Abstract—Current underwater end-effector technology has limits in terms of finesse and versatility. Because of this, the execution of several underwater operations - as archaeological recovery and biological sampling - often still requires direct intervention of human operators, exposing them to the risks of working in a difficult environment. This paper proposes the design and implementation of an under-actuated and compliant underwater end-effector, which embodies both grasp capabilities comparable to those of a scuba’s real hand and the large grasping envelope of grippers. The proposed end-effector, whose design is based on the the Pisa/IIT SoftHand, is composed of a modular watertight chamber with pressure compensation - hosting the electronics and motor - and of a set of two soft terminal devices - one with an anthropomorphic hand form and one with a gripper-like form, respectively for medium/small and large object manipulation - which implement an adaptive grasping function. These devices have been tested in laboratory to withstand a pressure of 50 bar without damage nor degradation in performance and are readily interchangeable through a custom fast toolchange system. The two parts are connected via a magnetic drive coupling to transfer actuator torque to the wet fingers. Field results, obtained with the end-effector controlled underwater by a human operator (10 meters depth), show good grasping performance in both dexterity and force tasks. Moreover, preliminary lab testing shows the possibility of implementing basic - yet meaningful - intrinsic force sensing for the reconstruction of basic grasp interactions.

I. INTRODUCTION

Performing underwater fine operations with current robotic manipulation technology is still a very challenging task. In contrast to human divers, ADSs (Atmospheric Diving Suits), ROVs (Remotely Operated Vehicles) and AUVs (Autonomous Underwater Vehicles) can readily and safely access the depths, yet they demonstrate limited manipulation abilities. Commericially available underwater systems are designed to perform simple and heavy mechanical work (i.e. construction, or pipeline maintenance). Generally, they use claw-like end-effectors, capable of opening/closing and wrist-rotation movements only. Such technological limit keeps any deep water\(^1\) fine manipulation task still a goal on the horizon. This is particularly true for underwater archaeological recovery and biological sampling. However, these fields presents imperative tasks, some of which are described below.

\(^1\)With the term “deep water” we address here any sea region which lies beneath diver depth, i.e. 60 m ca.
II. PROBLEM DEFINITION

Underwater archaeology consists mostly in locating, monitoring and preserving archaeological sites. Yet, sometimes, cultural heritage artifact rescue from such sites becomes mandatory, either for preservation or to prevent dispossession.

Another typical task is preventive conservation, that aim to prevent or reduce potential damage to artifacts. As with land archaeology, recovery and conservation techniques are essentially manual, relying on simple equipment and operator dexterity to handle man-made objects with different shapes, such as jewelry, dishes, weapons, and tools. In underwater biological sampling, most specimens consist in soft-bodied and fragile organisms, like anemones, sponges, and corals. So, scientists need to approach them with the greatest possible care. Regarding e.g. coral sampling, the most sustainable method is to manually collect loose fragments already broken off the parent colony, or to gently snip a small branch off the parent colony. More complex underwater biological operations consist in tissue biopsy techniques, which use syringes, fluorescence measurements with lamps and lasers, and RNA stabilizer application. Some of these tasks are represented in Fig. 2 (a-d). In general, many other underwater operations require a gentle grasp or working with tools made for the human hand, as in subsea IRM (Inspection, Repair and Maintenance) of offshore structure components, e.g. pipelines and umbilicals (see Fig. 2 (e-f)).

The industrial nature of existing underwater robotic manipulation technology does not allow to perform such fine activities: attempt at object grasping often results in damage through unwitting application of excessive contact forces, which introduces expensive delays or complete failure in task execution. Human skills are still needed, and mostly provided by scuba divers in shallow water, or by ADS operators, equipped with either unpractical pressurized gloves or primitive lobster-like claws, as presented in Fig. 2 (g-j). These approaches present risks for human life and are highly inefficient.
III. PROPOSED SOLUTION

The Pisa/IIT SoftHand [11] is an under-actuated, adaptive soft robotic hand, which is a flexible-joint robot [14], i.e. its compliance is concentrated in the joints. It is designed with the purpose of being robust and easy to control as an industrial gripper, while exhibiting high grasping versatility and a form factor similar to that of the human hand. It has 19 joints, but needs only one actuator to activate its grasping capabilities. Such simplification is enabled through the theory of adaptive synergies, resulting in a series of considerable advantages both for control and design simplification. The Pisa/IIT SoftHand implements one adaptive synergy, actuated with a transmission system that uses one tendon, pulleys, and a single gear motor. The SoftHand demonstrates excellent grasping skills in many different situations: in [11] a total of 107 objects of different shape was successfully grasped by the hand controlled by a human operator. Examples include a bottle, a pen, a cup, a hammer, a book, coins, etc. This grasping capability and the soft robotic mechanical design of the SoftHand appear to well suit fine underwater operations, considering in particular that i) the tendon-driven design itself has already been proven reliable in underwater use (as in [6], inspired by [12]), ii) the SoftHand joints are able to withstand the even severe disarticulations hydrostatic pressure could provide without losing their adaptivity (see e.g. Fig. 15 in [11]), and iii) no closed spaces are present in the grasping mechanism, so no pressure differential exists which can cause deformations and ruptures.

Thus we propose a solution based on the SoftHand technology, i.e. a set of two soft terminal devices, to be used in a waterproof end-effector. Such soft devices present i) the original SoftHand anthropomorphic hand form and ii) a gripper-like form with middle phalanges longer than the hand. They are intended for medium/small and large object grasping respectively. The soft gripper terminal device is designed having in mind an industrial diving scenario. In this environment it could be used to stabilize a ROV/AUV by firmly catching hold to a structure in a docking procedure. Then a second robot arm could employ the SoftHand to perform more fine maintenance operations. Finally, more complex underwater manipulation tasks could require an operator/robot to use both the developed tools (e.g. if a robot employed in an archaeological operation has to remove large debris in order to access the smaller artifacts to be retrieved with finesse). So we designed a custom toolchange system in order to enable fast and simple switching between different terminal devices.

A. Design and Implementation

The system design concept, shown in Fig. 3a, is a modular system composed of a waterproof servo-actuator core unit, a set of soft terminal devices readily interchangeable through a toolchange system, and an optional waterproof handle device for use by a human operator (e.g. as an ADS end-effector).

One of the main design issues in submarine operations is electronic waterproofing. Two common techniques are: 1) building a water and pressure tight enclosure, to place electronics in it; 2) encasing of all the electronics in some resin, a methodology known as potting. The first approach was chosen for the core module, as it allows easier modification and intervention on the system. Thus we designed a watertight enclosure that constitutes the central body of the underwater manipulation system. A section of the complete assembly is presented in Fig. 3b: its maximum diameter is 95 mm, its max length is 170 mm and its mass about 2 kg. The enclosure components consist of a cast acrylic tube (7), an o-
ring sealed flange (13), and openings for cable penetrators (14) to allow communication/electrical power supply from the outer environment. To further protect the enclosure from hydrostatic pressure the hull was filled with mineral oil, thus reducing the pressure excursion between inner and outer environments.

A second design choice is related to the necessity of transmitting the motor torque from inside the watertight enclosure to the outer underwater surrounding where the wet manipulation system interacts with the objects to be grasped. A waterproof shaft sealing between those two environments is not trivial to obtain: the rotating motion of the shaft can cause momentary pathways for fluids to leak through and, with enough pressure/depth, water will eventually penetrate past the seal and into the motor housing. A more reliable solution to this issue is to make the dynamic coupling between the actuated rotor (motor) and the operative rotor immaterial. This is obtained by using a \textit{magnetically coupled drive} consisting of two different sets of magnets, one on the motor side and one on the tool side. Magnetic couplings (MCs) are currently prized for their effectiveness when submerged in water for two main advantages [13, 14]: i) the technology is intrinsically a torque limiter that can help saving the system electromechanics. The coupling will slip in the case of a severe rupture of the load torque. Moreover, this failure mode can be easily detected through voltage and current monitoring of the motor (see also Subsec. IV-A); ii) they can be manufactured as dust-proof, fluid-proof and rust-proof, engineered to handle extreme operating conditions. Even if such coupling renders the device more heavy, this is less relevant in an underwater environment. Considering thus the trade-off between the coupling/device weight and its functionality, the design choice opted for a disc-type MC\textsuperscript{12} (2a and 2b) capable of transmitting a torque of 1 Nm with a gap between its two plates of about 6 mm.

The actuator (11) is a 12 V DC gear motor Maxon DCX 22 with 83:1 gear ratio. For motor position control we use two magnetic encoders (8). The encoder magnets are placed on two gears, with a different number of teeth, connected to a third gear mounted on the motor shaft. The combined readings of the two encoders enable the reconstruction of the absolute position of the motor shaft over a range of several turns thanks to the different gear ratio between the motor and the two sensors. Preliminary experiments proved that both i) being flooded in mineral oil and ii) proximity with the coupling magnetic field do not interfere with the sensors. Encoders and actuator are connected to the SoftHand PCB, which communicates with the outer environment by means of the cables passing though the penetrator. The employed bus carries power/ground and two lines which implements an

RS485 communication (see [15] for details).

Thanks to the manipulation system modular design and to the immaterial coupling provided by the MC, various terminal devices (robotic hands, grippers and/or tools) can be readily connected to the outer motor shaft by using a custom-made toolchange system (described in the next subsection). The developed core system, along with the two terminal devices currently designed, are shown in Fig. 3. The maximum lift, pinch grasp and power grasp forces exerted by the SoftHand are respectively 400 N, 20 N and 76 N. The lift force value refers to the force that the robotic hand/gripper exerts in order to hang a corresponding weight, as in Fig. 5c. The gripper maximum lift force results in about 150 N.

B. Toolchange System

The toolchange system consists, essentially, in a snap mechanism between the motor group and each tool group. A couple of springs (16) is fastened to the motor group coupling device (15). Such springs realize the snap mechanism, depicted in Fig. 4; placing them on the motor group make a unique motor coupling mechanism suitable for a set of tools, each equipped with its MC half. The coupling of different tools is rendered fast and simple thanks to both the MC magnetic attractive and the spring load, while the uncoupling is possible by means of a custom made tool housing. Once the motor group is positioned and ensured inside the housing, the spring work (i.e. the snap mechanism between tool and motor group) is unactivated. In such configuration the tool group (3) results fastened to the tool housing, both longitudinally and axially. In particular the longitudinal fastening is accomplished by a set of magnets that connects to a ferritic stainless steel ring (4) fastened to the MC half residing in the tool group (2a); the same magnets block the tool MC half, allowing to maintain the tool angle of a previously uncoupled tool when recoupling with it. The axial fastening makes use of special guides obtained in the tool housing which act as a prismatic joint for the tool group. So the motor group can be uncoupled by the tool group - that remains secured to the tool housing - and retrieved by the operator/robot simply by applying an axial force on it. The coupling/uncoupling procedure is schematically depicted in Fig. 4, along with the toolchange mechanism configuration in each phase.

IV. MAGNETIC COUPLING CONTROL

MCs can be modeled by a two-bodies system (see e.g. [16]) where a connection, due to a magnetic spring element, exists. Such an elastic element may cause oscillations during position control that could, in turn, degrade control performance. This high-compliance characteristic is known to represent a possible drawback when applied to robot motion control, and can limit the use of magnetic coupling to systems with a relatively low-bandwidth dynamic transients. Here, we verify that the latter is our case, i.e. oscillations provided by the MC are negligible.

Consider the representation of our device shown in Fig. 5a, where the recalled two-bodies model has been adopted for the MC. It is to point out that this is a roughly simplified model: no damping nor feedback control, which are obviously presents in the real system, are taken into account. In this manner, we are considering the worst operative conditions. The coupling behaves as a nonlinear soft torsional spring that, if linearized about the origin as in [16], has a stiffness coefficient $K_{C,lin} = pT_{max}$, where $p = 10$ is the number of coupling magnetic poles and $T_{max}$ is its maximum torque. The soft device equivalent stiffness coefficient is non-linear and depends on the actual motor angle $q$. Its linearized expression gives $K_{L,lin}(q) = K_1 + K_2q$, where $K_1$ and $K_2$ are numerical parameters, previously identified (see eq. (2) in Subsec. V-A). Such a varying stiffness coefficient is taken into account in the simplified subsystem also shown in Fig. 5a, which is an harmonic oscillator with impulse response/transfer function:

$$H(s) = \frac{\Theta(s)}{F(s)} = \frac{1}{J_L s^2 + \frac{1}{J_L} K_{C,lin} + K_{L,lin}(q)},$$

Refer to Table I for the numerical values of the quantities defined here. Eq. (1) is evaluated for each $q_0 \leq q \leq q^*$ where $q_0 = 0$ and $q^*$ are the motor angles that corresponds respectively to an open hand and to the hand max closure.

The resonance frequency $\omega_R(q)$ (in red) of the oscillator of Subfig. 5a with respect to $q$. c) Depiction of the SoftHand terminal device exerting a lifting force equal to $F$ (lift force value definition).

![Figure 5. a) Two-inertia representation of the system and analyzed oscillator subsystem. $J_M$ and $J_L$ are respectively the combined motor/first coupling half and second coupling half/load inertias; $\tau_M$, $\tau_C$ and $\tau_L$ are the motor, coupling and load torques; $q$ and $q_L$ are the motor and load angles; $K_C$ and $K_L$ are the coupling and load torsional spring stiffness coefficients. b) Resonance frequency $\omega_R(q)$ (in red) of the oscillator of Subfig 5a with respect to $q$. c) Depiction of the SoftHand terminal device exerting a lifting force equal to $F$ (lift force value definition).](image)

- $\omega_R(q)$ is the resonance frequency of the oscillator.
- $\tau_M$, $\tau_C$ and $\tau_L$ are the motor, coupling and load torques, respectively.
- $q$ and $q_L$ are the motor and load angles, respectively.
- $K_C$ and $K_L$ are the coupling and load torsional spring stiffness coefficients.

For example, the resonance frequency $\omega_R(q)$ for $q = q^*$ is computed as $\omega_R(q^*) = \sqrt{\frac{K_C}{J_L} + \frac{K_{L,lin}(q^*)}{J_L}}$.
trend is shown in Fig. 5b. It can be seen, from such a figure, that even in the worst conditions where the damping of the real system is neglected i) the lower \( \omega_R(q) \) results in \( \approx 650 \) rad/s, so employing the motor under this frequency will provide no sensible oscillations in position control, and ii) that \( \omega_R(q) \) itself is almost constant, so it can be filtered easily.

**A. Fault Detection**

As recalled in Subsec. III-A, one of the advantages of drive trains incorporating magnetic gears/couplings is its torque limiting nature: an excessive torque results in a pole-slipping condition, as opposed to the mechanical damage that is characteristic of normal gearbox systems. However, from a servo control perspective, the effect of a magnetic gear pole-slipping is a loss of control of the load/tool. Consequently, it is of interest to have a pole-slip detection method.

This can be done by analyzing the absorbed motor current \( I_m \). The algorithm used to identify the pole slipping is based on the grasp force reconstruction algorithm presented in Subsec. V-A. This detection could trigger abort/survival modes, or a software procedure to reset automatically the motor angular position at rest \( q_0 \), so to recover the tool functionality.

Pole-slipping can be induced even from the tool side of the magnetic coupling, e.g. if a traumatic event occurs at the terminal device fingers. However the finger robust, compliant nature helps preventing such event. The robust design of both terminal devices is shown in Fig. 6, were various kinds of finger deformations are reported.

**V. EXPERIMENTAL RESULTS**

The developed end-effector was validated carrying out both laboratory and field testings, which are presented in the following subsections.

A. Grasp Force Estimation

To aid the operator and/or the automated control system of a ROV/AUV a disturbance observer [17] can be used for grasp force estimation. Consider the following motor dynamic equation:

\[
J_n \ddot{q} = K_n I_{ref} - \tau_d = K_n I_{ref} - \tau_{model} - \tau_{int} = K_n I_{ref} - \tau_{model} - J(q)^T w_{ext}; \quad (2)
\]

where \( \dot{q} \), \( K_n \), \( I_{ref} \) and \( J_n \) denote the motor angular acceleration, torque constant, current and inertia, respectively, \( J(q) \) is the manipulator Jacobian that depends on motor position \( q \) and \( w_{ext} \) represents the wrench exerted by the end-effector on the environment (see e.g. [18]). The disturbance torque \( \tau_d \) combines all the internal and external disturbance torques and is assumed to be formed by two main components: the torque needed to close the hand \( \tau_{model} \) when there is no interaction with the environment (i.e. without grasping any object) and the interaction torque \( \tau_{int} \). So the identification procedure aims at obtaining an estimate of \( \tau_{int} \), relating it to the current absorbed by the motor. To do so, a calibration procedure is performed to identify the term \( \tau_{model} \), which can be decomposed into three components: the elastic torque generated by the hand tendons during closure \( \tau_e \), the gravitational effect \( \tau_g \), and the frictional torque \( \tau_f \), which is mostly due to friction in the actuator gearbox. Considering that \( \tau_e \) can be mostly neglected, especially for underwater operations, modeling \( \tau_f \) with a Hayward-Dahl friction model [19], \( \tau_{model} \) is defined as:

\[
\tau_{model} = D \dot{q} + K_1 (q - q_0) + K_2 (q - q_0) ||q - q_0|| + K_f(q - q_f); \quad (3)
\]

where \( q_0 \) is the motor angular position at rest (hand open), \( \dot{q} \) is the motor velocity, \( D \) is the viscous damping, \( K_1 \) and \( K_2 \) are coefficients of a simplified elastic model \( \tau_e = K_e(q - q_0) \approx K_1 (q - q_0) + K_2 (q - q_0) ||q - q_0|| \). \( K_f \) is related to the friction coefficient and \( q_f \) is the adhesion point of the Hayward model.

Supposing that the hand does not come in contact with the object to be grasped (i.e., \( \tau_{int} = 0 \) in eq. (2)) during the calibration procedure, the hand model torque can be computed from the motor current and its motion response:

\[
\tau_{model} = K_{int} I_{ref} - J_n \dot{q}; \quad (4)
\]

Such a calculation requires motor current and acceleration sensing. The latter would be sensitive to noise if computed from feedback position differentiation, so the equivalent contribution determined by the PID that controls the actuator is computed in feedforward instead. To identify the parameters of eq. (3), the hand was driven with several velocity reference trajectories from the fully open to fully closed position and reverse. Next, the resulting current, position, and velocity profiles are used to estimate the parameters (their numerical values are reported in Table I) by means of conventional least squares identification algorithm. This leads us to the estimated disturbance torque \( \hat{\tau}_{model} \) and the following equality holds:

\[
\hat{\tau}_{model} \approx K_{model} I_{cal}; \quad (5)
\]

where the calibration current \( I_{cal} \), which is the current the motor needs to close the empty terminal device, can now be determined. Taking \( I_{cal} \) as the current offset, experiments where the hand grasps various objects were carried over. Now we can establish the following relation:

\[
\hat{\tau}_{int} \approx K_{int} I_{res} \approx J(q)^T w_{ext}; \quad (6)
\]
Figure 7. Current residuals obtained during underwater grasping tasks (a-d) with the shown soft object (e) and stiff object (f). Object dimensions are 60x60x120 mm. Subfigures a) and c) refers to the SoftHand terminal device, subfigures b) and d) refers to the soft gripper. Both measured (in blue) and saturated (for analysis simplification, in red) current residual are reported. The soft gripper adsorbs more current than the SoftHand, by virtue of the former longer phalanges.

Then the motor stays still until \( t \approx 20 \) s, when the hand returns open. However now \( I_m \) results quite different compared to its open hand original value (which is set to be \( \approx 0 \) mA after a calibration procedure), i.e. before the pole-slipping occurring. If we compare Fig. 8 with Fig. 7, where \( I_m \) is shown in case of successful grasps, it is clear that an uncoupling can be diagnosed through this current monitoring. In this manner a simple fault detection algorithm without any sensor on the load side can be implemented.

B. Laboratory Experiments

To get an estimate of the end-effector grasping force, laboratory experiments with the estimation algorithm of Sec. V-A have been carried: after calibration, different (stiff or soft) objects are grasped and released by the system inside a water tank. The current residual resulting from these tasks is recorded and reported. An example of the grasp force experiment process and its resulting current residual is presented in Fig. 7, where the expected current variations between objects of different stiffness (also shown) can be seen. The experiment is performed for both terminal devices. A rubber foam block (Young modulus \( \approx 0.015 \) GPa) is used as soft specimen, while a small aluminum bar (Young modulus \( \approx 69 \) GPa) represents the stiff specimen. The two object shape and dimensions are very similar. During the grasp phase the SoftHand yields a mean current residual of \( \approx 250 \) mA for the soft object and of \( \approx 320 \) mA for the stiff one. Regarding the soft gripper, the same quantities results respectively in \( \approx 400 \) mA and \( \approx 470 \) mA. As expected, the current residual is proportional to i) the grasped object stiffness, i.e. to the total grasp force exerted by the end-effector, and to ii) the grasp Jacobian of the contact, which is larger for the soft gripper, by virtue of its longer middle phalanges.

Moreover, laboratory experiments of the developed fast
toolchange system have been carried out: a complete toolchange procedure is shown in Fig. 4.

Manipulation task of big objects, difficult to grasp with the SoftHand, have been simulated employing the soft gripper controlled by a human operator. Such tasks are shown in the first two rows of subfigures of Fig. 10.

Finally we performed a pressure test to better assess the pressure-tolerant behavior of our mechanical structure. The two terminal devices underwent a static depth test in a pressure chamber (provided to us by a company specialized in underwater robotic R&D, the Graal Tech Srl in Genoa). We inspected them after the test and they showed no sign of degradation or damage after being subjected to a pressure of 50 bar (≃500 m depth). Their performance too appeared to be unaffected by the pressure test, as we were able, right after removing the devices from the chamber, to grasp even complex objects with the SoftHand one (thanks also to the fast toolchange system).

Video footage of the test is shown in the attached multimedia material.

C. Field Experiments

Underwater experimental validation of the system has been carried on at various depths with the two terminal devices depicted in Fig. 3. The manipulation system was controlled by a human operator, similarly as in [11]. In Fig. 9 and 10 field experiments at a depth of ≃ 1 m are presented, employing respectively the SoftHand and soft gripper device.

In such experiments, considering the SoftHand terminal device, archaeological recovery (Fig. 9 (a-j)) and biological sampling (k-t) operations were simulated, along with a force operation (Fig. 9 (u-y)). The end-effector successfully grasped complex objects like stones, vase shards, coins, reproduced coral shards and reproduced aquatic plant stems, with the operator reporting a positive feedback about the ease of use. It can be seen, from Fig. 9, that natural, intuitive and human-like grasping gestures were achieved for every object. In the same field experiments several grasping tasks were simulated with the soft gripper (similarly to the SoftHand). Results are shown in the last panel row of Fig. 10.

Another field experiment, taking place in the sea near Pisa (Cecina location) at a depth of ≃ 10 m, is presented in the attached multimedia material. There, two professional scuba operators employ the soft hand terminal device via the mechanical handle. They perform several manipulation tasks, similar to those of the 1 m depth experiment. The goal of such an experiment is to point out that the manipulation tasks are accomplished with ease by the scubas, although it is the first time they use the device.

VI. CONCLUSIONS

In this paper a new under-actuated and compliant robotic underwater end-effector, based on the technology of the Pisa/IIT SoftHand, has been designed and developed. The manipulation system has a modular design that consists of: i) a watertight chamber with pressure compensation, hosting the electronics and motor, ii) a set of two soft yet robust terminal devices with the form factor of a SoftHand and of a gripper implementing an adaptive grasping function, iii) a custom fast toolchange system, and iv) a mechanical handle for human control of the end-effector. Moreover, the system terminal devices are readily interchangeable through a magnetic drive coupling that connects i) and ii), making the dynamic coupling between the actuated-operative rotors immaterial. This modular nature and the custom toolchange system opens the possibility of a simple use by an ADS operator or by a ROV/AUV robotic arm, and will allow, in the future, to extend the set of tools that can be mounted by including also power tools and the like. A grasping force estimation algorithm has been tested with various objects through preliminary lab experiments, along with a fault detection procedure. Laboratory testing assessed the pressure-tolerant nature of the two terminal devices, which were able to withstand a pressure of 50 bar without visible damage nor degradation in performance. Field results, obtained underwater with a human operator up to a depth of ≃ 10 m, demonstrate that this new robotic end-effector could be well suited for those operations requiring a fine, adaptable grasp (e.g. archaeological recovery and biological sampling) that are currently challenging to be performed underwater. In the authors’ view this could aid to remove human operators from those underwater tasks that still require their direct intervention, i.e. from the risks of working in such difficult environments.

VII. ACKNOWLEDGMENT

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REFERENCES


\[\text{Table I}\]

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\[\text{Table I}\] Numerical values of secs. IV and V-A parameters.

\[\text{References}\]


\[\text{References}\]

Figure 9. Experimental validation of the end-effector with the SoftHand terminal device at a depth of $\simeq 1$ m. First four rows of subfigures show dexterous operation and the last row shows a force operation. In particular: (a-e) archaeological recovery, grasping a coin; (f-j) archaeological recovery, grasping vase shards; (k-o) biological sampling, grasping a reproduced coral; (p-t) biological sampling, grasping a reproduced aquatic plant stem; (u-y) force operation, turning a valve. First column subfigures show grasped object dimensions and for every experiment.
Figure 10. Validation of the soft gripper terminal device. First column subfigures show grasped object dimensions for every experiment.


