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Seabed intervention with an underwater legged robot

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Abstract— **Efficiently performing intervention tasks underwater is crucial in various commercial and scientific sectors; however, propeller-driven vehicles face limitations due to their floating nature. In Remotely Operated Vehicles (ROVs) operations, this can be compensated by the ability of the operator, but they come with high operational costs. Instead, Autonomous Underwater Vehicles (AUVs) have shown promise, but demonstrated intervention tasks are limited to controlled environments or docked. To address these limitations, we focused on the use of Underwater Legged Robots (ULRs), which offer greater stability and agile seabed mobility thanks to their legged propulsion system. This paper presents the field demonstration of teleoperated pick-and-place tasks using the ULR SILVER2 for which a novel stance control, Graphic User Interface (GUI), and tendon-driven gripper have been developed based on the lessons learned through several hours of field use. The methodology is validated through four field trials, including missions in both shallow water and open sea environments. The trials involve picking and placing various objects, such as plastic bottles, bags, and cans. The results demonstrate successful teleoperated object grasping and manipulation in real-world conditions, with collection times ranging from a few minutes to around ten minutes. Overall, this research contributes to advancing the capabilities of ULRs and lays the foundation for future underwater intervention missions in various scientific and industrial applications, aligning with the goals of the Decade of Ocean Science for Sustainable Development.**

I. INTRODUCTION

The mainstream approach to most underwater operations consists in the use of work-class Remotely Operated Vehicles (ROVs) deployed from specialized support vessels and operated by highly trained personnel, with daily costs that can easily reach 50 k€ [1]. For this reason, research on Autonomous Underwater Vehicles (AUVs) has thrived in the last decades and enabled several monitoring and inspection tasks including seabed mapping [2], surveys of the water column [3], and inspection of offshore structures [4] and archeological sites [5], [6]. Nevertheless, AUVs have not reached the same Technological Readiness Level (TRL) in operations involving interaction with the environment, e.g. the maintenance of underwater pipes and cable networks, or the sampling of biological specimens [7]. These applications require AUVs to be equipped with adequate perception and one or two robotic manipulators and since the 90s, several research projects - e.g. DexROV [8], Trident [9], MARIS [10], OceanOne [11] - focused on the implementation of various kinds of intervention tasks, as clearly reported in a recent review paper [12]. One of the main reasons for such a technological gap, is the floating nature of these type of vehicles. This condition makes the simultaneous control of robotic arms and vehicle positioning extremely challenging [13], and deeply affects the accuracy of Simultaneous Localization And Mapping (SLAM) [14] or 3D reconstructions [15]. At the time of writing, research in autonomous underwater intervention mostly focused on demonstrating three different tasks, namely grasping objects on the seafloor, panel intervention, and force regulation tasks. However, most works have been carried out either in simulation or in pools, with field demonstrations reported only for object grasping and docked panel intervention [12].

In order to overcome the limitations of floating intervention, the research focused on upgrading the perception and control systems of propeller-driven vehicles to improve the floating-base manipulation performance, or in adding new functionalities to dock, land, or getting anchored to the environment to damp the floating motion and reduce the problem to a fixed-based manipulation one. An alternative approach consists of re-examining the conceptual design of underwater vehicles which, except for minor upgrades, has not changed much since their introduction, to make it more suitable to intervention tasks. With this regard, negatively buoyant benthic vehicles such as crawlers [16], [17] or Underwater Legged Robots (ULRs) [18] have the potential to outperform propeller-driven vehicles thanks to their stable positioning. Benthic crawlers have been mostly developed for long-term deep-sea monitoring. Some prototypes have been equipped with robotic manipulators [16], however, to the best of the author's knowledge, manipulation trials using this type of vehicles has never been thoroughly reported in the scientific literature. ULRs instead are being developed as more versatile alternatives to crawlers and teleoperated object grasping has been demonstrated in the field on CR200 by using its two front legs as manipulators to handle dummy archeological artifacts [19], and on SILVER2 equipped with a soft pneumatic arm to pick-and-place both fragile and deformable objects [20].

In this paper, we present the latest developments on object grasping with the ULR SILVER2 (Figure 1). With respect to the work presented in [20], which focused on characterizing the workspace extensibility, force, energy consumption, and grasping ability of the ULR-soft arm integrated system, the present work takes a step forward towards the field

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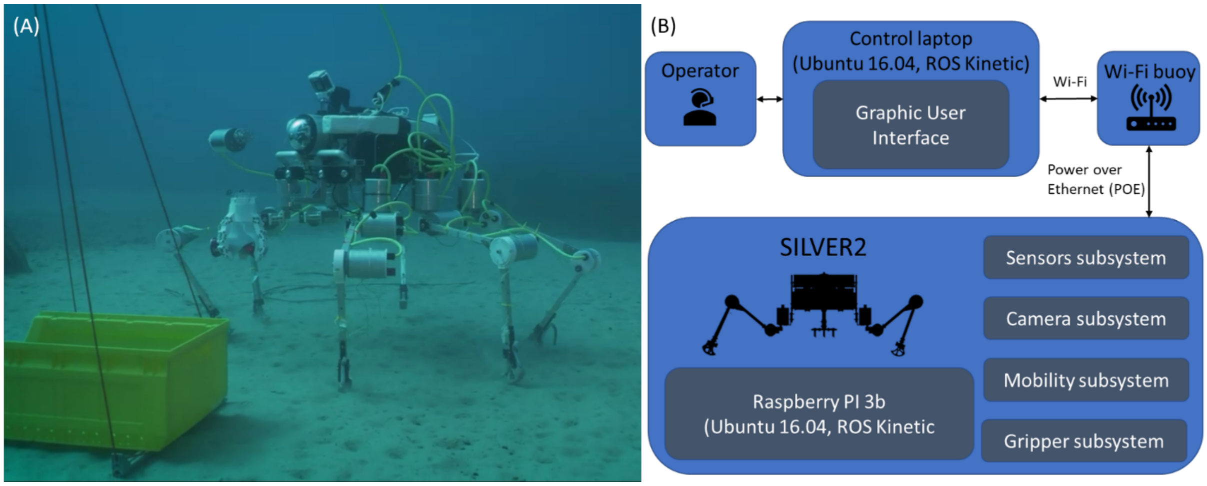


Fig. 1. (A) The ULR SILVER2 executing a pick-and-place task on a tin can at 16 m depth in Savona, Italy. Reproduced with permission from Igor D'India, 'Abyss Cleanup'.(B) Schematics of the functional architecture of teleoperation. The operator controls the robot through the GUI on the control laptop. The communication with the robot runs over Wi-Fi between the control laptop and a buoy equipped with a Wi-Fi router, and over Power Over Ethernet (POE) between the buoy and the robot's controller. The robot's controller is a Raspberry Pi 3b responsible for publishing the sensors' and camera's topics and exposing services for mobility, grasping, video recording, and camera gimbal control.

applications of ULRs in intervention tasks. Frequent use of SILVER2 in the field highlighted the need for an upgraded gripper design and a richer user interface, including a control strategy to regulate the stance of the robot for a fine positioning of the gripper base. These upgrades are presented in the methodology section to provide a complete picture of the hardware and software tools employed and allowed us to solve the problem of teleoperated object grasping for various kinds of marine litter. The proposed methodology is validated in two different locations with deployment of the robot from the shore, and from a rubber boat. The result section reports on such trials in terms of grasping success and grasping time.

II. METHODOLOGY

A. The ULR SILVER2

The reference platform used in this work is the ULR SILVER2, presented for the first time in [21] and shown in Figure 1A. The mechanical hardware has been designed to resist several hours of continuous field operations and it composed as follows. A structural subsystem, consisting of two parallel vertical poly-carbonate plates connected together by two aluminum bars and a Delrin™ plate provides structural integrity and attachment points for the canisters, the gripper, and the legs. A propulsion subsystem, consisting of six articulated legs with 3 independent joints with a Serial Elastic Actuator (SEA) on the knees, enables various forms of underwater legged locomotion with low environmental disturbance. Joints are enclosed in custom sealed canisters and actuated by Dynamixel X430-W350 (based on a coreless DC motors with stall torque of 4.1 N.m at 12.0 V, 2.3 A). Custom motor canisters were CNC-machined from aluminum Al 6061 with a thickness of 3 mm. Off the shelf canisters are made of anodized 6061-T6 aluminum with a thickness of 4 mm. Leg links were cut from Al 6061 profiles. Serial elastic actuators and feet were 3D printed in ABS. The robot has a dry weight of around 22 kg which makes it easily operable by two people. The control architecture of SILVER2 (Figure 1B) is based on a Raspberry Pi 3b running ROS Kinetic. The operator can interact with the ULR through a GUI installed on a control laptop running ROS Kinetic. The communication between the control laptop and SILVER2 is mediated by a buoy equipped with a Wi-Fi router, which allows wireless communication over Wi-Fi from the laptop to the buoy, and wired communication from the buoy to the robot Ethernet. This solution, as opposed to a direct wired connection between the robot and the control laptop, allows for more flexible deployment, harnessing the 50+ m range of the Wi-Fi buoy and the ability of SILVER2 to drag the buoy in good weather conditions. A summary of the main characteristics of the SILVER2 robot is reported in Table I. Average power consumption was calculated as the product of the mean current supplied by the battery times the nominal battery voltage, 12 V. Station keeping average power consumption refers to a low and wide stance typically employed in between behaviors [22]. Forward velocities have been derived by visual tracking of the ULRs on sandy sediment and were originally reported in [21]. Finally, the Noise introduced to the Environment ($NE_s = 10log_{10}\frac{E[x(t)]}{[E(n(t)]}$) was calculated as the ratio between the energy ($E[\cdot]$) of the acoustic signal measured during locomotion ($x(t)$) over the energy of the acoustic signal measured during station keeping ($n(t)$) [23] from a receiver directly attached to the robot chassis.

B. Soft tendon-driven gripper

Previous work on the integration of a soft-pneumatic arm on SILVER2 [20] highlighted the limitation of pneumatic technologies for underwater applications and the importance of employing a gripper based on clear specifications regarding the use case. Traditional underwater grippers are

SILVER2 Highlights

Weight	Dry:$W_d = 22kg$ Underwater:$W_u = 0.1 - 3kg$
Leg Length	$L = 0.6m$
Actuation	Dynamixel X430-W350 (based on a coreless DC motors with stall torque of 4.1 N.m at 12.0 V, 2.3 A)
Average Power Consumption	Static gait: $P_s = 60W$ Dynamic gait: $P_d = 42W$ Station keeping:$P_k = 30W$
Forward Velocity	Static gait: $V_s = 10cm/s$ Dynamic gait: $V_d = 25cm/s$
Seabed Types	Flat with moderate irregularities, sand, silt, pebbles, sand mixed rocks
Environmental Noise	Static gait: $NE_s = 17dB$ Dynamic gait: $14.8dB$
Deployment	Two operators from the shore or from a small vessel with no specialized equipment
Maximum tested Depth	$25m$

TABLE I

RELEVANT DATA ON SILVER2

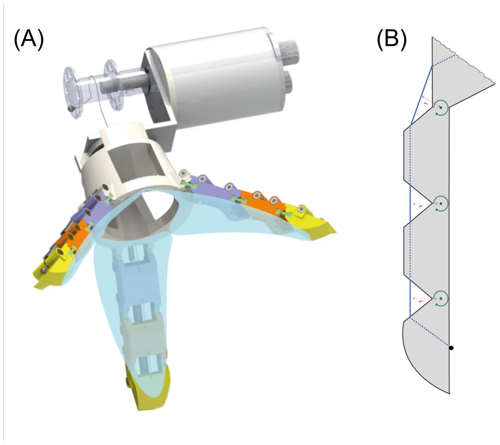


Fig. 2. The tendon-driven soft robotic gripper used in the presented work.

simpler to integrate with an electrically actuated robot such as SILVER2, but they are not suitable for handling soft deformable objects such as many types of marine litter or biological organisms. For these reasons, we have opted for designing our own gripper following a user-driven approach to account for the requirements of end-users, developers, and operators, specifically targeting litter collection and biological sampling tasks [24]. The end result is a tendon-driven gripper with three 12 cm fingers radially arranged around a hollow palm with a radius of 10 cm and a depth of 8 cm, and soft membrane to envelop samples and reduce the risk of losing them after the grasping (Figure 2A). The tendons of individual fingers are routed as shown in (Figure 2B) and are synchronously driven by a pulley attached to a servomotor. The fingers' joints are made of soft silicone to allow passive adaptation to the objects and load distribution. In parallel to the soft joints, linear springs have been integrated to dictate the stiffness of the grasp and to allow a passive return of the gripper to its open configuration. The gripper is mounted on the lower side of the ULR facing down to the seabed through a clear plexiglass component so as not to impair the camera visibility (Figure 1). A simple integration of the gripper was guaranteed by harnessing the same waterproof joint design and motor used for the legs for actuation. Having no feedback on the grasping force, the control of the gripper is obtained by simply regulating the motor angle between two extreme values representing a completely open and a completely closed configuration. When a stable grasp is obtained, the gripper can exert a maximum pull-out force $F = 37{\pm}3.7N$ [24] which is sufficient to lift almost 4 kg and allows SILVER2 to pull entangled or anchored objects. To obtain a stable grasp, the positioning of the gripper is crucial. We have intentionally decided not to add a manipulator to avoid increasing the total number of motors and to harness the mobility of SILVER2 to displace the gripper's base.

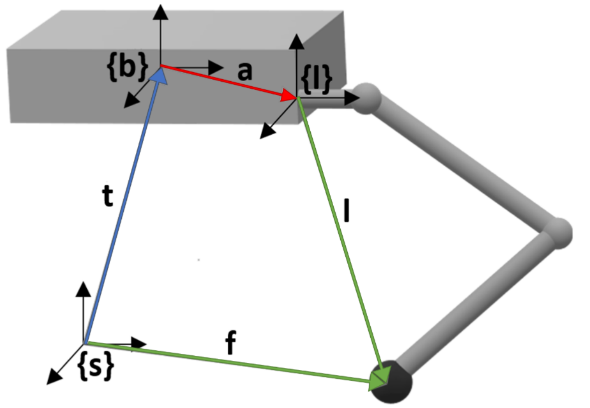


Fig. 3. Definition of vectors and reference frames for the calculation of the inverse kinematics of SILVER2

C. Inverse kinematic control

Once SILVER2 has reached the proximity of the target, the position of the gripper must be refined, prior to its activation, to secure a stable grasp. In this scenario, with the six feet on the ground, the ULR can be modeled as a Gough-Stewart (GS) platform, a classic parallel robot consisting of a platform actuated by six linear pistons. Adapting the well-known inverse kinematics of the GS platform to the articulated legs of SILVER2 allowed us to compute the joint angles to set a desired position and orientation of SILVER2's body, thus providing a convenient interface for the operator during the manipulation task. The derivation of the inverse kinematics of SILVER2 was presented for the first time in [25] and the final formulation is provided here for the reader's convenience. With a reference to Figure 3, the variation of the position of the $i-th$ leg $\dot{l}_{l,i}$ with respect to specific variations in the position $\dot{t}_b$ and orientation ω_b of the robot's body can be written as:

$$\dot{l}_{l,i} = -(\dot{t}_b + [\omega_b] \times (a_{i_b} + l_{l,i})) \tag{1}$$

where the subscripts indicate the reference frame (s is the world frame and the subscript is omitted, l,i is the $i-th$ leg frame, and b is the body frame), a_{i_b} is the position of the $i-th$ leg frame expressed in b, and $[\omega_b]$ is the skew-symmetric matrix of the angular velocity ω_b. By defining $J_{l,i}()$ as the analytical Jacobian of the $i-th$ leg and q_i as the corresponding joint angle vector, Equation 1 can be rewritten as:

$$J_{l,i}(q_i)\dot{q}_i = -(\dot{t}_b + [\omega_b] \times (a_{i_b} + l_{l,i})) \tag{2}$$

Assuming that none of the legs is in a singular configuration and thus the Jacobian $J_{l,i}(q_i)$ is invertible, both members of Equation 2 can be pre-multiplied by $J_{l,i}(q_i)^{-1}$ and after some algebraic passages we obtain:

$$q_i = J_{P_i}^{-1} \begin{pmatrix} \dot{t}_b \\ \omega_b \end{pmatrix} \tag{3}$$

$$J_{P_i}^{-1}(q_i) = [-J_{l,i}(q_i)^{-1} | (J_{l,i}^{-T}(q_i) \times (a_{i_b} + l_{l,i}))^T] \tag{4}$$

Where $\times$ is the cross-product operator, T is the transpose operator, and $J_{P_i}^{-1}$ is the contribution of the $i-th$ leg to the parallel robot's inverse kinematics which allows us to compute the joint angle displacements to obtain the desired change in position and orientation of the robot's body.

D. Teleoperated control

To allow the operator to intuitively control SILVER2, several pre-programmed behaviours have been implemented and exposed through the GUI shown in Figure 4. The central panel shows the streaming of the robot's camera, it allows the operator to record it, and regulate the intensity of the torches and the tilt (elevation) and pan (azimuth) of the camera gimbal. The left side of the GUI is dedicated to displaying sensor data including battery level, current absorption, motors' status, presence of leakages, temperature, depth, compass, accelerometers, and gyro. The right side, instead, allows the operator to select the next pre-programmed behavior from the drop-down menu, insert the desired parameters in the panel below, and start/stop the behavior. In terms of locomotion, two different strategies have been developed, namely the static omnidirectional gait and the dynamic punting gait. The omnidirectional walking gait is a general implementation of hexapod locomotion in which the operator can set the following parameters: walking direction, step length, gait period, stance height, stance width, ground clearance, duty cycle, and phase lag for each leg. The dynamic locomotion mode instead implements the underwater punting gait observed in crabs and other legged animals moving underwater [26] and it resembles a hopping locomotion. This gait presents interesting self-stabilizing properties even in the case of irregular terrains. It is faster than the static one, but it does not allow the operator to have full authority on the position of the ULR thus it is normally employed to approach the target. The parameters that can be selected by the operator are the hopping direction, stance height, stance width, ground clearance, and phase lag for each leg. Static and dynamic locomotion modes have been thoroughly presented in [21]. Besides locomotion, pre-programmed behaviors have been developed to activate the gripper and implement the so-called manipulation control mode, which allows the operator to finely regulate the position and orientation of the robot body as detailed in the previous section.

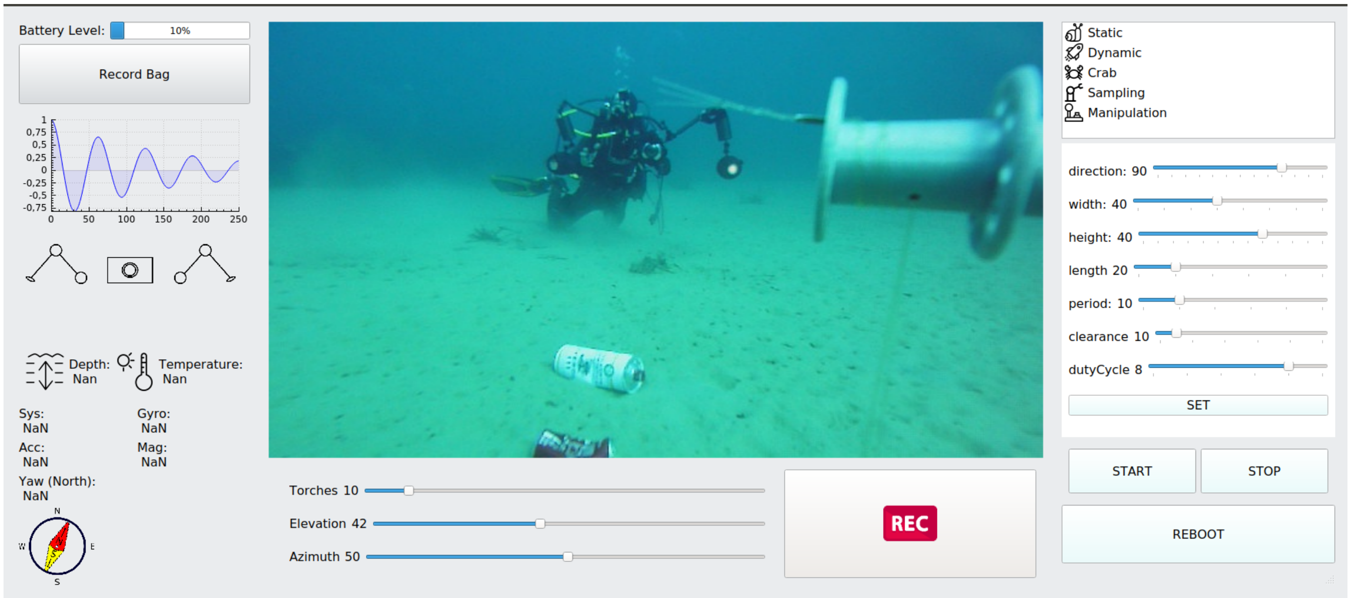
E. Experimental protocol

The presented methodology was validated through a series of four field trials according to the following experimental protocol. Ten target objects were randomly positioned in the testing area or found directly on site. In all cases, the trial consisted of the following steps: (0) move around the area until a target object is spotted by the operator through the camera feedback; (1) approach the target until it is in the workspace of the gripper; (2) obtain an adequate pre-positioning of the gripper using the manipulation mode and activate the gripper to grasp the object; (3) lift the object using the manipulation mode; (4) reach the collector box and activate the gripper to release the object. The target objects listed during the presented trials are listed in Table 1 and shown in Figure 6. Throughout the trials, an alternating tripod gait was used. For each object, the level of completion and collection time are reported. The level of completion is indicated by one to four •, indicating the number of steps of the sequence that were completed. The collection time indicated in Table 1 corresponds to the time elapsed between spotting the object and successfully releasing it in the collector box. For the objects that have not reached a level of completion of • • ••, it indicates the time between spotting the object and desisting from the task.

III. RESULTS

A. Shallow water trials

Missions I, II, and III took place in a shallow basin of water in the proximity of a touristic harbor in Livorno, Italy. The water depth was around 1.2 m with moderate turbulence, and the sediment was a mix of pebbles and sand. SILVER2 was deployed from a pier by two people harnessing the handles attached to the robot body. The target objects tested were a small plastic bottle, a plastic bag, a small ball with 5 cm of radius, a small piece of fishing net, a plastic jug, a larger plastic bag, a label, and a paper tissue. As shown by the completion levels in Table 1, a complete pick-and-place sequence (• • ••) was achieved on the small plastic bottle, plastic bag, ball, and fishing net. A complete pick-and-place sequence for the small plastic bag is shown in Figure 6. On the other hand, the plastic jug and large plastic bag slipped away from the gripper's fingers while moving towards the collection box (●●● ●), and the label and paper tissue slipped away in the act of being lifted (●● ●●). Three objects have target for two consecutive missions, namely the small plastic bottle, plastic bag, and ball observing a reduction of the completion time between 15% (ball) and 59% (small plastic bottle). Although the number of repetitions of these trials is not high, it can be said that the operator got easily used to the GUI and felt more confident in tackling the task. The objects for which the complete pick-and-place sequence was not completed are all lightweight and highly deformable so that they would considerably change shape and position during



Battery Level: 10%

Depth: Nan

Temperature: Nan

Sys: NaN

Gyro: NaN

Acc: NaN

Mag: NaN

Yaw (North): NaN

Torches 10

Elevation 42

Azimuth 50

direction: 90

width: 40

height: 40

length 20

period: 10

clearance 10

dutyCycle 8

Fig. 4. The GUI of SILVER2. The left panel shows the status of sensors including battery level, current absorbed, leakage sensors, depth, temperature, compass, and IMU. The central panel shows the streaming from the camera and allows the operator to set pan and tilt of the camera and regulate the torch intensity. The right panel allows the operator to send commands to the robot selecting different modes.

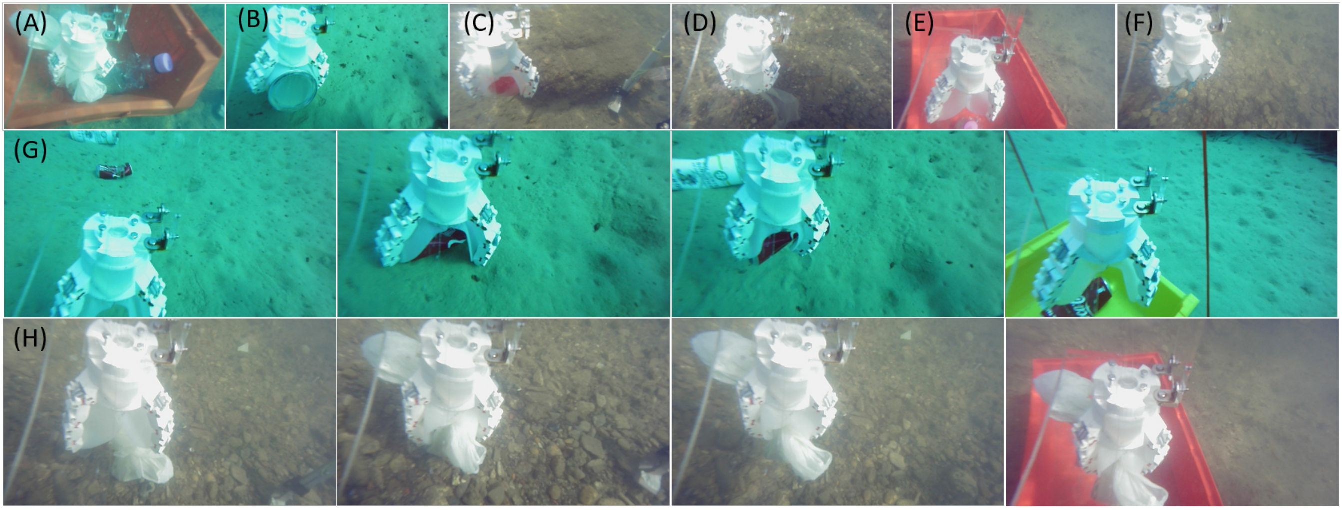


Fig. 5. Some objects picked by SILVER2 during the presented trials. (A) Plastic bag, (B) large can, (C) ball, (D) tissue, (E) plastic bottle, (F) fishing net. (G) Pick-and-place sequence of a plastic bag in Livorno, Italy. (H) Pick-and-place sequence of tin can in Savona, Italy.

the trial under the effect of currents (except for the plastic jug), thus making the task more challenging. However, it is worth noticing that we have achieved the completion of the pick-and-place sequence for a small plastic bag (Figure 6).

B. *Open water trials*

Mission IV took place off the coast of Savona, Italy. The water depth was around 16 m with absent/very low currents, and the sediment was sandy. SILVER2 was deployed from a small rubber boat by two people harnessing the handles attached to the robot body and made it gently reach the seabed by controlling the descent using a rope. The presence of lead ballasts in the lower part of the robot and foam in the upper part allowed SILVER2 to descend by keeping a stable orientation with legs down. The target objects tested were a small and large tin can. The complete pick-and-place sequence was successfully realized on the small can (Figure 7), whereas the large can slipped away while moving towards the collector box (● ● ● ●) probably because of its size with respect to the gripper.

IV. DISCUSSION AND CONCLUSIONS

In this paper, we presented the latest development on the implementation of teleoperated underwater intervention using a ULR. With respect to previous works from the same authors [20], here we have focused on enabling teleoperated intervention in the field and successfully completed pick and places experiments not only in a shallow body of water,

		Collection time (hh:mm:ss)			
Objects	**Level of Completion**	**Mission I**	**Mission II**	**Mission III**	**Mission IV**
Small plastic bottle	● ● ●●	00:15:10	00:06:13		
Plastic bag	● ● ●●	00:12:50	00:06:29		
Ball	● ● ●●		00:09:26	00:07:58	
Fishing net	● ● ●●		00:07:29		
Can	● ● ●●				00:10:18
Plastic jug*	● ● ● ○	00:02:05			
Large plastic bag	● ● ● ○			00:08:36	
Large can	● ● ● ○				00:11:34
Label	●● ○○		00:10:45		
Paper Tissue	●● ○○		00:12:03		
	Average	00:14:00	00:07:24	00:07:58	00:10:18
	Average● ● ●	00:14:00	00:08:44	00:08:17	00:10:56

TABLE II

COLLECTION TIMES OF THE OBJECTS REPORTED IN THIS WORK ACROSS THE FOUR FIELD TRIALS. THE COLUMN 'LEVEL OF COMPLETION' INDICATES WHETHER THE CORRESPONDING OBJECT HAS BEEN REACHED, GRASPED, LIFTED, PLACED IN THE COLLECTION BOX. THE * INDICATES THAT THE COLLECTION TIME WAS NOT INCLUDED IN THE CALCULATION OF THE AVERAGE BECAUSE IT WAS CONSIDERED AN OUTLIER.

but also in the open sea at a depth of 16m. In terms of object picking, the upgrades presented in this paper allowed successful pick and place of deformable objects such as plastic bags and fishing nets, that could not be picked in [20] due to the tendency of being pushed away by the pneumatic manipulator. Although not reported in [20], the operational times and overall complexity of the operations have also been drastically reduced. Indeed, the GUI and the stance control allowed the operator to command small linear and angular displacements of the body to rapidly reach a suitable position for grasping. Naturally, the expertise of the operator is also a crucial factor which can deeply affect the collection time and in the future, human studies will be carried out to further improve the interface, and track down the learning of operators. Additionally, the pneumatic soft manipulator was replaced with a tendon driven soft gripper inspired by the Ocean One hand [27] and developed in close collaboration with end-users [24]. The membrane attached to the fingers played a significant role in grasping neutrally buoyant objects that can be erroneously pushed away during operations, e.g. plastic bags or fishing nets. At the same time, the choice of using the same actuators of the legs, dramatically simplified the integration. In this work, we have decided not to add additional DoFs between the robot body and the gripper to reduce the number of actuators and harness the dexterity of SILVER2. However, for small displacements of the gripper, large coordinated joints movements are required with a potentially higher energy consumption. In the future, a study to compare different manipulation strategies in terms of efficacy, energy consumption and intuitiveness for the operators will be performed. Frequently deploying the platform SILVER2 in the field allowed the research team to implement several refinements and conceptualize the GUI, inverse kinematic control, and gripper which resulted directly from the lesson learned in the field. We believe that this approach, as opposed to focusing on getting the task perfectly executed in a controlled environment before moving to the field, has dramatically cut down development times by forcing the developers to continuously face the challenges of the field. Similar methodological considerations apply to all kind of field robots being them applied in agriculture, marine environment, or any other task in a real environment and are promoted by the several robotic competitions organized worldwide, from Darpa Challenges to Eurathlon. Even though very interesting and useful for the scientific community, a direct comparison between the presented results and other pick and place trials executed by propeller driven vehicles is not viable due to the heterogeneity of the experimental conditions. Indeed, using propeller driven vehicles, autonomous picking has been demonstrated in experimental tanks [12], while in this paper we report teleoperated picking but in the field. Notwithstanding this, the floating nature of propeller driven vehicles is directly affecting their ability to perform SLAM [14] or 3D reconstructions [15] and future autonomous implementations of pick and place tasks with ULRs based on the present work hold promises to outperform their pelagic counterparts. Underwater legged robotics is a new field at the interface of legged and underwater robotics [18]. At the time of writing only a few prototypes have been developed and thoroughly tested, but as the availability of waterproof sealed actuators will grow with technological advancements, several roboticists and end-users will deploy legged robots underwater adapting and extending existing algorithms to enable new capabilities and behaviours, to tackle both industrial and scientific challenges, especially related to the ongoing Decade of Ocean Science for Sustainable Development [28]. On a final note, performing such grasping trials on marine litter has proved to be a successful choice from a double perspective. On one hand, the great diversity of marine litter made the task more realistic and complex, especially in the case of plastic bags and other deformable objects. On the other, it allowed us to investigate a sensitive topic with great social impact and engage with the civil society through several dissemination events and involvement in the media.

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