Marine Sediment Sampling with an Underwater Legged Robot

Anna Astolfi*, Mrudul Chellapurath*, Giacomo Picardi*, Martina Capriotti, Kayla Mladinich, Cecilia Laschi, Sergio Stefanni, and Marcello Calisti

***Abstract*—In this work we present a novel system for marine sediment sampling aimed at microplastic (MP) assessment studies. The system is composed of a medium-sized Underwater Legged Robot (URL) equipped with a customized sampler consisting of a grab mounted on an underactuated mechanism. The system was developed following the requirements of marine biologists actively involved in MP pollution investigation. The requirements include the penetration depth, the weight of the sample, the possibility of collecting replicas without returning to the boat or the shore, the amount of sediment perturbation introduced by the system, and the sampling accuracy. The proposed system has been tested under controlled conditions in a tank, as well as in real conditions in two different field trials. Our results showed that the proposed system is capable of meeting all user requirements by taking advantage of the capabilties of ULRs in terms of low sediment resuspension, precise position control, and increased station-keeping capabilities coupled with the custom sampler design. Sediment collected during field trials has been analyzed, extracting information about the quantity and composition of MPs, in order to provide an overview of the complete procedure. This work represents an important step towards the use of legged robots in marine operations, and contributes to highlight the importance of multidisciplinary collaborations among roboticists and scientists to develop novel solutions and increase the sampling capabilities of end-users.**

***Index Terms*—marine robotics, ocean conservation, legged robots, microplastics**

I. INTRODUCTION

Marine sediment sampling plays an important role in enhancing our understanding of marine ecosystems, including their geological characteristics, biodiversity, pollution levels, and interconnected ecological processes. Various methods and equipment have been proposed for obtaining sediment samples from the seabed. The most suitable choice depends on the type of analysis, with factors to be considered including the desired sediment quantity, and sampling depth [1]. For example, sampling for microplastic assessment requires a relatively small amount of sediment, extracted from the superficial layer of the seabed with a high spatial and temporal resolution. Most importantly, the sampling action should not perturb the sediment to prevent the suspension of lightweight particles and affect the results of the studies [2]. Traditional methodologies for sediment sampling fail to simultaneously meet all the requirements of microplastic assessment studies while keeping the operational costs low. Expert SCUBA divers equipped with various types of samplers can meet the aforementioned requirements. However, SCUBA divers can only operate in coastal waters and with limited operational time, thus making sampling too expensive to be employed systematically or even dangerous, especially in deeper regions. Other widely used techniques, such as dredging, box corers, grab samplers, and push corers, enable sampling in deeper regions, but they typically rely on the use of research vessels, cranes, winches, and wires [1], which increase the operational cost and feature low spatial resolution. Furthermore, there is little to no control on the interaction between the sampler and the sediment with a high risk of causing undesired sediment suspension during the sampling action. Remotely Operated Vehicles (ROVs) offer a better and more precise way to collect samples from specific locations on the seabed, allowing the operator to monitor the sampling process in real time with their onboard cameras [3], [4]. Most ROVs with sampling capabilities fall under the category of heavy working class vehicles [5], which require huge machinery and a specialized medium crew for transportation and mission execution [4] at costs that are not affordable for many marine scientists around the world. Light-weight mini-ROVs are a feasible alternative that is more effective in terms of cost and effort, and previous works have attempted the design and integration of core samplers directly attached to the vehicles and pushed onto the ground by thrusters [6], [7]. However, regardless of the size, when operating close to the seabed, the propellers' slipstream can suspend the sediment, disturbing the natural state of the surface layers. Additionally, due to their buoyant nature, ROVs can drift away under the effect of currents affecting the overall sampling operation [8]. Recently, with the aim of overcoming the limitation of propeller driven vehicles in seabed operations, the use of Underwater Legged Robots (ULRs) have been proposed [9]. Previous studies on URLs have demonstrated minimal compaction or suspension of the sediment [10]. Moreover, they showcase improved station-keeping capabilities with respect to ROVs, harnessing a low stance and frictional interaction with the seabed to counteract current disturbance [11]. In particular, bioinspired URLs are

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preferred for applications for conservation tasks [12] due to their ability to blend into the marine ecosystem with minimal noise [13] to explore and collect samples [14].

This study introduces an innovative sediment sampling system designed to concurrently fulfill all the requirements for microplastic assessment studies, all the while maintaining cost-effectiveness. Through collaboration with marine biologists engaged in microplastic pollution research, a set of specifications is derived, serving as a guiding framework to both inform and validate our design. The envisioned system comprises a ULR equipped with a purpose-built sediment sampler tailored specifically for this application. Additionally, a sampling protocol linked to the proposed system is established, and the system's adherence to specifications is validated through a series of tank and field tests. The sediment collected during field trials has been analysed with the aim of showcasing the complete procedure and highlighting possible improvements. The results confirmed the effectiveness of the proposed approach and laid the foundations for the use of legged robots in marine sediment sampling applications.

II. DESIGN AND DEVELOPMENT

A. *End-users specifications for the design of a sediment sampling system for microplastic assessment*

Sediment sampling for microplastic assessment presents specific requirements related to the physical characteristics of the particles and their dispersion in the environment. In particular, leveraging existing literature and hands-on experience of marine biologists, we have identified the following specifications that a sediment sampling system for MP assessment must meet:

R1: Penetration depth. MPs pollution occurs as a deposition process and particles are more likely to be found in the superficial layer. As required by standard protocols [2], the sampling system must collect sediment from the first 5 cm.

R2: Sediment resuspension. Do not perturb the sediment upon sampling. Suspended MP particles are likely not collected during sampling, causing an underestimate of the amount of microplastic in a given area.

R3: Sampled weight. Collect a sufficient amount of sediment from the interesting strata for data analysis. This amount ranges from 30g to 400g according to [15].

R4: Collection of replicas. Collect different replicas from the area of interest without the need to come back to the boat, to minimize the sample contamination.

R5: Sampling accuracy. The system must be accurate in order to prevent damage to living organisms or erroneous sampling on rocks, seaweed, or underwater structures.

B. *Design framework*

On the basis of the design specification introduced in section II-A and the limitations of the state of the art, it was decided to design a sediment sampling system consisting of a small ULR equipped with a customized sediment sampler. Resorting to this category of underwater robots potentially allows to retain the benefits of ROVs in terms of ability to monitor the sampling action in real-time and accurately select the sampling location, while mitigating the sediment suspension and improving the rejection of currents. The reference platform used in the work is SILVER2, a remotely operated hexapod robot, designed for environmental monitoring and research and presented for the first time in [10] (Figure 1). In previous works, SILVER2 was equipped with different tools for marine intervention, such as grippers and soft arms, which have been used for the collection of litter and biological specimens [16], [17]. For the purpose of MPs analysis, a novel sediment sampler has been created, and presented with more details in the next section.

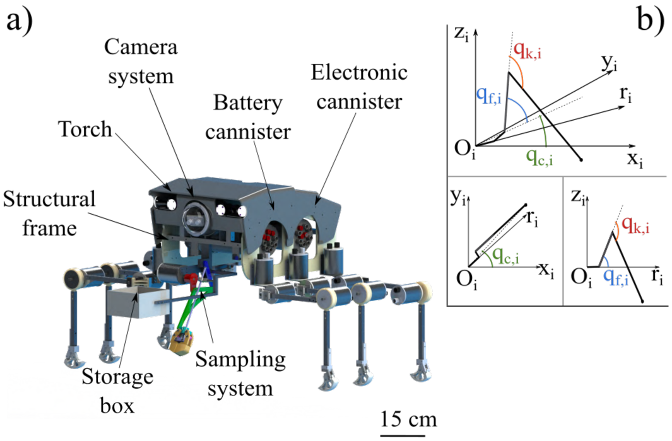

Fig. 1. a) The underwater legged robot, SILVER2, and its components. b) The definition of joint angles of its leg.

C. *The Sediment Sampler*

During sediment sampling operations working-class ROVs are generally equipped with push-corers which help to collect sediment without mixing between the layers [18]. However, corers are not suitable for lightweight vehicles which do not posess sufficient inertia and thrust to push them into the ground. For this reason, it was decided to design a customized sampler. The mechanical considerations underlying the design of the sampler were the following:

- The sampler should use as fewer actuators as possible to reduce the overall weight and complexity of the system, while relying on the mobility of ULRs to increase its workspace.
- Sampling ability should not be hindered by the light weight of the ULR.
- The sampler should be able to extend towards the seabed to collect the sediment and then retract towards the storage box of the robot.

With these considerations in mind, a compact sediment sampler was designed using an underactuated mechanism, consisting of three components: a four-bar linkage arm, a grab mechanism, and a storage box (Figure 1 and 2). The grab should open and collect the sediment when it is close to the seabed, close and transfer to the storage box without any escape of the sediment, and finally open and deposit the

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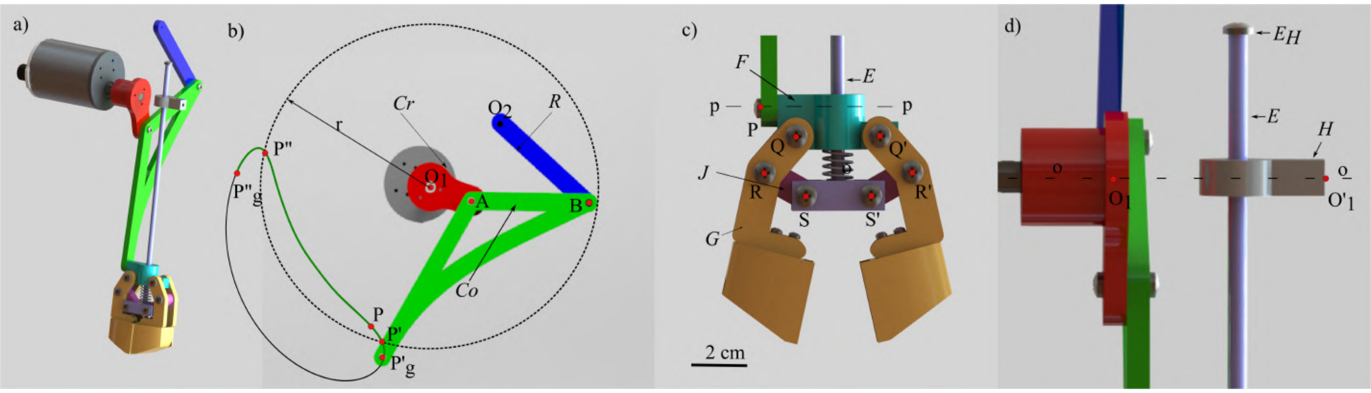

Fig. 2. The CAD model of (a) the sediment sampler, (b) the four-bar linkage arm, (c) the components of the grabbing mechanism and its connection to the coupler point, P, and (d) to the robot at O_2

sediment in the storage box. The three components of the sampler are described below.

Four-Bar Linkage Arm. The function of the four-bar linkage arm is to move the grab mechanism from the seabed to the storage box and *vice versa*. We chose a crank-rocker type mechanism with a crescent-like shape coupler curve as shown in Figure 2b. The crank Cr was fixed to the shaft of the motor at O_1, and the rocker, R was connected to the structure of the robot at O_2 by a revolute joint. The coupler Co was connected to the crank and the rocker at A and B with revolute joints. Segment O_1O_2 has to be considered the ground of the mechanism. The crank was rotated such that the coupler point moves from point P'_g to $P"_g$ (green path in the coupler curve (Figure 2b)). At P'_g, the coupler point, where the grab is located, was at the surface of the seabed, and at $P"_g$, it was inside the storage box. The grab mechanism was designed in such a way that the grab is in an open state when the coupler point is between P'_g and P' as well as between $P"_g$ and $P"$. It remains closed when the coupler point moves from P' to $P"$.

Grab Mechanism. The grab mechanism was a single Degree-of-Freedom (DOF) linkage mechanism that opened and closed its grab by the movement of a long cylindrical rod, E (Figure 2c). It was connected to the structure of the robot through the link H at point O'_1 and link F at the coupler point, P through revolute joints, which allowed free rotation about the axis $o-o$ (Figure 2d) and $p-p$ (Figure 2c), respectively. The rod, E was connected to links F and H through cylindrical joints which allow free movement along its length. The grab, G was connected to the link H and link J at points R and Q through revolute joints (Figure 2c). The sliding motion of E is transferred to the opening and closing of the grab through linkage motion. However, the linkage motion was restricted by the compression spring whose two ends are fixed at two ends; one at the base of E and the other at the lower side of F. The length of the rod was chosen such that when the distance of the coupler point, P was greater than the radius, r, the rod head E_h touched the link H and prevents the further sliding of E (Figure 2b and d). At this condition ($O_1P > r$), link F was forced to slide down by compressing the spring, resulting in the opening of the grab. Hence, when the coupler point was between P'_g and P' as well as $P"_g$ and $P"$ (i.e. $O_1P > r$), the grab opened and remained closed between P' to $P"$ (i.e. $O_1P < r$). The connections and the movement of the two grabs were symmetric, allowing scooping of the sand while closing (Figure 2c).

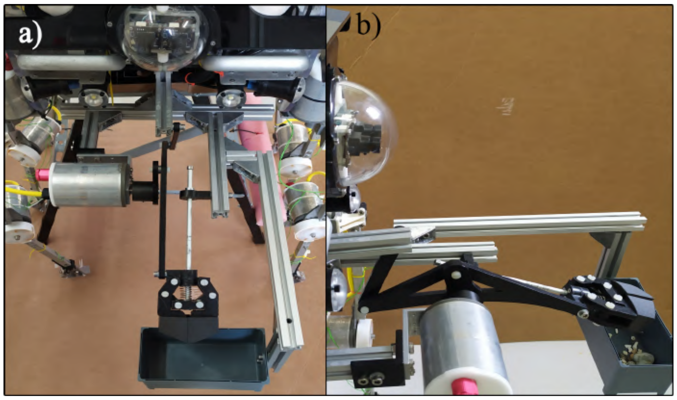

Fig. 3. The a) top and b) side view of the sampling system after integration into the SILVER2 robot

Storage Box. The storage box was a rectangular box open at the top. It was fixed to the robot structure directly under $P"_g$ and $P"$, to allow the sediment to fall into it when the grab opens while avoiding interferences with the grab and the arm (Figure 1).

The linkage lengths are selected on the basis of kinematic analysis. The components were fabricated, assembled and then integrated with SILVER2 as seen in Figure 3a and b.

D. Teleoperated Controller

The control architecture of SILVER2 is based on the Robotic Operating System (ROS). A series of preprogrammed behaviors can be invoked by the operator through the associated ROS services. These behaviors represent a convenient interface for the operator as they convert inputs at a high level of abstraction (e.g. locomotion direction, step length, legs' duty cycles, etc.) into low-level commands for the motors (see Figure 4a). Moreover, the operator harnesses the visual feedback from the robot's camera to be aware of the context

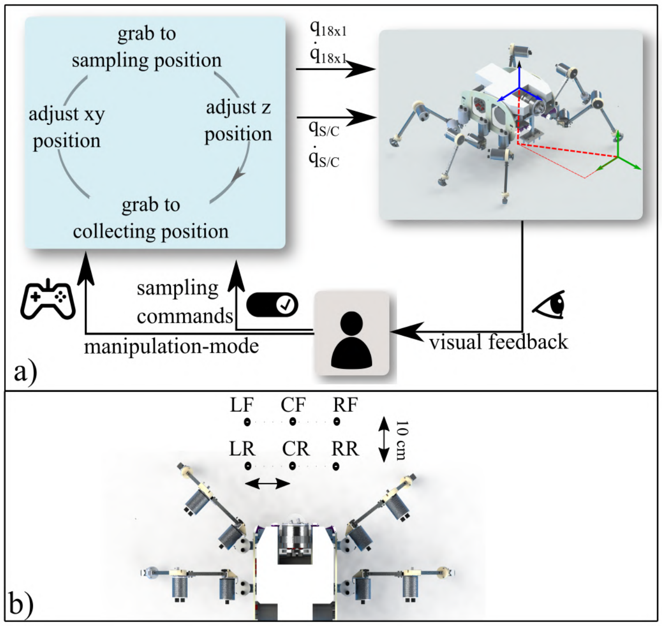

Fig. 4. a) The teleoperated controller: first the user resorts to the available locomotory behaviours to navigate the environment around the deployment site (not shown) while the sampler is in the retracted *collection position* not to hit the sediment. Once the desired sampling site is reached, the user resorts to the parallel robot behaviour to adjust the pose in the x-y plane and select the exact sampling position. The manipulative behaviour is used to position the sampler in the extended *sampling position*. Later, the parallel robot behavior is employed to adjust the vertical position of the grab (z-direction) and let the grab penetrate the sediment. Finally the manipulative behviour is used again to activate the sampler which collects the sediment, and transition to the *collection position* while letting the sample fall into the collection box. The robot cameras provide the user with visual feedback to switch between these behaviors. b) The sampling position chosen for the sea experiments protocol.

surrounding it and to make decisions. Three different kinds of behaviors are currently available on SILVER2:

Locomotory behaviors. Used to displace the robot using different gaits and allowing the user to select relevant locomotion parameters.

Manipulative behaviors. Used to actuate the sampler or other end effectors. In the context of this work, it consists of a position controller for the sediment sampler's actuator (Dynamixel X430-W350 smart servomotor). The rotational motion of the actuator allows the grab base to move along the green trajectory of Figure 2b from point P_g'', namely the *collection position* to P_g', namely the *sampling position*.

Parallel robot behavior. Allows the operator to finely regulate the displacement and orientation of the robot body when it is in a stationary configuration with all six legs on the ground, similarly to a Stewart Platform [11].

These behaviors have been used to define a protocol to perform sediment sampling with the robot, as detailed in the next section.

E. Sampling protocol

A sampling protocol was defined based on the available teleoperated behaviour described in the previous section. A schematic of the teleoperated routine is depicted in Figure 4a-b. First, the robot is moved to the site, according to the composition of the substrate, using one of the locomotory behaviors implemented and presented in [10]. While moving, the grab is set to the *collecting position* as a safety measure to avoid hitting the mechanism against the environment with the possibility of damage. When the desired spot is reached, SILVER2 is controlled using the parallel robot behaviour to finely regulate the robot's pose relative to the sampling location. This is a two-step process, where first small increments in the x and y directions are applied to align the sampler with the target site. Then the sampler is activated using the manipulative behaviour to move the grab in the extended *sampling position* P_g'. Finally, the robot's height is decreased using the parallel robot behaviour until the tip of the open grab penetrates into the sediment (*adjust z position*). At this point, the actual sediment collection occurs by commanding the sampling mechanism to move toward the *collection position*, and a new sediment sampling cycle can start over.

In order to collect an adequate amount of sediment, the sampling cycle is repeated at slighlty different sampling locations, with the robot legs in the same position. To standardize the collection of sediment we selected points that were located on two lines, one closer (rear -R) and one further (front-F) from the robot base. We selected three points along each line: on the center, right, and left (C, R, L). The points were located approximately 10 cm from one to another, as depicted in Figure 4b.

III. RESULTS AND DISCUSSION

A. Protocol Testing

The sampling procedure was tested in a tank to get the operator accustomed to the procedure and to assess the effectiveness of the routine without disturbances of the environment, such as waves or currents. The tank ($4m$ x $2m$ x $1.5m$) was filled with water up to $1.4m$ (Figure 5). Three different types of sediment (sand, gravel, and a 1:1 mixture of sand and gravel) were used (Figure 5). A box open at the top was filled with the sediments and kept on the floor of the tank. The box was filled with sediment up to the height of the platform, where the robot was placed (Figure 5a). The experimental protocol was executed step by step for each sediment. During the trials we collected (1) high resolution video of the sampling system from a fixed camera outside of the tank, (2) high resolution video of the sampler from a camera inside the tank, (3) streaming of the onboard camera of SILVER2, (4) robot vertical position from the pressure sensor positioned on the control canister, (5) overall current absorbed by the system, (6) linear acceleration of SILVER2 body from the onboard IMU, and (7) contacts of the robot's feet with the ground.In Figure 5, we report the vertical excursion of the robot and the current absorption, during the collection of the three sediments. We can clearly distinguish the four phases of the sampling cycle, as shown in Figure 5a-c. Starting from a high-stance, the position of the grab in the x-y plane is adjusted to reach a target sampling spot (Figure 5a1). The robot leans forward without changing its height. When the

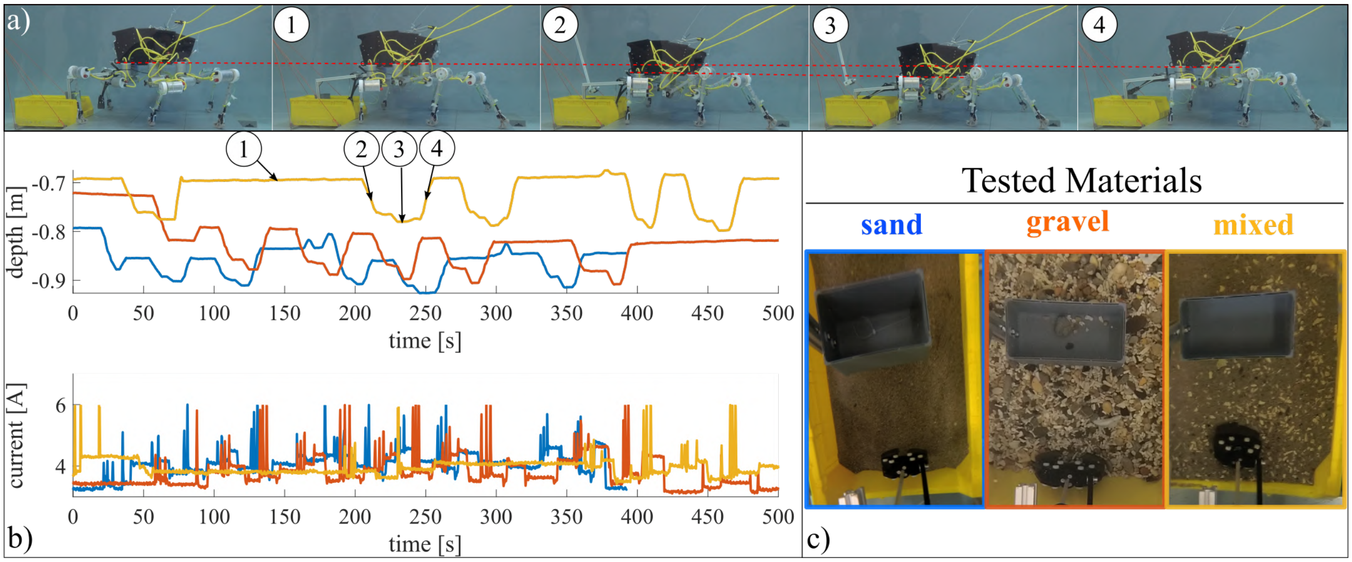

Fig. 5. Tank experiments with SILVER2. (a) Snapshot of the different stages of the sampling routine. (b) Robot Base Position and Current Absorption during 5 repeated sampling of different sediments: sand, gravel, and mixed sediment respectively, represented in (c).

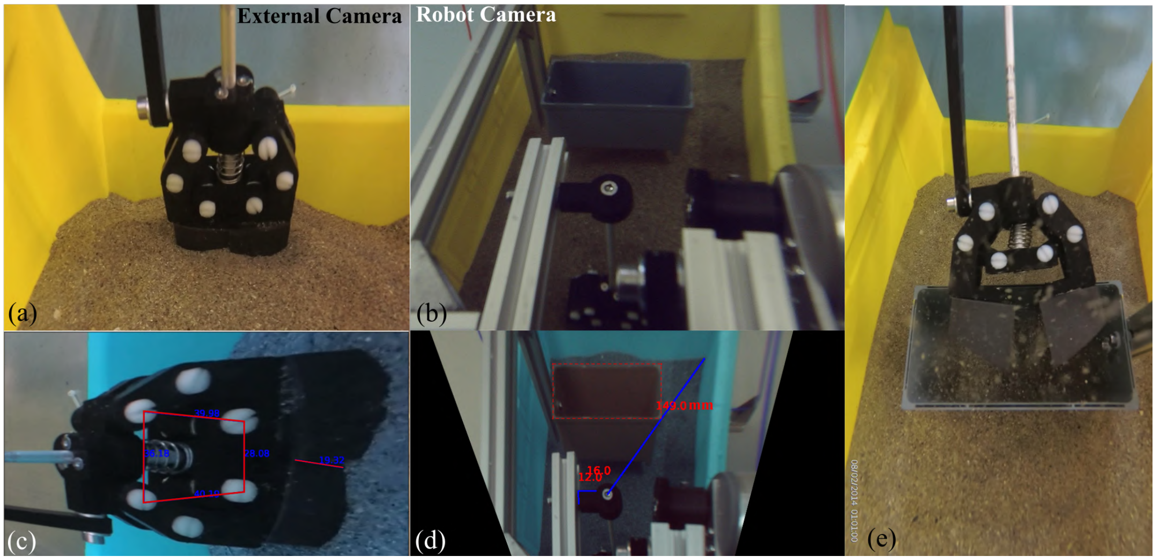

Fig. 6. (a) Penetration depth image from an external camera and (c) perspective correction to retrieve measurement. (b) Robot POV during the sampling operation; (d) visual servoing of the grab position relative to an external reference frame. (e) sediment resuspension from an external camera.

operator is satisfied with the visual feedback from the onboard camera, the grab is moved to the *sampling position*, and the robot is moved downward (Figure 5a2) until the grab touches the ground (Figure 5a3). The operator decided to perform this action with smaller steps when close to the sediment to avoid mechanical shocks to the system. The robot then restores the initial height (Figure 5a4). The average vertical excursion for these experiments was around 10 cm from the initial high-stance posture. No significant differences in current absorption have been observed for the three sediments types.

Following these initial tests, the sediment sampling system has been validated in field experiments. The same data of the tank trials were recorded with the exception of the high resolution video from an external fixed camera. The trials were performed in the Tyrrhenian Sea in two different locations near the coast of Livorno (Figure 7), namely the *Scoglio della Regina* or simply SCOGLIO (43.539, 10.301), and the *Bagni Rex* or simply REX (43.488, 10.329). In all the experimental trials, the robot was controlled from the shore.

B. System validation

In this section we outline how the presented sediment sampling system meets the end-user requirements for MP analysis.

R1: Penetration depth. The penetration depth of the grab was assessed with a video analysis by applying a perspective correction to the image from the external camera focused on the sampler (Figure 6a and c) and using the length of the grab claw (3.3 cm) as a reference. The analysis was performed on the sand sediment experiment and showed that the grab compenetrates the substrate by 1.1 cm along its central axis. Although this estimate confirms the ability of the system to sample in the surface layer, it must be noted that a higher penetration would reduce the chances of underestimating the microplastic presence. Furthermore, by looking at the current data shown in 5 b, we did not observe significant differences between the sediment types tested, and the absence of peaks in correspondance of point 3, suggest a gentle interaction between the robot and the sediments.

R2: Sediment resuspension. In the absence of dedicated equipment such as a turbidy sensor, or a particle camera,the sediment resuspension upon sampling was qualitatively observed using an external camera (Figures 6e and 7) and from the robot on-board camera. Supplementary videos show very little sediment suspension during both locomotion and sampling tasks. Furthermore, it can be observed that the suspension occurred due to the motion of the grab within the substrate after the grab was closed, which means that the sample is representative of the actual composition of the sediment.

R3: Sampled weight. The maximum volume that can be collected in a single deployment depends on the number of repetitions of the sampling action and the size of the collector box, which for the prototype shown in this paper is 840 cm^3. The average volume collected for a single sampling cycle depends on the sediment type. The volume of samples was obtained by observing the water level rise in a container after the sample was deposited. The average volumes per sampling cycle were 8.75 cm^3 for the sand, 4.5 cm^3 for the gravel, and 7.75 cm^3 for the sand-gravel mix. These quantities are inversely related to the density of the material, i.e., less volume per sampling action as the volume of sediment increases (see Supplemental Video). Therefore, to meet the required sampling weight for MP analysis, it is necessary to repeat the sampling cycles. Generally, considering that all sediments have a density greater than $1g/cm^2$, 5 repetitions of the sampling cycle are sufficient to guarantee a total amount greater than $30g$. In field experiments, the size of samples collected from each location was 314.8 g (REX) and 98.75 g (SCOGLIO).

R4: Collection of replicas. The five repetitions carried out during this test campaign took between 6 and 8 minutes per sediment type (Figure 5b) for a non-trained user. This confirms that the procedure is simple to carry out and that it can be repeated several times considering an average battery duration of more than 6 hours. The presented system is thus capable of collecting several different replicas. Currently, all samples are mixed in the collection box, which limits the resolution of the analysis to the overall deployment area. If a higher resolution study is required, an automatic cartridge for the samples can be added to the system to allow separate storage of samples. Finally, if higher amounts of sediment are required, the whole system can be scaled to larger ULRs.

R5: Sampling accuracy. By "sampling accuracy" we mean the ability to collect the substrate from an area where the composition properties can be thought of as the same. In the field, wave motion and the lack of external markers make it very hard to assess such a metric quantitatively. For technologies deployed from vessels, this is even more challenging, as the vessel itself may be subject to movements in the surge and sway directions induced by waves. Our proposed solution exploits the interaction with the sediment itself through the legs of the ULR, allowing us to evaluate its station-keeping capabilities, i.e. holding a position relative to the ground, by means of inertial measurement units (IMU). From a theoretical point of view, the robot's base position and orientation accuracy can be calculated using the Jacobian of SILVER2 for the case in which all feet are in contact with the ground (details on the calculation of the Jacobian can be found in [19]), and the angular resolution of its actuators. As an example, we can consider the starting configuration of the parallel robot mode depicted in Figure 4, where the knee joint angles are $q_{k,i} = 130deg$, the femur joint angles are $q_{f,i} = 50deg$ and the coxa joints angles are $q_{c,i} = [45, 0, -45, -45, 0, 45]$ moving clockwise from the front right leg. Considering the angular resolution of the actuators $r = 1.53e-3$ rad, the errors in the linear displacement are in the order of the millimeters, $p_{err} = [-3.16, -6.52, -1.58]e-2mm$, whereas the errors in the orientation are fractions of a degree, $or_{err} = [-0.01, 0.030.03]$. The positioning error of the robot's base translates to the end-point of the grab, as they are rigidly connected. It is worth noticing that this is a lower estimate of the actual error as the presented analysis does not account for slippage of the feet, mechanical clearance, compressions of the SEAs, and current disturbances. Such a theoretical analysis was complemented with data extracted during tank experiments. Here, a visual servoing strategy was employed to locate the grab position in an external reference frame and estimate the variation of the sampling point over repeated actions (Figure 6b and d). The positional error estimated through this technique is 0.61cm (4 repetitions considered on the sand substrate). In the field experiments, where visual servoing strategies are not practical, we performed the sampling operations adopting a low and wide stance (Figure 7b) to better counteract external disturbances. In Figure 7c, we report the vertical position, linear acceleration, and contacts of the robot over 220s during a stationary phase. Contact with the ground was maintained for the whole duration of the data acquisition for all feet, and the robot experienced low accelerations in the x-y plane during the field experiment ($0.012 \pm 0.008m/s^2$), suggesting no overturning and negligible drifting during the operation [11].

C. *Comparison with the state-of-the-art*

To compare our proposed system with the state-of-the-art technologies we summarized the user-requirements for MPs analysis in Table I. To these co-design features, we added a crucial metric in the usage of technologies for science, which is the cost. SCUBA divers can be regarded as the benchmark for dexterous and low-invasive operation in the sea, even though limitations in operational depth and time call for the use of technologies to automate some tasks. Moreover, considering the risks of these operations, the associated cost can be considered as medium.

Large volume samplers require a specialized vessel and lack a

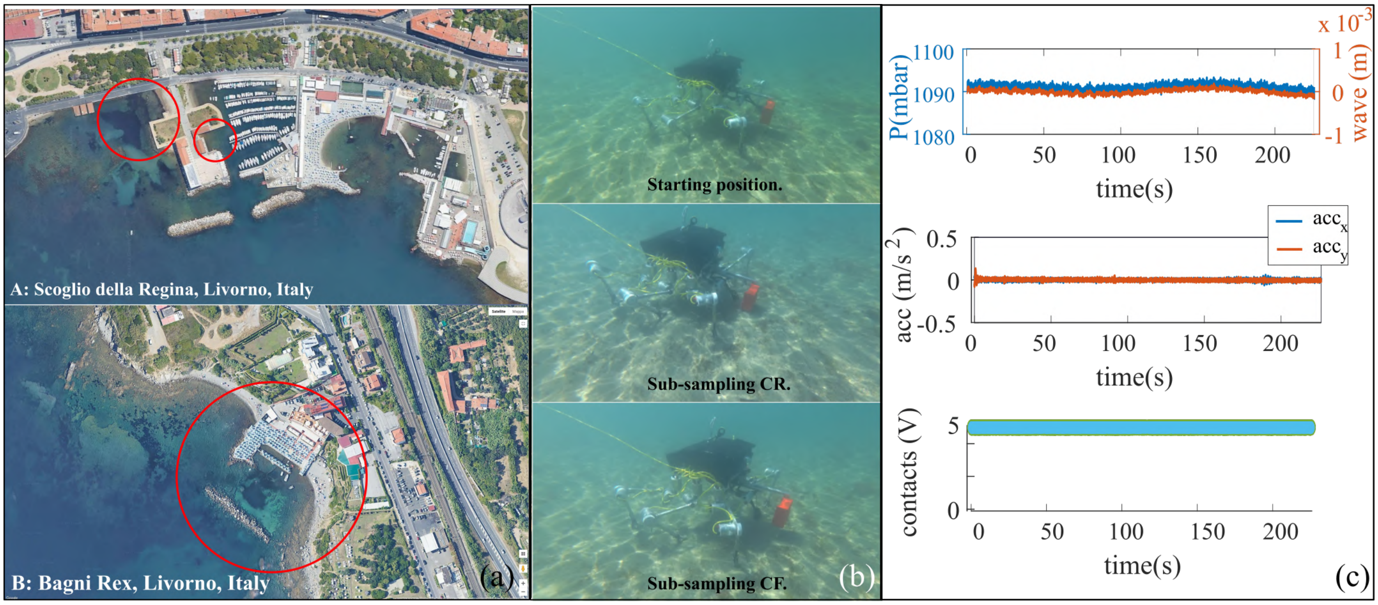

Fig. 7. a) Map of the sites where the field experiments took place, b) The sediment sampling system during the operation, in three different stages. c) Pressure, acceleration and foot contacts during the sea experiments.

Sampling Method	**Deployed From**	**Depth < 5cm**	**Perturbation**	**Weight [30, 400]g**	**Replica Collection**	**Sampling location accuracy**	**Cost**
Scuba divers	Shore/vessel of opportunity	yes	no	yes	depends on depth	$< 10cm$	medium
Large volume samplers (*various types)	specialized vessel	no	yes	yes	depends on sampler	$10m$ca.	high
Small volume samplers *	vessel of opportunity	depends on sampler	yes	yes	depends on sampler	$1m$ca.	low
Work Class ROV+ various samplers	specialized vessel	no	yes	yes	depends on sampler	$< 10cm$	high
mini-ROV+ various samplers	vessel of opportunity	depends on sampler	yes	yes	depends on sampler	$10cm$ca.	low
Lightweight ULR + grab sampler	shore/vessel fo opportunity	yes	no	yes	yes	$< 10cm$	low

TABLE I
COMPARISON OF EXISTING SEDIMENT SAMPLING TECHNOLOGIES WITH THE PROPOSED SOLUTION AGAINST THE USER REQUIREMENTS INTRODUCED.

means to monitor the sampling site and precisely control the sampler yielding high costs, high risk of sediment suspension, and low spatial resultion. Smaller samplers, can be deployed from vessels of opportunity to reduce the operational costs, but still suffer from the same limitations in terms of sediment suspension and spatial resolution. Working-class ROVs can definetely improve the sampling resolution thanks to the visual feedback from their on board cameras, but require specialized vessel and personnel increasing the costs and may cause sediment resuspension with their thrusters. Integrating small samplers on an ROV can result in cheaper operations with the ability to real time monitoring of the sampling action. However, their station-keeping ability is questionable even for slow currents affecting the sampling resolution and they generate sediment resuspension when operated close to the seabed. The proposed sampling system instead has been shown to meet all specifications. The system can be deployed directly from the shore or from a vessel of opportunity without the need to resort to specialized vessels, with associated low costs of usage. The legged mobility allows the collection of several replicas in the target area without significant sediment resuspension and for each sampling action, the exact location can be determined by the robot operator thanks to the visual feedback offered by SILVER and the good current rejection capability. SILVER2 has been tested in the field for depths as deep as 25 m and has a longer working time (16 hours of standing, 10 hours of hopping, and 7 hours of walking) compared to commercial mini-ROVs [10].

D. Sediment analysis

Samples collected during field trials were processed following the protocol described by [20]. Briefly, samples were weighed and sieved using deionized water (1mm, 250µm, 45µm). MPs were extracted using a two-step density separation procedure using sodium bromide. The extracted material was then filtered onto a 20µm PCTE membrane filter and stored at room temperature in covered Petri dishes until analyzed. MPs were quantified, and the polymer identified using µFTIR (Thermo Scientific Nicolet iN10 MX IR Microscope) at the Center for Environmental Science and Engineering, University

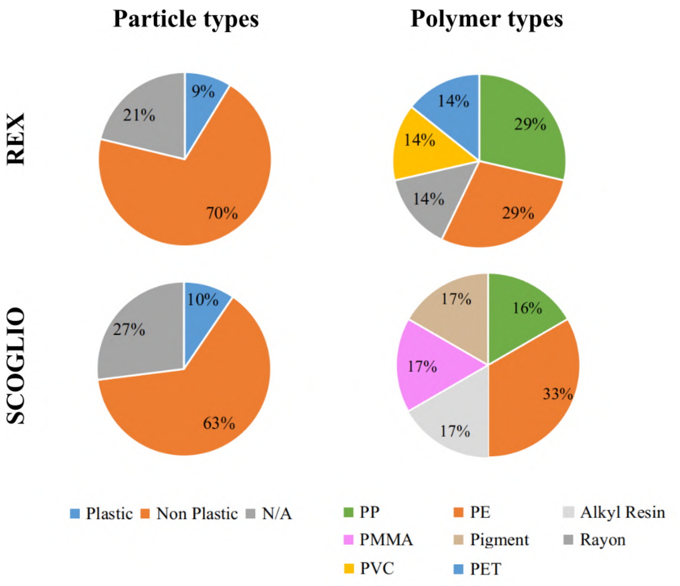

Fig. 8. Results of MPs analysis from the field experiments

of Connecticut. Particles with a match >65% of a known plastic polymer were classified as MPs. Non-plastic particles were additionally recorded, while particles with a weak spectral signal or that were lost or crushed were pooled as N/A group. The particle count was finally standardized to the sediment weight. No plastic particles were recovered from the dust quality control. However, all the particles identified as polylactic acid of red/pink color were excluded from the count as originated from the sample storing container of the robot highlighting the need for different construction materials. A total of 810.13 particles/Kg were recovered from the REX station, with 70.89 MP/Kg identified as "plastic", 567.09 as "non-plastic" and 172.15 as "not identified" (N/A). The polymer spectra were characterized by 28.57% of Polypropylene (PP) and Polyethylene (PE), and 14.29% of Rayon, Polyvinyl chloride(PVC), and polyethylene terephthalate(PET) (Figure 8). From SCOGLIO station sediment, a total number of 200.13 particles/Kg was recovered with 19.06MP/Kg classified as plastic, 127.06 as non-plastic, and 54.00 as N/A. The polymer spectra of this station were represented by 16.67% of PP, Polymethyl methacrylate (PMMA), Pigment and Alkyl Resin, and 33.33% of PE (Figure 8).

IV. CONCLUSION

Underwater-legged robots (ULRs) like SILVER2 are expanding the frontiers of marine science and will soon make seabed exploration and research more affordable to researchers in various fields. In this article, we proposed a novel sediment sampling system, specifically design for microplastic assessment studies, consisting of an underactuated grab-like sampler integrated on the ULR SILVER2. The design was based on the requirements of marine biology experts in microplastic pollution and on existing literature. First, we have presented the end-user requirements and the design of the sampler, highlighting our design choices. Later, we presented a teleoperated sampling protocol and tested it both in controlled conditions and in the field. Our results confirmed that the proposed system was capable of sampling in the most superficial layer of sediment, while causing minimal sediment resuspension. By repeating the sampling cycle described in the paper multiple times, the system is capable to collect enough sediment for a meaningful analysis and to collect several replicas in a single deployment with a high accuracy. Beside the specific application to microplastic assessment, our results suggest that ULRs could be employed in other sampling applications, such as geological studies, biodiversity analysis, or ocean acidification studies, with modifications to the sampling device and the sampling protocol to meet specific requirements. Additionally, the study highlights the significance of tight collaboration between robotics engineers and end-user to develop tools for any specific research application. Such collaboration is crucial to guide the technological developments of engineers and to increase the data collection capabilities of scientists.

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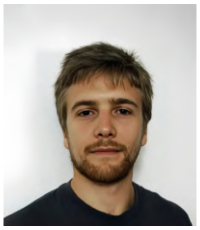

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