver by increasing the degrees of freedom of the underactuation of the gripper design. The figure shows a classical rigid robotic hand as an example of a controllable end-effector allowing us to perform precise maneuvers applying high forces. The soft tentacle-type design can adapt and interact in an underwater environment, but this underactuated design is highly uncontrollable and has a reduced ability to apply strong forces. However, the compliance offered by soft manipulators usually overcomes the need for precise control, at least in grasping operations. In any case, the payload of the soft gripper is a critical factor for real-world applications. Human hands lie on the diagonal line of the design space shown in Figure 1, which describes the quantitative properties of actuators depending on their stiffness [23]. The "hybrid" soft-rigid design concept is studied on locomotion problems [24], showing promising results for the successful soft-rigid design of human-inspired robotics hands.

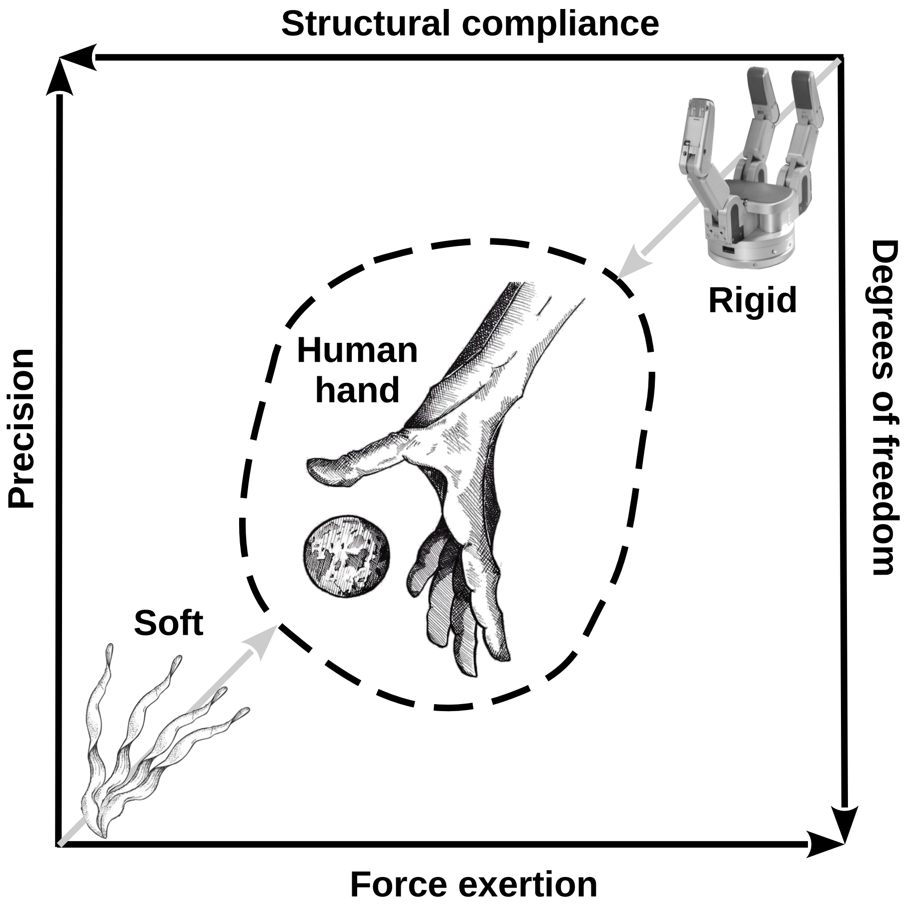


Figure 1. Dependence between the rigidity/softness properties of materials and quantitative functionalities of soft actuators (Reprinted/adapted with permission from Ref. [23]).

Thus, we have to find a tradeoff between conflicting design variables that make nontrivial the soft-gripper design problem. The proper choice of such variables requires not only the selection of materials and manufacturing process but also some issues related to operability and maintenance factors. Among others, we can mention the manufacturing complexity, the strain requirements to prevent damage and failures, and the actuation needed to provide functionality as factors to consider.

The most popular materials for manufacturing soft fluidic elastomer actuators are silicone rubbers and flexible thermoplastics. The former usually uses mold-based production processes for fabrication, which enable relatively complex designs and reproducible properties. The latter can use additive manufacturing technology to fabricate very complex shapes or geometries with high precision and repeatability. The process consists of depositing fused material in layers, the so-called Fused Deposition Modeling (FDM) technique.

Using two-component liquid silicone rubbers facilitates the mold-based fabrication process because we only have to mix the two liquid compounds for curing the silicone rubber in the mold. We can mention KE-1603-A-B [25], Sylgard 184 [26], and EcoFlex 00-30 [27] from Smooth-on Inc. We can use excimer lamps to cast and bond parts fabricated in different molds by surface activation technology [25]. However, complex designs require using other techniques, such as stereo-lithography in early works for manufacturing micro-actuators of resin with shapes that are difficult to fabricate by molding [28].

Additive manufacturing technology allows us to perform rapid prototyping with thermoplastic materials. One of the more popular flexible materials for 3D printing is Thermoplastic Polyurethane (TPU), which offers the mechanical performance characteristics of rubber, but we can process it as a thermoplastic. This elastomer provides high elasticity and abrasion resistance, making it suitable for several applications. However, this type of material exhibits nonlinear hyperelastic behavior with strong hysteresis, time dependence, and cyclic softening, which makes complex the modeling and simulation of the deformation behavior of such material [29].

The main advantages of actuators fabricated with silicone rubbers are that they are robust to impact and blunt collisions and are not affected by dirt, dust, or liquids. They inherently increase the underactuation in the contact by adapting to the geometry during the manipulation and distributing grasping forces. Soft elastomer actuators made of silicone with embedded fluidic channels have demonstrated impressive adaptability [30]. However, they can easily be cut or pierced, and the application of significant forces requires large deformations limited by the maximum strain of the silicone to prevent damage and failures. We usually have to embed the silicone rubber with inelastic fabric or hard materials to make the actuator bend around such a stiff material. Using fibers or threads is also needed to stabilize the actuator cross-section in the bending [31].

On the other hand, using flexible thermoplastics enables us to use additive manufacturing tools, including rapid design tools and fabrication recipes for low-cost manufacturing. The mechanical properties of these thermoplastics allow us to increase the force applied with much less strain than the silicone rubber's counterpart. In addition, the actuators using thermoplastic do not require reinforcing some parts with fibers, threads, or hard materials to force the bending, which facilitates the manufacturing and maintenance of the device. We have diverse commercially available TPU materials with different Shore hardnesses. We can find the characterization and comparison of 70A, 82A, 85A, 90A, 95A, and 98A TPU materials manufactured using FDM in [32]. This characterization shows the tensile test up to the point of fracture, detailing the elongation at such a point and Young's modulus after the printing. This work reveals that the Shore hardness slightly decreases after the printing concerning the one provided by the supplier. We selected the TPU 95A due to the Shore hardness required for exerting the force, and the maximum elongation (262%) satisfies the application requirements. We also take Young's modulus $E = 34$ MPa obtained from such a characterization to simulate the behavior of the TPU material after printing using FDM.

Another thing to consider is the shelf life of some properties of flexible thermoplastics. The principal mode of deterioration of polyester-based TPU material is slow hydrolysis, but polyether- and polycarbonate-based TPUs show better resistance to this problem. A secondary cause of damage is oxidation due to ozone exposure or other oxidative agents staining the material. A possible solution is to sterilize it using some coating. We also have to remark that the TPU has good resistance to radiation, which contributes to extending the service life. In any case, these flexible thermoplastics are extremely flexible and durable. They are also easily printable with high accuracy and repeatability.

For these reasons, we combine the use of flexible thermoplastic and silicone rubbers to take advantage of the properties of both materials and fabrication processes. Using flexible thermoplastic with additive manufacturing allows us to use the tools available for this technology, such as parametric CAD design, rapid prototyping, and robust mechanical properties, simplifying the fabrication and maintenance. In addition, we can increase the underactuation in the grasping and protect the thermoplastic from damage and abrasions using silicone rubbers. In particular, we use the flexible thermoplastic TPU 95A and the two-component liquid silicone rubber EcoFlex 00-30 from Smooth-on Inc.

3. Soft Fluidic Actuator

We use nonlinear finite element analysis to model and simulate the behavior of parameterized fluidic elastomer actuator designs. We can check that the model satisfies the actuation requirements using simulation techniques. Once we find a set of parameters defining a model that achieves the design requirements using simulation techniques, such a design is fabricated, validated, and characterized to use this information to develop the soft gripper.

3.1. Actuator Design

The design of the soft fluidic actuator consists of finding the parameters of a parameterized geometry that allow us to bend the actuator within a given range of maximum displacements avoiding twisting. We can combine these devices to design a gripper to perform grasping operations. We show the parameterized CAD model in Figure 2 and the description of each parameter in Table 1. The actuator has multiple, separated chambers in the monolithic structure, similar to the configuration reported by the early work of Ogura et al. [25]. Such an actuator can bend using the difference in extension quantity of chambers caused by applying internal pressure. Since we fill the channel using a fluid, the walls will not be traction-free but are subject to pneumatic/hydrostatic pressure. The parametric variables allow us to modify the geometry and constraints that permit both to bend it by applying internal pressure and recovery to the initial geometry without using threads and fibers. In particular, the internal pressure increases the cavity of chambers bending around the support, which is in charge of recovery to the initial geometry after stopping the internal pressure. The parametric design allows us to explore the design space by varying the parametric variables, which modify the shape and size of the soft actuator, the shape and size of the chamber, the stiffness of the passive layer, and the maximum strain of the flexible thermoplastic. All these design parameters modify the stiffness and bending behavior and limit the range of actuation of the soft actuator [31].

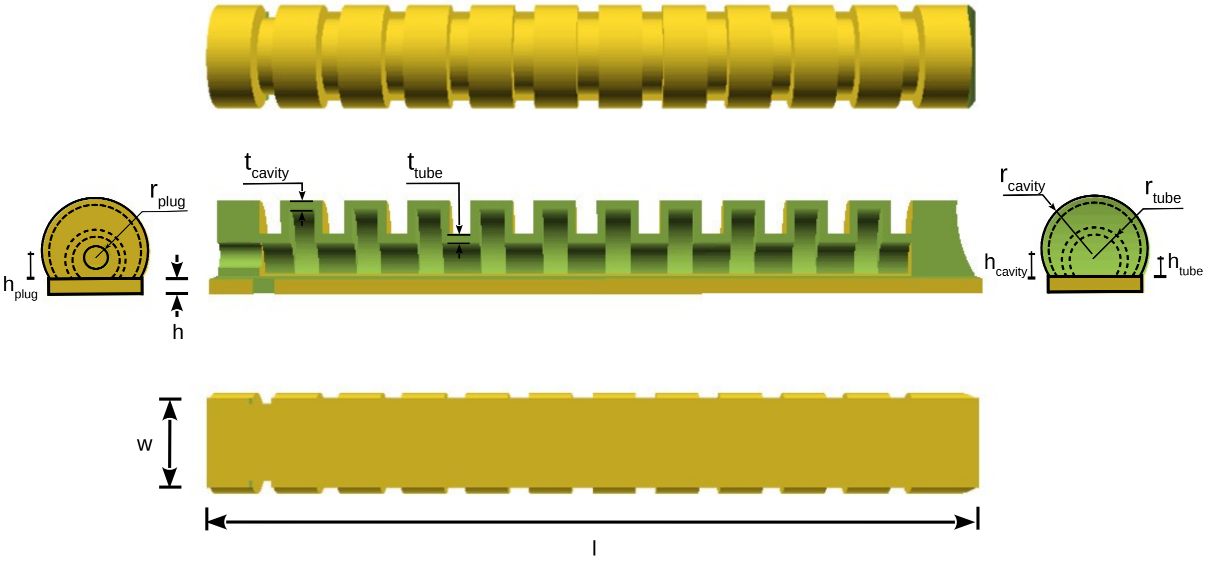


Figure 2. Parametric soft actuator design.

Table 1. Selection of parameters for the soft actuator detailed in Figure 2.

Parameter	**Description**	**Value**
l	Length of the actuator	90 mm
w	Width of the actuator	10 mm
h	Height of the actuator	1.75 mm
h_{cavity}	Height of the center of cavity	5 mm
h_{tube}	Height of the center of internal cavity	2.5 mm
h_{plug}	Height of the hole's center to pressurize the actuator	2.5 mm
t_{cavity}	Thickness of the cavity	1 mm
t_{tube}	Thickness of the internal cavity	1 mm
r_{cavity}	External radious of the cavity	6 mm
r_{tube}	External radious of the internal cavity	4.5 mm
r_{plug}	External radious of the hole to pressurize the actuator	1.75 mm

We aim to find a combination of parameters that provide a design able to withstand higher-actuation pressures and hence apply larger forces. In addition, we do not require a soft actuator with high extensibility and flexibility, which can induce damage and failures. Figure 3 shows the flowchart of the recursive process to determine the set of parameters defining the soft fluidic actuator. We implement the parameterized CAD model using OpenSCAD, a multi-platform and free software focusing on 3D CAD modeling. It works using a script file for the parameterized definition of the design. We start the design using a random set of parameters providing a feasible CAD model.

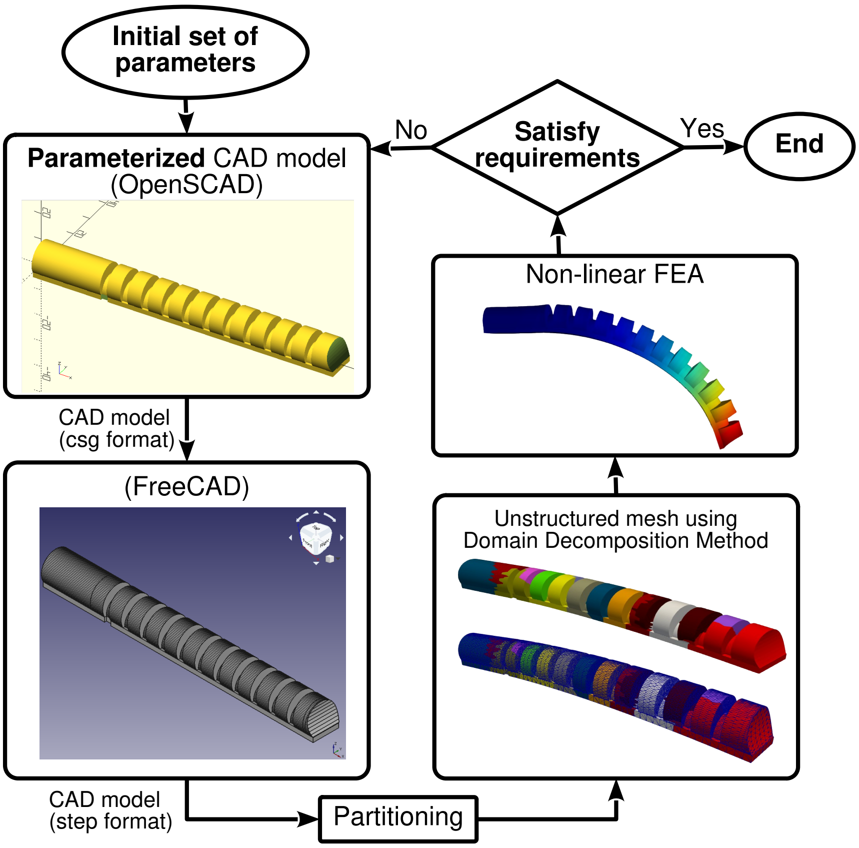


Figure 3. Flowchart of the recursive process for selecting the CAD parameters and the tools used.

OpenSCAD software uses the Constructive Solid Geometry (CSG) technique for solid modeling using Boolean operators to combine simpler primitives to define complex models. We need the FreeCAD software to export the CSG model to the STEP format, which can be parsed by our custom-developed software [33] for finite element analysis using distributed computing. We reduce the computational burden and memory requirements of non-linear finite element analysis using Domain Decomposition Methods (DDMs).

We tessellate the domain into a set of non-overlapping subdomains, which are then solved using parallel computing. This tessellation minimizes the number of finite element connections between subdomains, reducing the data exchange between processes, which decreases the computing performance due to bandwidth problems. We obtain this optimized partitioning by defining each finite element as a vertex of a dual graph connected with other finite elements sharing faces. Then, we use a multilevel k-way partitioning method [34] to generate the subdomains considering optimization criteria, including minimizing the resulting subdomain connectivity graph and the contiguous partition enforcement. Figure 3 depicts the mesh partitioned into sixteen subdomains using the ParMetis library [35]. We then obtain the displacements of the model using non-linear finite element analysis. If the result does not satisfy the design requirements detailed in the next section, we modify some parameters constraining the search space until the design requirements are satisfied. Although this process clearly consumes some time, it takes less than actually building, testing, and characterizing the physical actuators. With the presented approach, a single person can characterize 4–6 configurations in a working day, while it could take more than 24 h to produce and test a single physical hand.

3.2. Modeling and Simulation

We use additive manufacturing to fabricate the soft actuator using TPU 95A. As previously mentioned, this material exhibits nonlinear hyperelastic behavior with strong hysteresis, time dependence, and cyclic softening, which make complex the modeling and simulation of the deformation behavior of such material [29]. We simplify the modeling by obviating the hysteresis and time dependence, and we adopt a second-order polynomial strain energy function to fit the (average) stress–strain relationship [36]; in particular, we use a Mooney–Rivlin model. Since the Poisson ratio ν ranges from 0.48 to 0.50 for natural rubbers [37], we assume a Poisson ratio of $\nu = 0.48$ for fitting the Mooney–Rivlin material constants [29] considering the characterization of TPU material after printing presented above [32].

Table 1 shows the geometric parameters chosen after evaluating the behavior of the soft actuator in different configurations using a trial-and-error approach. We specify the requirements of the soft actuator as the bending, translating the endpoint of the fluidic actuator acting with a given internal force. We usually fix the parameters defining the size of the support of the actuator (h, w, l) and then initialize the other parameters shown in Table 1, scaling the values of a known design [25] with the support volume. This approach reduces the search space, and then the trial-and-error method consists of independent variations of a reduced set of parameters to satisfy the operative requirements. In our case, the design criteria consist of obtaining bending with endpoint displacement of about 60% of the actuator length with actuation ranging between 200 kPa and 500 kPa. This pressure provides the forces required in the grasping operations.

3.3. Fabrication

We fabricate the previously specified soft actuator using the FDM additive manufacturing technique with commercial TPU 95A material. Figure 4a shows the 3D printing of the soft actuator using a Creality CR-10 V3 printer. We can observe the details of the final design and the chambers at half of the fabrication in Figure 4b. Figure 4c depicts the actuated device of TPU 95A material using air pressure in the interior cavity. Note that we can use whatever fluid to actuate the soft device, such as air and water.

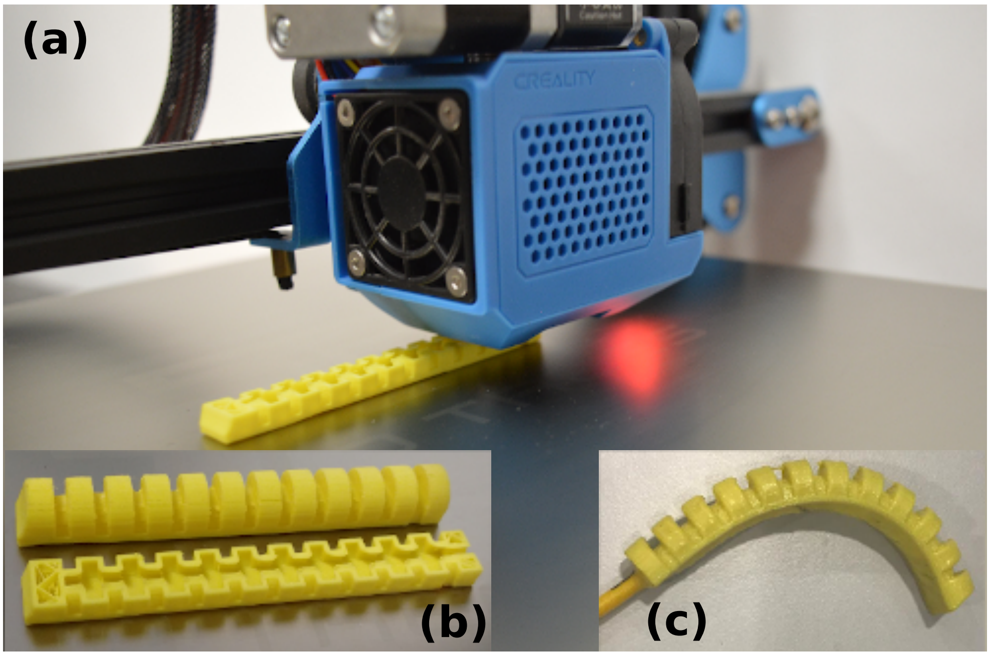


Figure 4. (**a**) Printing the soft actuator using a Creality CR-10 3D printer, (**b**) the 3D printed device and a section of partially printed soft actuator using TPU material, and (**c**) the actuated soft actuator with an internal pressure.

We use molding to cover the fabricated soft actuator with silicone rubber, EcoFlex 00-30c. We commonly use this fabrication process for manufacturing silicone elastomer-based pneumatic actuators. The covering with silicone aims to increase the underactuation in the grasping and protect the soft actuator from TPU damages and abrasions. Figure 5a shows the molds fabricated using additive manufacturing with Polylactic Acid (PLA) thermoplastic material. We can observe the curing process of silicone rubber in Figure 5b and the resulting soft actuator using multiple materials in Figure 5c.

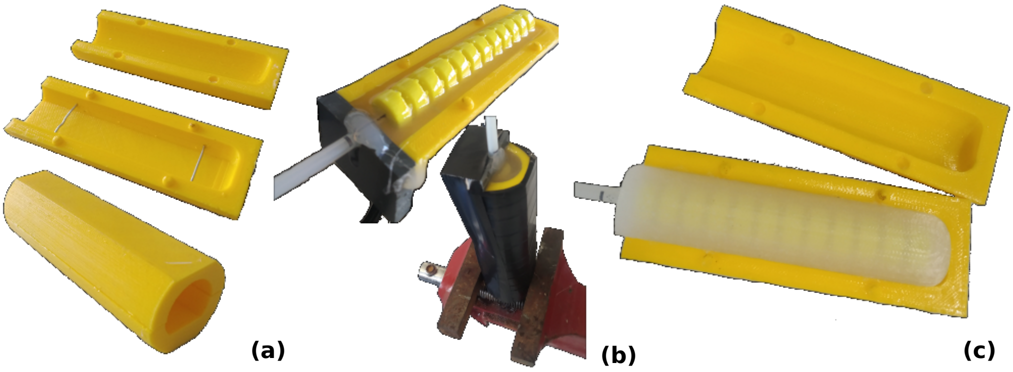


Figure 5. The manufacturing process to include silicone rubber around the 3D printed actuator: (**a**) the molds printed using PLA material, (**b**) the curing of two-component liquid silicone rubber (EcoFlex 00-30 from Smooth-on Inc), and (**c**) the resulting multi-material soft actuator.

3.4. Characterization

We characterize the soft actuator in underwater conditions, recording the behavior applying different internal pressures. The video includes a grid in the background that allows us to measure the relative displacement of the endpoint in the sequence of frames. We use this information to measure the response of the soft actuator from applying pressure to reaching the equilibrium point.

Figure 6 shows the frames of the soft actuator when it has reached the equilibrium point for different interior pressures. It also depicts the displacement solution of the nonlinear finite element analysis in similar conditions using the fitted material constants. We can observe a similar field of displacements of the simulation and the actual behavior of the soft actuator.

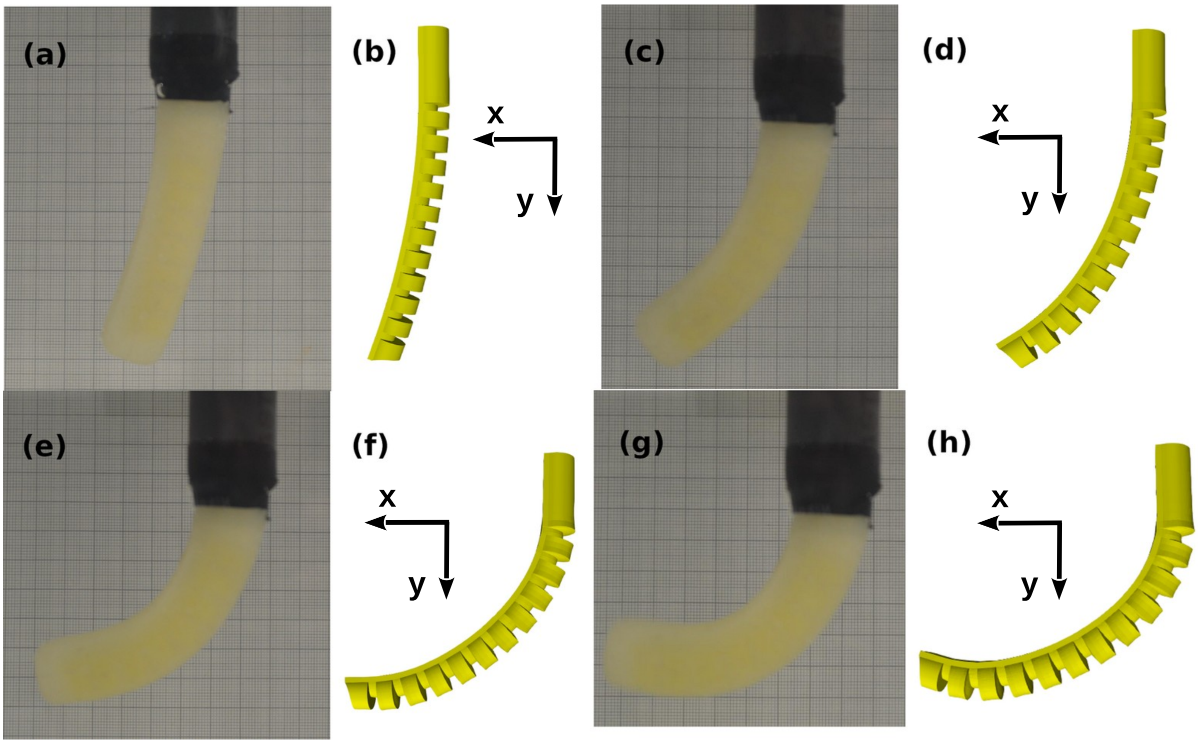
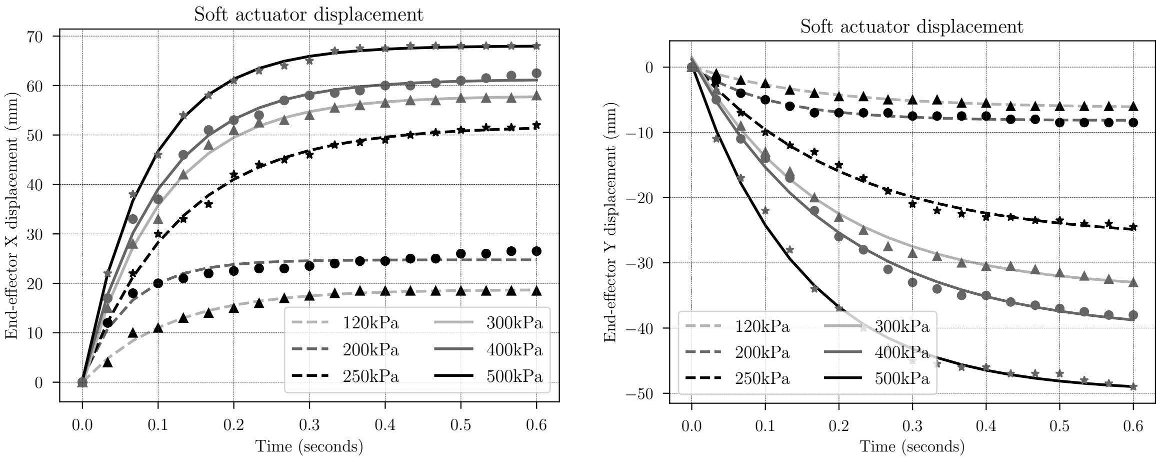


Figure 6. Displacement measurements of the soft actuator in underwater conditions and the resulting displacements of the non-linear finite element analysis applying an internal pressure of (**a**,**b**) 200 kPa, (**c**,**d**) 300 kPa, (**e**,**f**) 400 kPa, and (**g**,**h**) 500 kPa.

Figure 7 shows the experimental trajectory of the endpoint of the soft actuator with different internal pressures measured with the photograms of the video. We use this information in the control of the grasping maneuver to consider the delays between the pressure increase and the actuation of the soft device.



(**a**) (**b**)

Figure 7. Experimental data of the endpoint of the soft actuator with different internal pressures in the (**a**) x and (**b**) y reference axes of Figure 6.

4. Soft Gripper Design

We use the geometric details and characterization of the soft fluidic actuator to design, manufacture, and evaluate the performance of the soft gripper, including the fluid circuit, control, and energy consumption, which are crucial for underwater operation in an ROV.

4.1. Mechanical Design

We use the fluidic soft actuator to develop a soft gripper to operate in underwater environments. We use the characterization of the displacement of the endpoint of the soft actuator to design the support for actuators acting together in grasping operations. The procedure consists of selecting an operative pressure of the ones characterized in Figure 7 and then using the endpoint displacement to determine the arm diameter. We can also fix an arm diameter and then select the operative pressure for such a design parameter. In our case, we use three soft actuators operating at 400 kPa for the gripper design. The gripper support feeds the pneumatic/hydraulic circuit and installs it on the chassis of the underwater vehicle. We fabricate this support using additive manufacturing with PLA thermoplastic material. Figure 8a shows the support design considering the geometric constraints when the soft fluidic actuators have the maximum deformation. Figure 8b shows the soft gripper installed in the ROV. We depict the details of the gripper support and the balanced three-way valve used for acting the soft actuators in Figure 8c.

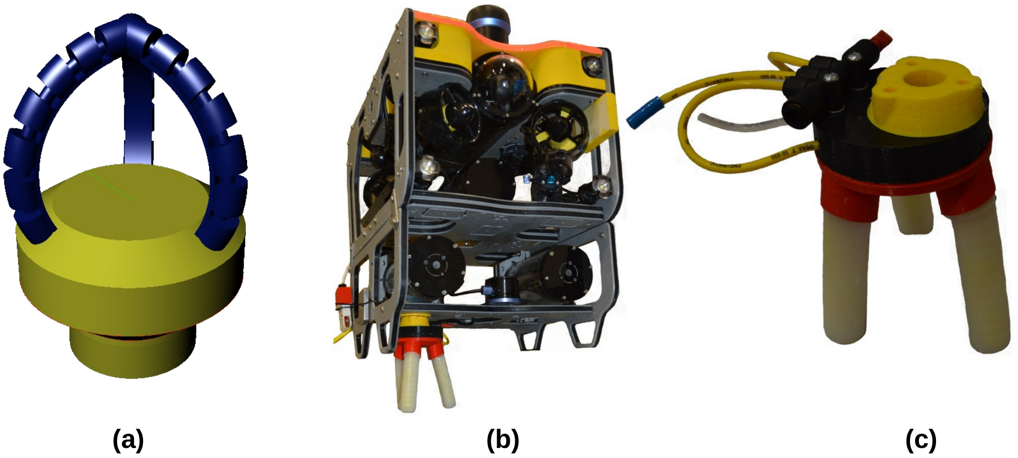


Figure 8. Soft gripper (**a**) design considering the maximum displacement of soft actuators, (**b**) installed in the ROV, and (**c**) showing the details of the support.

4.2. Electronics Design

We aim to develop a fully functional low-cost soft gripper for underwater grasping. While for laboratory use and specific applications, like a fish farm, relying on compressed air can be feasible, in general, it is not a good approach for autonomy or pressure constraints. We design the system so it can operate using water from the spot of depth the ROV is operating in. In this way, we save the increment of pressure.

We design and build an Arduino-based electronics package that receives orders from the ROV computer (serial link) or the user for testing purposes (dial and buttons). The board contains the power electronics and filters to operate a commercial small-size and low-cost diaphragm pump, a proportional solenoid valve, and an on/off solenoid valve. We also include a manometer in the system, connecting its pressure sensor to the board. Figure 9a shows a laboratory setup of the different electronics and hydraulics components included in the ROV.

As previously mentioned, we configured the hydraulics system to operate under a high range of external pressures, as described by the hydraulic scheme shown in Figure 9b. We feed seawater through the pump to the gripper actuator, and the exiting flow is directed back to the sea through the two valves. Such valves control both the operating pressure and flow rate. Since the pressure at the spot of depth determines the incoming water conditions and the elements of the hydraulics system, the pump pressure rise is independent of the ROV depth. The operating range of the vehicle is about 100 m.

The board operates the system in an open-loop mode, receiving a pump operation set-point command as a percentage of the operating range and generating a Pulse Width Modulation (PWM) signal, which controls the pump. While the gripper is in standby mode, the proportional solenoid valve is left open. When the gripper switches to operation mode, we open the valve 30% of the maximum opening allowed. We can minimize the pulsating effects of the diaphragm pump using this strategy and avoid much hydraulic head loss. We can also mitigate these pulsating effects using a hydrophore tank [22] at the cost of preventing operating at a high-pressure range. The incoming water to the hydrophore tank is at the spot of depth pressure, and we have to set the internal air pressure at such a pressure, which in practice is difficult to achieve. Figure 9c shows the pressure provided to the soft actuators depending on the pump PWM signal. It also shows the power consumption, which is crucial to keep a certain level of autonomy of the underwater vehicle.

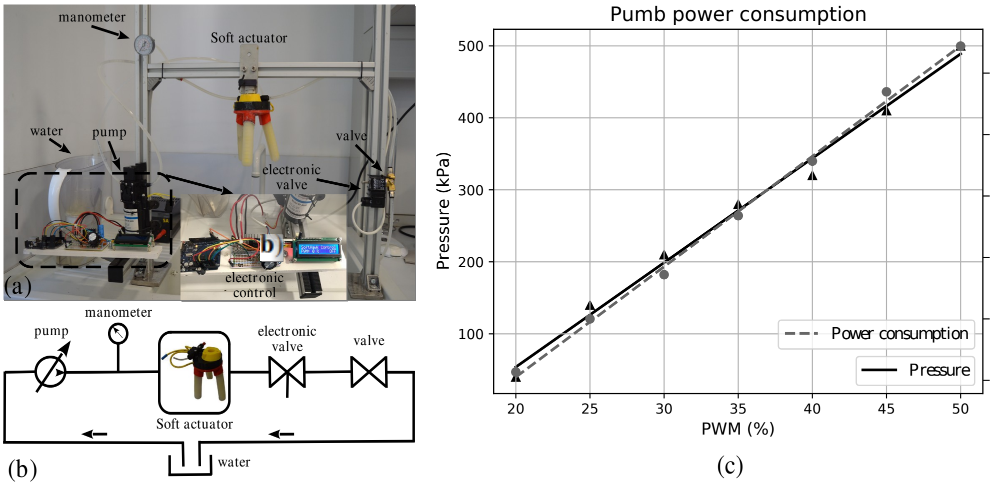


Figure 9. (**a**) Hydraulic system for controlling and acting the soft gripper, (**b**) hydraulic scheme, and (**c**) pump consumption under different operating pressures.

5. Experimental Results

We demonstrate the applicability of the proposed low-cost soft gripper in underwater environments performing operations in a commercial ROV. We place the developed soft gripper and the devices needed for the hydraulic circuit in the commercial Sibiu Pro underwater vehicle from the Nido Robotics company. Such an underwater platform is based on previous developments of Blue Robotics company used for inspection tasks [38] and improves the design, robustness, and capabilities to operate in more aggressive environments. The Sibiu Pro standard platform is a fully operational underwater vehicle operated with an umbilical cable. Its design is conceived for the inspection and maintenance of submerged systems. The propulsion system uses a TVC (Thrust Vector Control) with eight propellers that allow the vehicle to move/rotate in any direction by combining them [39]. Figure 8b shows the soft gripper installed on the underwater platform.

The experiment consists of grasping and transporting a complex object on the pool bottom. We emulate the conditions of the depths of the open sea by running the purification pool, which generates currents that make it difficult to operate the underwater vehicle. The object that the ROV should grasp can move due to the water flow generated by the purification pool. We anchor the load with a weight to constrain the movements in the pool bottom. In these conditions, the ROV should be able to grasp the object and transport it to another place in the pool.

Figure 10a shows the underwater vehicle approaching the object, a plastic lobster tied with a rope to a weight of 250 g. We have to remark that we do not anchor the plastic lobster at the bottom of the pool due to the water flow. The ROV aligns the object and pushes it to the pool bottom, as shown in Figure 10b,c. The soft actuators adapt to the shape of the plastic lobster and the bottom pool. This fact facilitates the maneuver because such an adaptation would be a collision using rigid end-effectors for the grasping. Therefore, we can affirm that using these soft devices increases the safety of complex maneuvers under uncertain conditions. The underwater vehicle generates a pressure of about 400 kPa to the soft gripper bending the soft actuators and grasping the plastic lobster. Figure 10d,e show the soft gripper grasping the plastic lobster tied with a rope to the weight of 250 g and the underwater vehicle transporting the load for several seconds. We can watch similar experiments using objects of different weights and sizes in the video attached to the paper (the video can be watched in the following https://youtu.be/UmutuhY7Das, accessed on 10 October 2022).

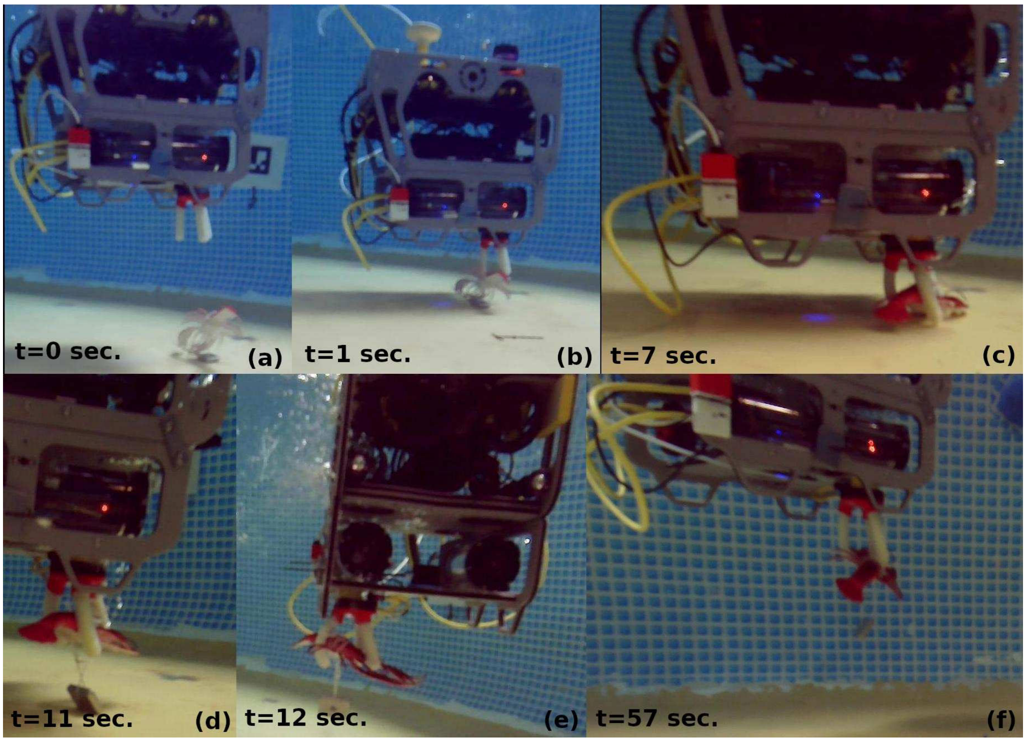


Figure 10. Underwater manipulation using the soft gripper. (**a**) The ROV aligns with the target, (**b**) gets closer to the objective, (**c**) begins the grasping, (**d**) lifts the weight, (**e**) navigates transporting the load, and (**f**) places the target in a different location.

6. Conclusions

We present the design, fabrication, and validation of a soft gripper composed of three soft actuators for underwater applications. We adopt a low-cost and quick fabrication method, which facilitates the design cycle, deployment, and maintenance of the development in underwater applications. Combining flexible thermoplastics and silicone rubbers in the soft actuator design, we take advantage of the properties of both materials. We use additive manufacturing tools for the low-cost rapid design and fabrication of flexible thermoplastics. In addition, the strain of soft actuators of flexible thermoplastics is smaller than the strain using silicone materials, which allows us to increase the force applied by the soft actuator and prevent damage and failures. The use of silicone rubber to cover the soft actuator, fabricated using additive manufacturing with flexible thermoplastic, increases the under-actuation in the contact adapting to the geometry in the manipulation by distributing the grasping forces, providing good sensitivity and mechanical reliability. This adaptation is crucial for robust grasping maneuvers in uncertain scenarios, such as underwater applications. We validate the proposal in a subaquatic setting showing the skills to deal with complex and uncertain grasping operations. Although flexible thermoplastics can suffer from durability, the commercial ones used are stable enough for the application. We have kept immersed in fresh water a complete hand in our laboratory for more than 9 months and have experience no degradation (except some slight changes in coloring of the silicone). In addition, the first prototype hand has been kept in air for more than 18 months, and we have not experienced any degradation as well.

Author Contributions: D.H.-P.: conceptualization, formal analysis, investigation, formal analysis, software, and writing; H.M.-B.: conceptualization, funding acquisition, investigation, software and supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We acknowledge the support, suggestions, and the initial design of the soft actuator of Fernando Martínez-Barberá.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mura, D.; Barbarossa, M.; Dinuzzi, G.; Grioli, G.; Caiti, A.; Catalano, M.G. A Soft Modular End Effector for Underwater Manipulation: A Gentle, Adaptable Grasp for the Ocean Depths. *IEEE Robot. Autom. Mag.* **2018**, *25*, 45–56. [CrossRef]
2. Petillot, Y.R.; Antonelli, G.; Casalino, G.; Ferreira, F. Underwater Robots: From Remotely Operated Vehicles to Intervention-Autonomous Underwater Vehicles. *IEEE Robot. Autom. Mag.* **2019**, *26*, 94–101. [CrossRef]
3. Fernández, J.J.; Prats, M.; Sanz, P.J.; García, J.C.; Marín, R.; Robinson, M.; Ribas, D.; Ridao, P. Grasping for the Seabed: Developing a New Underwater Robot Arm for Shallow-Water Intervention. *IEEE Robot. Autom. Mag.* **2013**, *20*, 121–130. [CrossRef]
4. Peñalver, A.; Fernández, J.J.; Sanz, P.J. Autonomous underwater grasping using multi-view laser reconstruction. In Proceedings of the OCEANS 2017, Aberdeen, UK, 19–22 June 2017; pp. 1–5.
5. Bemfica, J.R.; Melchiorri, C.; Moriello, L.; Palli, G.; Scarcia, U. A three-fingered cable-driven gripper for underwater applications. In Proceedings of the 2014 IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, China, 31 May–7 June 2014; pp. 2469–2474.
6. Ribas, D.; Ridao, P.; Turetta, A.; Melchiorri, C.; Palli, G.; Fernandez, J.J.; Sanz, P.J. I-AUV Mechatronics Integration for the TRIDENT FP7 Project. *IEEE/ASME Trans. Mechatronics* **2015**, *20*, 2583–2592. [CrossRef]
7. Simetti, E.; Wanderlingh, F.; Torelli, S.; Bibuli, M.; Odetti, A.; Bruzzone, G.; Rizzini, D.L.; Aleotti, J.; Palli, G.; Moriello, L.; et al. Autonomous Underwater Intervention: Experimental Results of the MARIS Project. *IEEE J. Ocean. Eng.* **2018**, *43*, 620–639. [CrossRef]
8. Koganezawa, K.; Takeuchi, K.; Sakagami, N. Multi Joint Gripper for Underwater ROV-Experimental Verification. In Proceedings of the OCEANS 2019, Marseille, France, 17–20 June 2019; pp. 1–6.
9. Suzumori, K.; Iikura, S.; Tanaka, H. Development of flexible microactuator and its applications to robotic mechanisms. In Proceedings of the 1991 IEEE International Conference on Robotics and Automation (ICRA), Sacramento, CA, USA, 9–11 April 1991; pp. 1622–1627.
10. Suzumori, K.; Iikura, S.; Tanaka, H. Applying a flexible microactuator to robotic mechanisms. *IEEE Control Syst. Mag.* **1992**, *12*, 21–27.
11. Caldwell, D.G.; Tsagarakis, N. Soft grasping using a dextrous hand. *Ind. Robot* **2000**, *27*, 194–199. [CrossRef]
12. Catalano, M.G.; Grioli, G.; Farnioli, E.; Serio, A.; Piazza, C.; Bicchi, A. Adaptive synergies for the design and control of the Pisa/IIT SoftHand. *Int. J. Robot. Res.* **2014**, *33*, 768–782. [CrossRef]
13. Lane, D.M.; Davies, J.B.C.; Casalino, G.; Bartolini, G.; Cannata, G.; Veruggio, G.; Canals, M.; Smith, C.; O'Brien, D.J.; Pickett, M.; et al. AMADEUS: Advanced manipulation for deep underwater sampling. *IEEE Robot. Autom. Mag.* **1997**, *4*, 34–45. [CrossRef]
14. Lane, D.M.; Bartolini, G.; Cannata, G.; Casalino, G.; Davies, J.B.C.; Veruggio, G.; Canals, M.; Smith, C. Advanced manipulation for deep underwater sampling: The AMADEUS research project. In Proceedings of the 1998 IEEE International Conference on Control Applications (Cat. No.98CH36104), Trieste, Italy, 4 September 1998; pp. 1068–1073.
15. Galloway, K.C.; Becker, K.P.; Phillips, B.; Kirby, J.; Licht, S.; Tchernov, D.; Wood, R.J.; Gruber, D.F. Soft Robotic Grippers for Biological Sampling on Deep Reefs. *Soft Robot.* **2016**, *3*, 23–33. [CrossRef]
16. Rus, D.; Tolley, M.T. Design, fabrication and control of soft robots. *Nature* **2015**, *521*, 467–475. [CrossRef] [PubMed]

17. Navas, E.; Fernández, R.; Sepúlveda, D.; Armada, M.; Gonzalez-de Santos, P. Soft Grippers for Automatic Crop Harvesting: A Review. *Sensors* **2021**, *21*, 2689. [CrossRef] [PubMed]
18. Stuart, H.; Wang, S.; Khatib, O.; Cutkosky, M.R. The Ocean One hands: An adaptive design for robust marine manipulation. *Int. J. Robot. Res.* **2017**, *36*, 150–166. [CrossRef]
19. Vogt, D.M.; Becker, K.P.; Phillips, B.T.; Graule, M.A.; Rotjan, R.D.; Shank, T.M.; Cordes, E.E.; Wood, R.J.; Gruber, D.F. Shipboard design and fabrication of custom 3D-printed soft robotic manipulators for the investigation of delicate deep-sea organisms. *PLoS ONE* **2018**, *13*, e0200386. [CrossRef] [PubMed]
20. Feng, H.; Sun, Y.; Todd, P.A.; Lee, H.P. Body Wave Generation for Anguilliform Locomotion Using a Fiber-Reinforced Soft Fluidic Elastomer Actuator Array Toward the Development of the Eel-Inspired Underwater Soft Robot. *Soft Robot.* **2020**, *7*, 233–250. [CrossRef]
21. Kurumaya, S.; Phillips, B.T.; Becker, K.P.; Rosen, M.H.; Gruber, D.F.; Galloway, K.C.; Suzumori, K.; Wood, R.J. A Modular Soft Robotic Wrist for Underwater Manipulation. *Soft Robot.* **2018**, *5*, 339–409. [CrossRef]
22. Shen, Z.; Zhong, H.; Xu, E.; Zhang, R.; Yip, K.C.; Chan, L.L.; Chan, L.L.; Pan, J.; Wang, W.; Wang, Z. An Underwater Robotic Manipulator with Soft Bladders and Compact Depth-Independent Actuation. *Soft Robot.* **2020**, *7*, 535–549. [CrossRef]
23. Hughes, J.; Culha, U.; Giardina, F.; Guenther, F.; Rosendo, A.; Iida, F. Soft manipulators and grippers: A review. *Front. Robot. AI* **2016**, *3*, 69. [CrossRef]
24. Stokes, A.A.; Shepherd, R.F.; Morin, S.A.; Ilievski, F.; Whitesides, G.M. A Hybrid Combining Hard and Soft Robots. *Soft Robot.* **2013**, *1*, 70–74. [CrossRef]
25. Ogura, K.; Wakimoto, S.; Suzumori, K.; Nishioka, Y. Micro pneumatic curling actuator-Nematode actuator. In Proceedings of the 2008 IEEE International Conference on Robotics and Biomimetics, Bangkok, Thailand, 22–25 February 2008; pp. 462–467.
26. Johnston, I.D.; McCluskey, D.K.; Tan, C.K.L.; Tracey, M.C. Mechanical characterization of bulk Sylgard 184 for microfluidics and microengineering. *J. Micromech. Microeng.* **2014**, *24*, 035017. [CrossRef]
27. Park, Y.L.; Majidi, C.; Kramer, R.; Bérard, P.; Wood, R.J. Hyperelastic pressure sensing with a liquid-embedded elastomer. *J. Micromech. Microeng.* **2010**, *20*, 125029. [CrossRef]
28. Suzumori, K.; Koga, A.; Riyoko, H. Microfabrication of integrated FMAS using stereo lithography. In Proceedings of the IEEE Micro Electro Mechanical Systems An Investigation of Micro Structures, Sensors, Actuators, Machines and Robotic Systems, Oiso, Japan, 25–28 January 1994; pp. 136–141.
29. Qi, H.J.; Boyce, M.C. Stress–strain Behavior of Thermoplastic Polyurethanes. *Mech. Mater.* **2005**, *37*, 817–839. [CrossRef]
30. Ilievski, F.; Mazzeo, A.D.; Shepherd, R.F.; Chen, X.; Whitesides, G.M. Soft Robotics for Chemists. *Angew. Chem. Int. Ed. Engl.* **2011**, *50*, 1890–1895. [CrossRef] [PubMed]
31. Deimel, R.; Brock, O. A novel type of compliant and underactuated robotic hand for dexterous grasping. *Int. J. Robot. Res.* **2016**, *35*, 161–185. [CrossRef]
32. Georgopoulou, A.; Vanderborght, B.; Clemens, F. Fabrication of a Soft Robotic Gripper With Integrated Strain Sensing Elements Using Multi-Material Additive Manufacturing. *Front. Robot. AI* **2021**, *8*, 615991. [CrossRef] [PubMed]
33. Herrero-Pérez, D.; Martínez-Castejón, P. Multi-GPU acceleration of large-scale density-based topology optimization. *Adv. Eng. Softw.* **2021**, *157–158*, 103006. [CrossRef]
34. Karypis, G.; Kumar, V. Multilevel k-way partitioning scheme for irregular graphs. *J. Parallel Dist. Com.* **1998**, *48*, 96–129. [CrossRef]
35. Karypis, G.; Schloegel, K. *ParMeTis: Parallel Graph Partitioning and Sparse Matrix Ordering Library, Version 4.0*; Technical Report; University of Minnesota: Minneapolis, MN, USA, 2013.
36. Scharff, R.B.N.; Wu, J.; Geraedts, J.M.P.; Wang, C.C.L. Reducing Out-of-Plane Deformation of Soft Robotic Actuators for Stable Grasping. In Proceedings of the 2019 2nd IEEE International Conference on Soft Robotics (RoboSoft), Seoul, Korea, 14–18 April 2019; pp. 265–270.
37. Ward, I.M.; Sweeney, J. *Mechanical Properties of Solid Polymers: Third Edition*; John Wiley & Sons, Ltd.: Chichester, UK, 2012.
38. Laranjeira, M.; Dune, C.; Hugel, V. Catenary-based visual servoing for tether shape control between underwater vehicles. *Ocean Eng.* **2020**, *200*, 107018. [CrossRef]
39. Martínez-Barberá, H.; Bernal-Polo, P.; Herrero-Pérez, D. Sensor Modeling for Underwater Localization Using a Particle Filter. *Sensors* **2021**, *21*, 1549. [CrossRef] [PubMed]