PoseiDRONE: Design of a soft-bodied ROV with crawling, swimming and manipulation ability

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PoseiDRONE: design of a soft-bodied ROV with crawling, swimming and manipulation ability

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***Abstract*—The design concept and development of a multipurpose, underwater robot is presented. The final robot consists of a continuum composed for 80% of its volume of rubber-like materials and it combines locomotion (*i.e.* crawling and swimming) and manipulation capabilities. A first prototype of the robot is illustrated based on the integration of existing prototypes.**

I. INTRODUCTION

At present there exist a number of tasks in marine operations for which relying on robots, such as Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs), constitutes the only option [1]. Offshore industry is progressively demanding ROVs to be capable of dealing with increasingly complex tasks in always more forbidding scenarios. However, certain environmental conditions at sea pose challenges which can hardly be dealt with by current ROV technology.

There is plentiful of difficulties occurring with underwater operations which have so far not found exhaustive solutions, many of these are thoroughly addressed in [2]. The most challenging tasks are those encountered during construction and maintenance missions such as those addressed by Underwater Vehicle-Manipulator Systems (UVMSs) in which the need arises to deal with precise manipulation tasks in such an hostile environment as the submerged world. Major obstacles to safe and accurate marine operations concern the poor predictability of the hydrodynamic effects, the complexity of treating the dynamic coupling between the manipulator and the vehicle and, indeed, the low bandwidth of the sensor readings. Sensors inaccuracies and hydrodynamic disturbances make the problem of positioning and station keeping especially hard to deal with. This, in turn, gives rise to a whole set of problems associated with the risk of unexpected impacts and the need to manage the manipulator-environment contact problem.

This implies that there occurs a wide range of scenarios where ROVs will not be in the condition to operate safely. The work presented in this paper takes the cue from this point in order to suggest a disruptive new approach to the design of underwater robots.

II. MARINE SOFT ROBOTS

Soft robotics is a branch of research which aims at exploiting the compliant nature of soft materials in order to develop robots capable of overcoming the limitations of traditional design criteria [3]. In this paper the design concept of a new kind of marine soft robot is presented and employed to support the hypothesis that investment on soft robotics in the marine sector may foster a disruptive improvement in marine technology.

In the scenario of offshore intervention, where highly perturbed conditions and a high degree of uncertainty are standard, the design criteria borrowed from soft robotics could represent a winning strategy for a great variety of tasks. As a consequence of the employment of rubber-like materials, marine soft robots are mostly inert to salt water and the external coating provides a natural water-proof insulation for the internal components; in addition, they benefit from lower inertia which, if coupled with adequate thrusting actuators, may provide unprecedented manoeuvring skills. More importantly, their high degree of compliance and low risk of damage from impact offers the chance to deal with maintenance or construction tasks by adhering to a structure, rather than working detached from it, thus relieving the control from the need to manage the contact, the grip-loss problem as well as the risk of unexpected collisions. These features could not only make these kind of robots more suitable for a broad range of tasks currently infeasible, but they could also greatly simplify the control problems during complex tasks by transferring part of the computational burden to the intrinsic compliance of the structure. Reduced computational requirements in turn implies a lower degree of dependency on the communication system, which currently represents one of the major bottle neck in underwater control.

In addition, a wealth of research has lately focused on designing underwater vehicles endowed with the locomotor capabilities of aquatic animals which provide a clear insight as to what concerns unsteady hydrodynamics. Aquatic animals sport a plethora of outstanding feats such as hovering, short

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radius turning, fast start/slowdown and low-speed manoeuvring as well as combinations of the above. Interestingly, aquatic animals bring inspiration not only in terms of their swimming strategy, but also with respect to legged underwater locomotion, which becomes essential when we intend to develop a UVMS capable of moving over submerged substrates. In this respect the design of underwater robots can benefit enormously from the study of such animals and the resulting implementation of the biomechanics principles they exploit into man-made, programmable devices especially suited for delivering extremely complex tasks.

Bioinspiration has not limited itself to locomotion, but to a large extent has also addressed the advantage intrinsic to manipulation as it is encountered in the animal kingdom. The holy Grail of bioinspired manipulators technology is embodied by the effort to develop a continuum, compliant, infinite degrees of freedom manipulator. This is one among the most pursued topics in robotics research and there exist a copious literature of acclaimed examples [3].

Rephrasing Bandyopadhayay [4], who rightly describes aquatic animals as the perfect autonomous undersea platform, we further argue that, among aquatic animals, soft-bodied ones may constitute the paradigm of inspiration to design a new breed of working class underwater vehicles. The scope of this paper is to present the preliminary effort to develop an underwater robot mostly composed of soft materials and designed according to those bioinspired principles which enable it to benefit from a multi-functional locomotor system and essential manipulation skills. Altogether these set of skills could, for the first time, provide a robot with a simple strategy to deal with complex problems such as those which ROVs are subject to.

III. DESIGN OF THE ROBOT

The robot developed herein is inspired by the octopus. Indeed, this cephalopod displays a number of features of interest to the present work: it is an aquatic animal, almost entirely devoid of rigid structures, capable of both legged and swimming locomotion and gifted with fairly advanced manipulation skills. Based on its biological counterpart, the robot unifies a crawling and a swimming component in a single soft body. These components have already been developed and tested separately by the authors, see [5] and [6]. This work reports on the first attempt to integrate these constituents in a unified soft-bodied structure endowed with legged locomotion, manipulation and swimming ability, Fig. 7. The authors have chosen to use underactuated mechanisms in the solutions adopted for manipulation, locomotion and swimming that drastically reduce the variables needed to control the robot; this brings to a simplified control that potentially expands the current ROV capabilities. To the reader convenience a brief description of the constitutive elements is presented below, then the design concept of the robot comprising of these unified components is introduced. Finally, a first, small-scale prototype is introduced which is used to demonstrate the feasibility of the ideas put forward throughout the paper and eventually the prototype is tested in water in order to prove the benefits of its underlying design criteria.

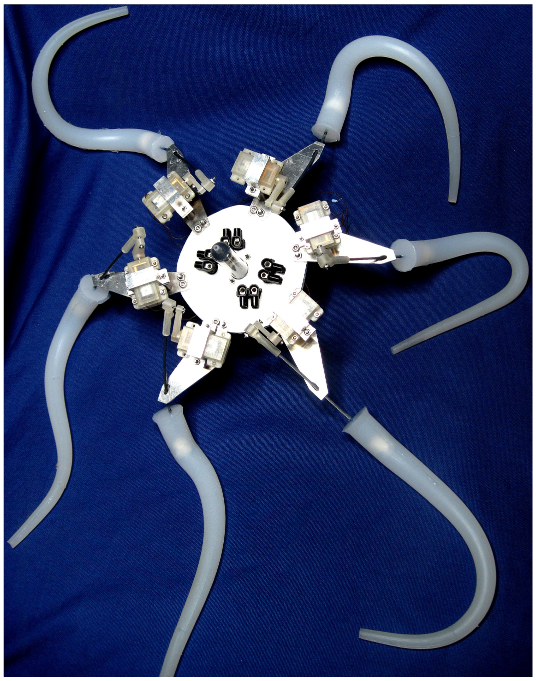

Fig. 1. The crawling unit.

A. Crawling and Manipulation

The crawler, Fig. 1 is made of several radially distributed arms and endowed with manipulation capability. Single one actuator for each unit (manipulation and locomotion) allows respectively bending and elongation capabilities: examples of implementation of both features are shown in [7], where details on the design are also reported. Each soft arm has its own actuation mechanism, that is used to bend, elongate or shorten the arm. Compliant legs are becoming very popular in robotics for their capability of compensating external disturbances and

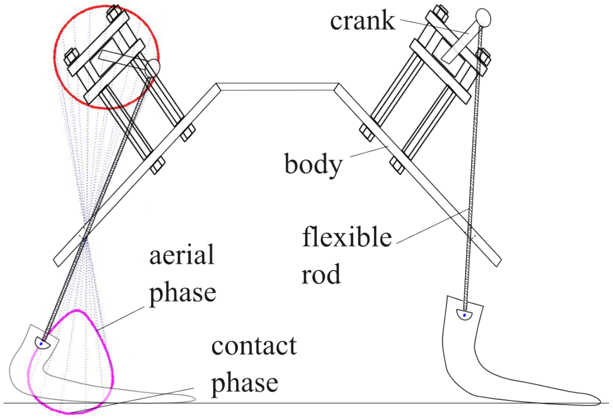

Fig. 2. A schematic of the actuation mechanism of the crawler. The components of the mechanism together with the end-loop is depicted.

for their energy efficiency [8], [9]. There are several designs of compliant legged robots, some of them presented in [10], some of which exhibit impressive performances. However, while there is a huge number of legged robots that work outside water, very few are designed to work underwater.

One of the earlier example of soft legged underwater robot has been presented by the authors [7]. The design is clearly oriented to exploit the soft components of the robot and to minimize the influence of the rigid ones: for this purpose, the robot uses an underactuated systems to bend the arm and a three-bar mechanism with one compliant element (flexible rod) to achieve crawling. The necessary rigid parts, reduced to their minimum number, are then embedded in a continuum of rubber-like material. For the manipulation unit, a cable driven mechanism was employed. Longitudinal Dyneema® cables runs from the base to the tip (where they are attached) of the conic rubber-like arm: by pulling these cables the arm bends with a curvature that increases from the base to the tip, thus allowing to curl around objects with different shape and sizes [5] (see Fig. 4).

Increasing the number of cables embedded in the silicone arm, it is possible to increase the manipulation skills of the robot. For example with several cables attached at different lengths, it is possible to have different bend points (see Fig. 3). To achieve locomotion, the three-bar mechanism already presented in [7] was used, the three bars which are respectively: the crank, the flexible rod and the body of the robot. Thanks to the constraints of this particular mechanism the rotation of the motor, gives rise in the distal part of the flexible rod a well-determined cycle, called *end-loop*, which can be divided into two distinct phases: the contact phase (in which the leg pushes the robot forward) and the aerial phase (in which the leg returns to the initial position of the loop) as shown in Fig.2. By this locomotion strategy the body of the robot is pushed forward and a crawling-like gait is obtained: the radial distribution of the arms allows an omni-directional locomotion.

B. Swimming

The swimming unit [6] consists of an elastic, deformable shell made of rubber-like materials and exploits cephalopod-like pulsed-jet propulsion, Fig. 5. For a detailed discussion on cephalopod propulsion the interested reader is referred to [11]. The benefits of pulsed-jet propulsion have been highlighted in several works, [12], [13], [14], which associate the nature of the vortex issuing from a nozzle to the nozzle-exit over-pressure responsible for the production of enhanced thrust. To the author's knowledge, there exist at least three pulsed-jet driven underwater vehicles which employ various mode of actuation, [15], [16],[17]. In the present frame of work, however, pulsed-jet propulsion is not only chosen for its beneficial contribution to thrust generation, but also because it is especially suited for implementation in a soft-bodied thruster and hence incorporated in a soft underwater robotic platform.

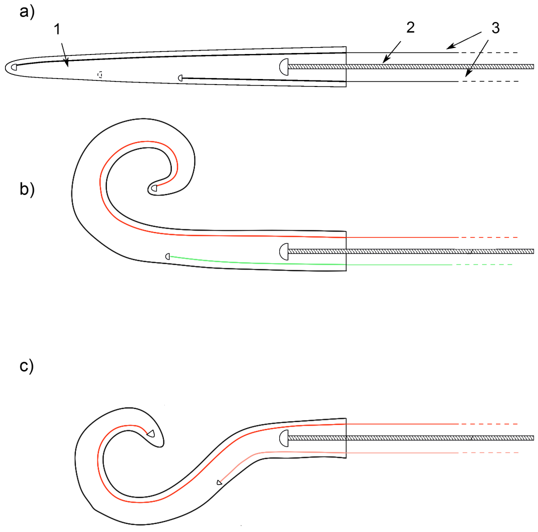

Fig. 3. A schematic of the Dyneema® and flexible rod arrangement within the conical silicone arm and its working principle. In (a), the numbers refer to (1) the flexible rod, (2) the attachment point of the Dyneema® cable at the arm tip and (3) the fitting point of the flexible rod. In (b) it is demonstrated how, by pulling on the Dyneema® cable, the arm curls with a non-constant curvature hence providing a spiral twirl.

The authors have already experimented with two different designs for pulsed-jet propelled soft underwater vehicles, previously reported in [6] and [18]. The thruster employed in the present paper exploits a more recent development of the earlier prototypes in order to be capable of towing the crawling platform during swimming. Details of this more recent design are provided in [19].

The working principle of the thruster employed for the PoseiDRONE platform entails an ovoid, silicone chamber with a nozzle and one ingestion valve. The actuation mechanism comprises of a gearmotor immersed in the silicone and a crank

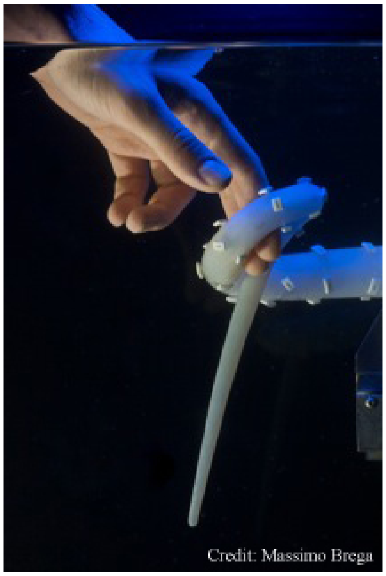
Credit: Massimo Brega

Fig. 4. Manipulation unit: an example of the grasping capability of the soft manipulator employed in the PoseiDRONE is shown.

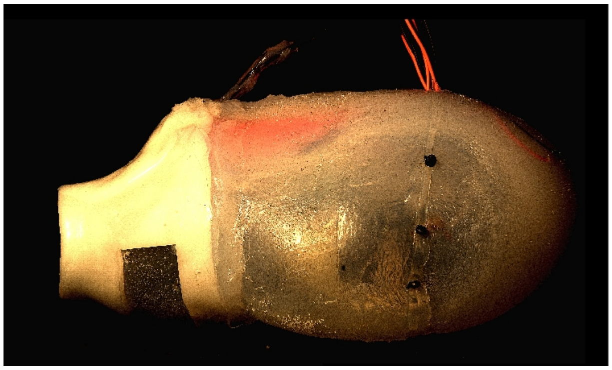

Fig. 5. Swimming unit: the Soft Unmanned Underwater Vehicle of [6].

which alternatively pulls and releases a series of cables. The cables are attached, at one end, to the walls of the silicone chamber, gathered through a flexible fairlead immersed in the silicone and eventually attached, at the opposite end, to the motor crank. Expulsion of a finite slug of fluid occurs due to the collapse of the chamber which is driven by the pulling of the cables actuated by the rotation of the crank. The ingestion of water, i.e. the refill of the chamber, passively takes place once the cables are released and the stresses arose within the silicone walls due to the earlier cable-induced strain drive this spontaneous inflation. This sequence of expulsion and ingestion of water, that is inflation and collapse of the elastic chamber, determines the swimming routine which enables the vehicle to swim.

This kind of design has the benefit of limiting the amount of rigid components, hence making the thrusting unit almost entirely soft. Cable transmission also aids in dislocating the point of application of the force. This enables to freely arrange the point of attachment of the cables over the entire silicone shell and at the same time store the motor inside the silicone body.

C. PoseiDRONE

The integration of the separate elements entails a single body of silicone where the crawler and the swimmer are merged, this self-contained body will constitute the PoseiDRONE. The conceptual design, illustrated in Fig. 7, involves a body of silicone incorporating all actuators and electronic components which, in turn, are lodged in *ad-hoc* housings, see Fig. 7. Special housings are designed to host the three bar mechanism which drives each single leg and encloses the trajectory of the flexible rods which connects the motor crank to the leg anchorage. This device enables each distinct actuation unit of the crawler to work while immersed in the silicone matrix.

The swimmer and the crawler are bound via a silicone joint, Fig. 7, which allows the relative orientation of one component with respect to the other. In this way, the swimmer is dragged behind the crawler during legged locomotion and the crawler is towed behind the swimmer during navigation. Altogether the PoseiDRONE will be the first underwater soft robot capable of multi-functional locomotion and basic manipulation. In this context, by manipulation it should be intended the ability either to grasp objects or enable the robot to hold on to submerged structures. This ensemble of features will provide this robot with a set of completely new skills for an underwater vehicle thanks to which it will be possible to perform missions where it is required to walk over a surface or swim towards a certain target until contact is established and then hold on to it via coiling of the silicone arms. The overall compliance of the whole body will permit cruising in cramped environments as well as squeeze through narrow apertures smaller than the nominal diameter of the robot. In addition, transportation and deploy of the robot in water will be greatly eased both because of its limited weight and because it will be largely unaffected by impacts. The mode of operation according to which the working procedure takes place by direct contact with the submerged structures upon which a job has to be performed can potentially bring a solution to some of the most challenging problems encountered by UVMSs during construction/maintenance operations. It is envisaged that, once a firm hold has been established, the robot could perform common tasks such as maintenance, construction, survey, etc. by employing dedicated tools hosted in the central part of the crawling unit.

IV. FIRST PROTOTYPE

In order to demonstrate the feasibility of the design concept advanced in the previous sections, a first prototype is manufactured which encompasses the three components of the PoseiDRONE in a more simplified version of the robot. We refer to this first prototype as the PDR1, which differs from the PoseiDRONE in a number of ways. The PDR1, Fig. 8, sports a simplified version of the crawler discussed in [7]. In this case the crawling platform is composed of four arms distributed at the vertices of a cross shaped aluminium joint. The four

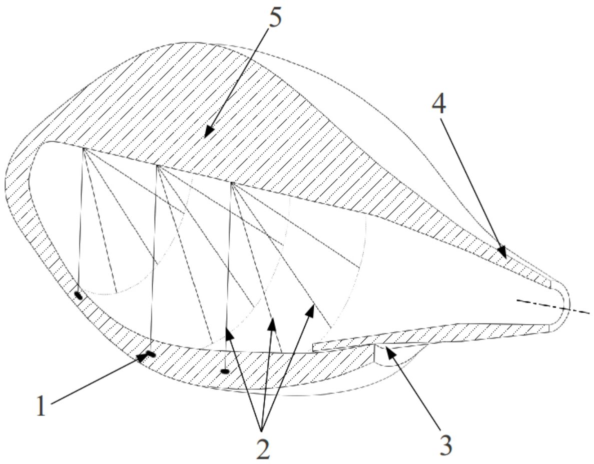

Fig. 6. A schematic of the mechanism of the soft underwater thruster. The numbers respectively refer to: (1) the cable attachment points, (2) the cables, (3) the ingestion valve, (4) the outflow nozzle, (5) the silicone mould hosting the motor and the axial fairlead.

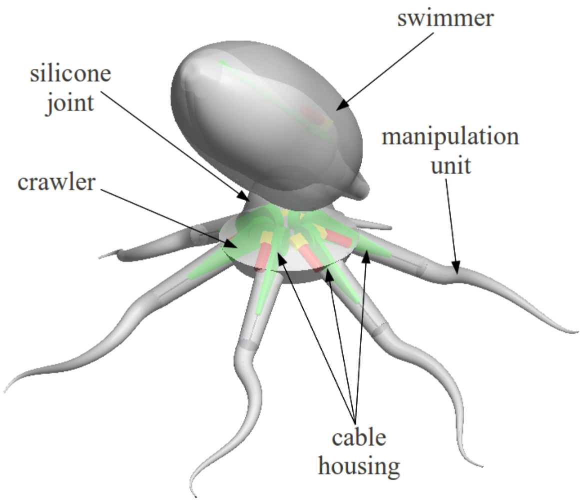

Fig. 7. A concept design of the integrated Soft Unmanned Underwater Vehicle PoseiDRONE in its intended final configuration.

arms work by means of the three bar mechanism discussed in section III-A, but only one of these exhibits manipulation skills by means of a longitudinal Dyneema® cable which permits curling around objects. The central part of this structure hosts a plate purposely perforated in order to fit the cross-joint onto the upper part of the swimming module. This enables a purposely designed buoyancy adjustment module to be linked to the aluminium plate and be actuated from the external. The robot is composed for 76.4% of its volume of soft elastomeric rubber (Smooth-On EcoFlex® 00-30 silicone), the actuation of the crawling unit relies on Solarbotics GM12a DC Motors while the swimmer is actuated by 441435 Maxon DC Motor. The whole robot weights $0.755Kg$, each silicone arm is $0.245m$ long, the swimmer is $0.2m$ long from the rearmost to the foremost end, the whole robot, with the arms extended on a plane is $0.78m$ long from the tip of the rearmost arm to the tip of the foremost one.

V. TESTING PHASE

The vehicle is tested either in a tank and in the sea. In this section we briefly report on two tests performed in a tank in order to demonstrate the capability of the robot to shift from swimming to crawling mode and assess its performance during each mode of locomotion. More importantly, these tests provide a first insight into the dynamics of this complex vehicle during gait transition. To evaluate the performance of the robot in a real scenario, tests similar to those that took place in the tank were carried out in the sea. Deployment of the robot in the sea is portrayed in Fig. 9 to prove the ease with which the robot is handled.

The robot moved in a working space delimited by 8 markers placed on the vertexes of the tank. The 8 markers that define the working space were used to calibrate two cameras (25 fps) to perform the Direct Linear Transformation (DLT). This transformation allows from 2 or more bidimensional images

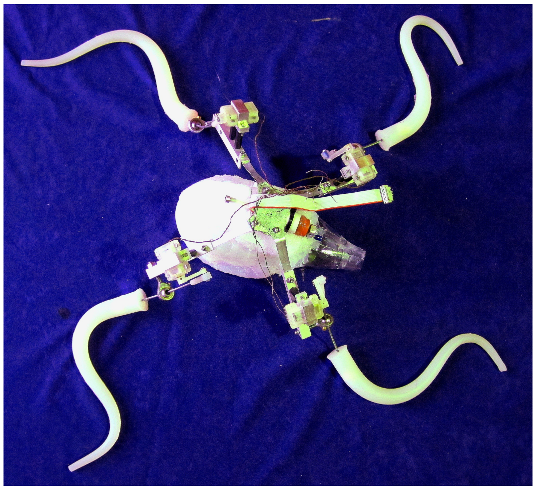

Fig. 8. The first working prototype of the PoseiDRONE, referred to here as the PDR1.

Fig. 9. A sequence demonstrating the deployment of the robot PDR1 in water during sea water testing. The robot is indexed by a green circle in the figures.

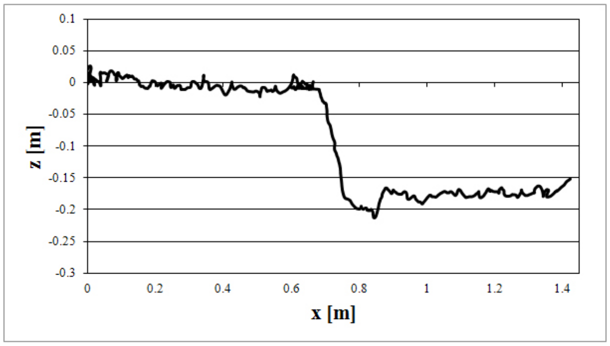

Fig. 10. Projection on the plane xz of the centre of mass of the robot. The swimming and crawling phases are clearly identified by the z coordinates. PDR1 swims initially close to the water surface then toward the ground. When it reaches the tank surface, it starts to move the limbs to walk forward.

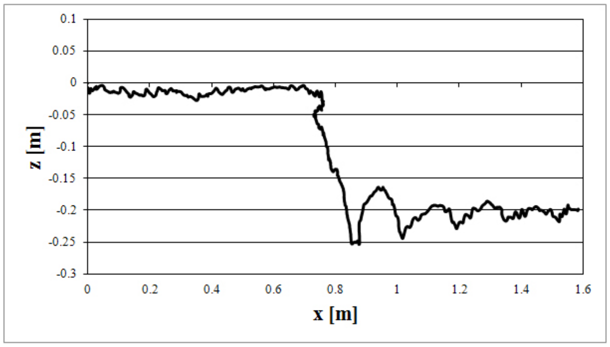

Fig. 11. Projection on the plane xz of the centre of mass of the robot. The robot is holding a screwdriver with one arm.

the reconstruction of a 3 dimensional scene. In this trials, using the least square method, we derived 11 DLT parameters for each camera: $C_{i,j}$ with $i = 1, 2$ and $j = 1, ..., 11$. The 8 markers of the working space were used as control points to derive the DLT parameters: notice that the minimum number of control points required to derive 11 DLT parameters is 6. However, since all the vertexes of the control space are available, 8 control points were used. Other 3 markers were placed onto the robot. The position of the centre of the robot and the orientation of the body were retrieved by the 3 markers on the lateral platform; this is possible when the 3 points do not belong to a line. After the calibration, the 3 dimensional positions of the 3 robot markers were reconstructed. To extract the parameters of the diverse trials of the robot, the state of the robot is defined as the x, y, z positions of the centre of mass and its orientation with respect to the yaw, pitch and roll angles. This method was successfully used in [6] and [7].

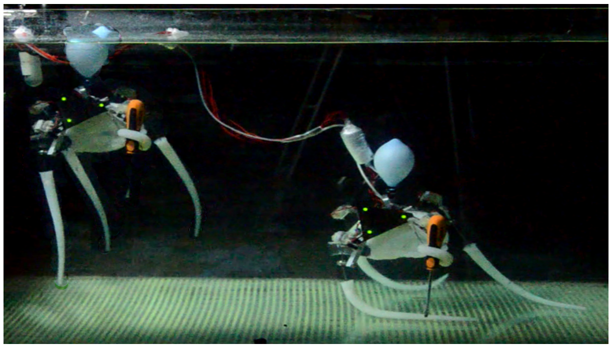

Fig. 12. Two overlapped snapshots that show the robot carrying the screwdriver while swimming and crawling.

TABLE I

SPEED, LENGTH AND MASS OF PDR1. L: BODY LENGTH OF THE ROBOT, M: TOTAL MASS OF THE ROBOT, S: SWIM, C: CRAWL, v: MEAN SPEED, V: MAXIMUM SPEED.

			v [m/s]		V [m/s]		V/L	
test	L [m]	M [Kg]	S	C	S	C	S	C
1	0.20	0.755	0.62	0.63	0.20	0.20	1	1
2	0.20	0.816	0.59	0.56	0.17	0.16	0.85	0.80

During the swimming phase, the buoyancy module is inflated and the robot has a relative density (with respect to salt water) equal to 0.97, and this enables the robot to lift from the ground and swim. Conversely, to switch from the swimming to the walking phase, the buoyancy module is deflated and the relative density increases to 1.05. The transition from one gait to other is manifest by the shift in depth of Fig.10 of the test 1, where is depicted the track of the centre of mass of the robot. Notice that the origin of the reference frame is set at the initial position of the robot while waterborne. When the motor of the swimmer is turned-off and the buoyancy module is deflated, the robot moves forward and toward the ground. The robot reaches after few seconds the deepest point, with the legs compressed to the ground. When the frontal limbs of the crawler are activated, the robot rises from the deepest point and starts walking.

Further on, we demonstrate the fitness of this prototype at grasping simple object and transporting them in water. In test 2, Fig.11, the manipulator is employed to curl around a screw driver and then performs a swimming-crawling routine down to an imaginary point of delivery of the object, Fig.12. The tracks with and without the screwdriver are quite similar. In doing so we demonstrate how the robot exploits the redundancy of its morphology by employing one arm to hold the screw driver while the others crawl with minimal decrease in the performance. The length and mass of the robot, together with the speeds for the swimming and crawling phase, are reported in Tab.I.

As a last test a real world operative scenario was performed in which the robot is deployed in water, and a cycle analogous to that performed in the tank was carried out. The test entails five consecutive tasks: deployment, swimming, sinking on the sea bottom and crawling over the substrate and surfacing. The deployment is performed without any precautionary procedure given the nature of the robot which enables even careless handling, Fig 9. The remaining stages of the test performed as efficiently as observed in the controlled environment. The robot swam over a distance of about 4.5m and crawled back over the irregular and uneven sea bottom at a depth of 3m.

VI. CONCLUSION

This work introduces the preliminary design to the actual development and testing of the first soft-bodied ROV. This robot is the first in its kind in that it is almost exclusively composed of soft materials. The occurrence of this soft materials permits the development of a continuum robot which encloses in a single body three distinct functions: crawling, manipulation and swimming. The following stages of development and testing of the robotic platform will prove whether this new kind of robot might represent a disruptive technological advancement in marine operations.

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