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Mechatronic design of a miniature underwater robot for swarm operations

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***Abstract*— Due to extreme and unpredictable conditions, oceanic missions are still a persistent challenge in robotics. With the aim of improving decision autonomy and robustness against unforeseen circumstances, the EU-funded CoCoRo project is developing a cognitive swarm of underwater robots. Swarm and cognition algorithms will be studied and validated with a large number of miniaturized and affordable AUVs, named Jeff, whose custom mechanical design is described in this paper. Jeff is conceived for high-mobility in 3D cluttered environments and has distributed sensors for multi-directional perception and communication. The propulsion and the buoyancy systems are designed with watertight and energetically efficient solutions to improve system reliability and energetic autonomy. The manuscript also describes the design of a docking system that allows Jeff to passively align and connect to a submerged docking station for battery charging.**

I. INTRODUCTION

Potentialities of autonomous underwater vehicles (AUVs) have greatly increased during the past thirty years due to the progress in sensing technologies as well as the substantial improvements in materials and computational capabilities. AUVs are nowadays adopted for multiple missions such as extensive monitoring, exploration, search and rescue and maintenance of underwater infrastructures [1].

Current missions usually involve complex AUVs equipped with multiple and expensive long-range sensors and communication systems. These AUVs mainly operate individually based on pre-programmed mission plans that specify the platform behavior during the entire mission [2]. This method limits the capability to react to unforeseen circumstances and the possibility to accomplish complex tasks without a periodic communication with a human operator. In order to improve flexibility and robustness of underwater robots, the CoCoRo project (Cognitive Cooperative Robots) investigates the development of a swarm of AUVs that run cognition-generating software running on suitable mechatronics systems [3]. Since robotic swarms are scalable, flexible, robust and redundant, potentially they can be more efficient in complex and unforeseen circumstances [4]. For example, toxic wastes like leaking barrels on the seabed produce very weak and irregular gradient with multiple local concentration peaks of toxic chemicals. Due to its local sensing capabilities, a single AUV is likely to stop in a local concentration peak, without being able to track the source of the pollution. Conversely, a swarm of AUVs, because of their distributed sensing capabilities, could effectively navigate in such a weak and irregular toxic gradient and locate the source of pollution.

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Only few projects investigated in the past the topic of underwater swarm robotics. Serafina [5] paved the way in this field addressing AUVs localization, communication and shoaling of small groups of robots. AMOUR [6] studied cooperative control algorithms for robots and submersed sensor nodes. The Co3-AUVs project [7] deals with a swarm of AUVs that can seamlessly monitor critical underwater infrastructures and detect anomalous situations. Munsun II [8] is a swarm of small and inexpensive AUVs for environmental monitoring. With respect to the aforementioned projects, CoCoRo focuses on a larger swarm (30-40 AUVs) driven by biologically inspired motion algorithms and self-organization principles for an emerging individual and group awareness [3].

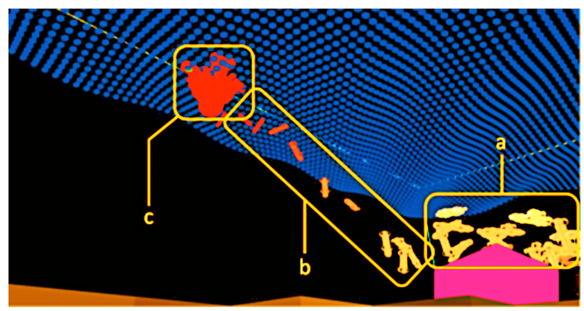

Figure 1. The figure shows how the CoCoRo swarm acts during a mission. The swarm is composed of a floating station (c) and two groups of AUVs: one is searching for targets on the seafloor (a) while the other (b) is establishing a communication chain with the floating station.

As shown in Fig.1, a CoCoRo swarm is composed of multiple miniature AUVs and a floating station. Part of the swarm is close to the seafloor searching for a target, while other AUVs are recruited for establishing a communication bridge connecting the floating station with the AUVs in depth. The floating station can transmit the information collected by the AUVs to a remote supervisor and it stores an energy reservoir that can be shared with the AUVs through a dedicated docking system for charging batteries. Additionally, the floating station can emit sounds creating a virtual fence in order to confine the mission of the AUVs in a desired region.

In order to facilitate and reduce experimental costs, the CoCoRo swarm is composed of small and affordable AUVs. Research in the field of miniaturized AUVs (volume of the order of 1-10 dm^3) is recently increasing for both industrial and academic purposes. For example, EyeBall ROV [9] and μAUV [10] are two miniaturized AUVs that are conceived for inspection and monitoring of submerged sites that are dangerous or inaccessible to humans. The interest in small scale AUVs is also driven by the possibility to effectively perform experiments, with relatively low costs, in confined environments such as swimming pools. For example ANGELS are reconfigurable small AUVs [11] that are conceived to investigate underwater navigation and communication through a bioinspired electric sense [12][13]. The development of such as miniaturized AUVs is challenging due to the lack of off-the-shelf components, thus a custom design of the main AUV's systems being often required.

In this article we present the mechatronic design of Jeff, a miniature AUV conceived as a fully featured yet affordable test bed for underwater swarm experiments. The paper is organized as follows: section II starts with an overview of the robotic platform. Propulsion, buoyancy and docking systems are respectively presented in sections III, IV and V. Section VI describes the perception and communication capabilities. Finally, section VII concludes with some proposals for improvements and future works.

II. JEFF MECHATRONIC DESIGN

Jeff is designed in order to respect three main requirements: swarm operations, cognition capabilities and affordable experimental costs. In more detail:

- swarm operations are facilitated in 3D environments. Indeed, the efficiency of a swarm tends to increase with its density, because of the growth in the number of local interactions between agents. Nevertheless, a high swarm density could cause "traffic jams" between the agents, thus negatively affecting the performance of the whole system. 3D environments offer the opportunity to increase the number of local interactions while reducing the possibilities of traffic jams. Hence, in order to increase swarm capabilities, Jeff is designed to ensure a high level of mobility in a 3D environment and multi-directional sensing and communication;
- cognition is fundamental for the success of a swarm. In fact, AUVs with awareness capability can efficiently share and balance different tasks between them. In order to support a cognition generating software, Jeff is equipped with a wide range of proprio and exteroceptive sensors and local communication systems;
- affordable costs are essential to perform experiments with a large swarm of AUVs. To reduce the costs yet being able to perform significant swarm experiments in a conventional swimming pool (3m of depth with 10 m^2 of surface), Jeff is conceived as a miniature AUV with a size of 250×120×50 mm and adequate diving capabilities (3m). Long-lasting experimental sessions are ensured by custom high efficiency solutions for propulsions and by docking capability for underwater battery charging.

As shown in Fig. 2, Jeff has a streamlined shell (a) manufactured in rapid prototyping. It is neutrally buoyant with a weight of 970 g. Jeff can actively control surge, pitch, yaw and heave. Indeed Jeff's stern is equipped with two propellers (b1 and b2) parallel to the surge axis while Jeff's nose houses a bow thruster that is parallel to the sway axis (c) and a buoyancy system (d). Roll is not actively controlled and the stability of the AUV around this axis is achieved passively by tuning the distribution of the internal ballast, which allows to modify the position of the center of mass with respect to the center of buoyancy. Jeff is controlled with custom electronic boards (e) and energy is stored in a lithium battery pack (f) located in Jeff's stern.

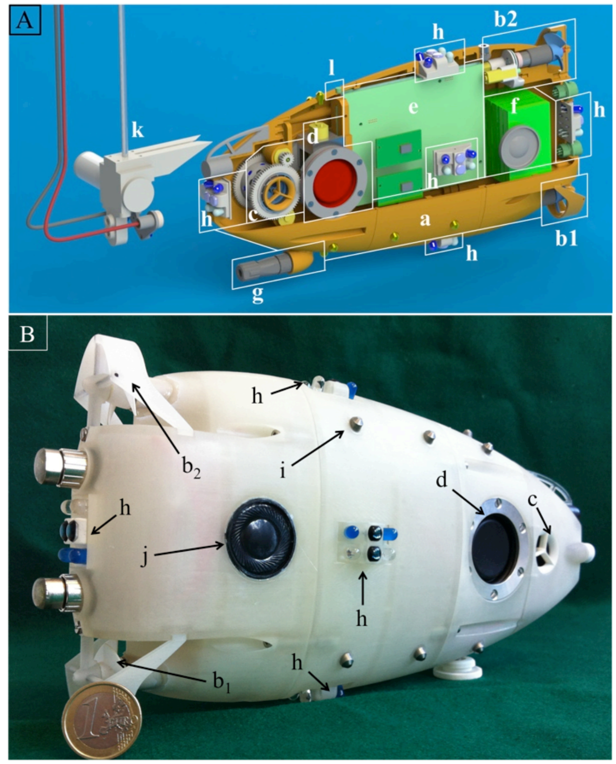

Figure 2. Overview of Jeff design. Fig. 2A shows a 3D model of Jeff's main mechatronics systems: a. shell, b. aft propulsion units, c. bow thruster unit, d. buoyancy system, e. control and power management PCBs, f. battery pack, g. expansion connector for sensors, h. blue lights, k. underwater docking station, l. microphone. Fig. 2B is a picture of Jeff in which can be seen: i. the electrodes for the potential field communication (only one is point out) and j. the right loudspeaker.

TABLE I

Main Jeff's features and characteristics

Size and weight	250x120x50 mm 1.2 kg
DOF	Surge, 500 mm/s Yaw, 90 °/s Dive, 80 mm/s up to 3 m
Energy source	8 Li-Po cells with a capacity of 880 mAh each. Autonomy up to 120 minutes.
Sensors	Pressure Magnetometer, gyro and accelerometer Battery status monitoring
Communication (up to 1 m range)	Blue light Electric fields
Sensorized payloads	Temperature, chemicals, camera
Cost	Mechanics 800 € Electronics + sensors 400 €

Each AUV is equipped with a wide range of sensors and local communication systems. Underwater navigation relies on a pressure sensor to measure depth and a gyroscope, an accelerometer and a magnetometer to control attitude and locomotion. Each platform is aware of its residual energy thanks to dedicated circuits that monitor battery life. Jeff can be specialized thanks to additional sensor payloads (e.g. temperature, concentration of chemicals, camera) that can be plugged into Jeff's shell (g). Presently, communication between AUVs relies on BlueLight units (h) [5] and potential fields (i) according to a bioinspired approach [12][13]. The layout of the communication systems (multiple blue light cluster and multiple electrodes) ensures a wide coverage allowing Jeff to exchange information from multiple directions up to 1 m.

The main features and capabilities of Jeff are summarized in Table I.

III. AFT PROPULSION SYSTEM

Although many artificial and biomimetic systems are proposed in the literature, only few of them are suitable for small-scale AUVs [10]. Propellers are reliable and widely used since they are well studied and their design and control is simpler compared to other propulsion devices (e.g. bio-inspired locomotion systems [14]).

The propulsion unit of miniature AUVs requires a design, which is at the same time compact, waterproof and energetically efficient. A solution to this problem is given by rim driven thrusters and custom designed brushless motors, where the rotor forms a ring around the propeller and the stator is encapsulated in a thin duct that surrounds it. In this design electronics is fully encapsulated, making the system entirely waterproof and pressure tolerant. A cheaper, but less optimized approach consists of directly using brushless motors [8] that are properly coated to avoid corrosion and electrical short circuits. The authors adopt an intermediate approach that involves the use of commercially available DC motors in combination with custom designed magnetic coupling to ensure waterproofness. Although this design is used on multiple large scale AUVs (e.g. SeaBED AUV, AutosubLR, Tethys, Delphin2), its application to small robots benefits from scale effects of the magnetic forces. To the best of our knowledge, miniaturized magnetic coupling have been used only in ANGELS [11].

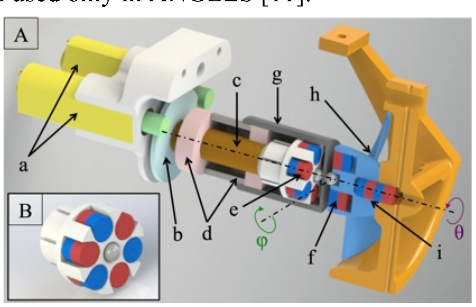

Figure 3. A. Partial section of the aft propellers highlighting the main components. B. Detailed view of the magnetic coupling.

Fig. 3 shows the aft propulsion system with its main components: two DC motors (a) (Precision Microdrives 108-104) in parallel configuration generating the torque required by the propeller (experimentally measured up to 1.2 Nmm); a series of gears (b) with a ratio of 9:48 and a shaft (c) supported by two radial ball bearings (d); a series of internal (e) and external (f) magnets that are coupled across the thin septum (0.4 mm) of the dry magnets housing (g); a propeller (h) with an outer diameter of 25 mm and two additional magnets (i) that compensate the static instability of the magnetic coupling. The magnetic coupling transmits the torque from the motor to the propeller without any mechanical connection ensuring complete waterproofness.

A. The magnetic coupling

The magnetic coupling is composed of a dry (Fig. 3B) and a wet part: the former is directly connected to the shaft of the motor, while the latter is integrated within the hub of the propeller. Each part of the magnetic coupling consists of six cylindrical N35 neodymium magnets with height and diameter of 3 mm and axial magnetization. The magnets are arranged in a circular path (diameter of 6.3 mm) with alternate magnetization. Because of the aforementioned magnetic layout, the magnetic coupling behaves like a torsional spring. When the dry part of the magnetic coupling rotates axially with respect to the propeller (angle ϑ in Fig. 3), a torque (T_m) is generated. The propeller remains attached to the robot because of an attraction force (F_m) between the dry and the wet magnets. The value of T_m and F_m as a function of ϑ are shown in Fig 4.

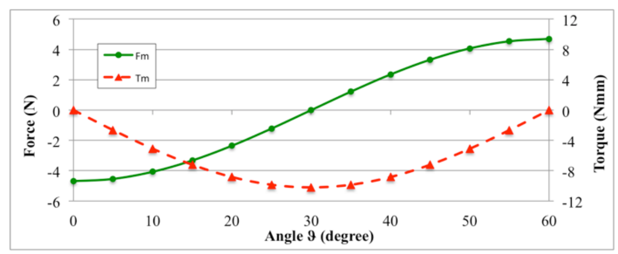

Figure 4. The two graphs shows the trend of F_m and T_m as a function of the angle ϑ. Both T_m and F_m are evaluated with a magnetostatic finite element analysis.

There is a sphere (2 mm diameter) on each side of the magnetic coupling. The two spheres are in contact with the septum of the dry magnets housing (g) and are compressed by the attraction force F_m. Therefore, suitable materials need to be considered in order to prevent and reduce wear effects. Conductive materials are not compatible since the rotation of the magnets generates eddy currents causing a braking effect. For this reason, two non-conductive materials with high mechanical and thermal resistance are employed: PEEK for the housing (Polyether ether ketone) and ceramic for the spheres.

Over being watertight, the proposed design is intrinsically more efficient than the use of conventional seals (e.g. o-ring, spring seals) around the propeller shaft (c). Indeed, while in the magnetic coupling the transmission losses are concentrated in the contact between the two spheres and the dry magnet housing (g), conventional seals works compressed around the propeller shaft causing high frictional losses. Experimental measurements reveal that the frictional torque generated by the contact of the two spheres has an average value of 0.5 Nmm, while, in a motor shaft safely sealed with a 006 o-ring (internal diameter of 1/8 inches), frictional torque can reach 6 Nmm [15].

A. *The magnetic stabilization system*

Since magnets are statically unstable, the propeller tends to pivot around the external contact sphere until it touches the PEEK housing (g). This drawback is solved with a dedicated stabilization system.

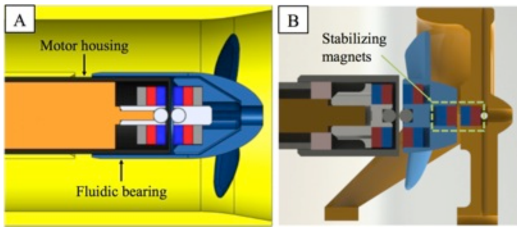

Figure 5. Two stabilization systems: A with a fluidic bearing, B with stabilizing magnets.

As shown in Fig. 5A, in a previous design [11] the authors used a dynamic stabilization system with a fluidic bearing composed of a thin film of water within the motor housing and an external cylinder. The film of water ensures stability during rotation by generating a force that counterbalances the oscillation of the propeller. This solution has two main drawbacks: it adds friction to the system due to the viscous forces in the fluidic bearing, and it does not provide stability at low speed.

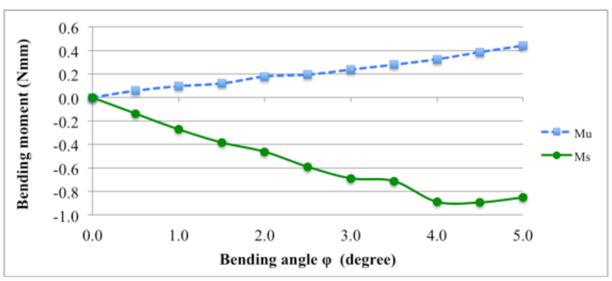

Figure 6. Bending moment as a function of the corresponding pivoting angle φ. Mu (unstabilized bending) considers uniquely the effect of the magnetic couplings, while in Ms (stabilized bending) the effect of the two stabilizing magnets is added. According to the trend of Ms, the two additional magnets have a stabilizing effect since the bending moment acts against the pivoting motion of the propeller.

In order to overcome these limitations (Fig. 5B), Jeff's propulsion units are equipped with a stabilization system composed of two magnets: one is housed in the propeller, while the second one is connected to Jeff's shell and is aligned with the internal shaft (c in Fig. 3A). Since the two magnets are attracting each other, they produce a stabilizing moment that prevents the propeller to pivot around the contact sphere. The stabilization effect of the magnets is highlighted in Fig. 6.

B. *Propeller performances*

The performances of the aft propulsion system have been experimentally measured in static conditions. The system has been modified with a longer dry magnet housing (150 mm) in order to submerge the propeller while maintaining the DC motors outside. During the test, voltages from 0.2V to 4V with 0.2V steps were applied to the DC motors. Current was recorded as well as the thrust of the propeller (measured with a ±10N load cell connected to a 4464 Instron machine).

The static tests were repeated 10 times and the results were averaged. The thrust generated by the propeller as a function of the overall electrical power consumption is shown in Fig 7.

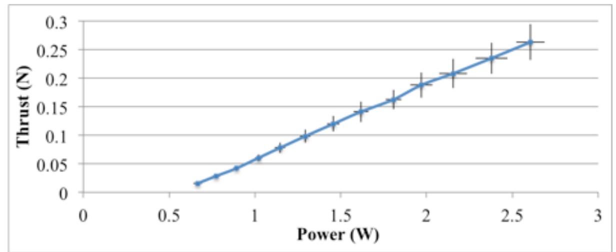

Figure 7. The graph shows the thrust generated by the aft propeller, versus the electric power consumption.

C. *Bow thruster*

Jeff is equipped with a directional propeller to steer the robot left and right. Since this propulsion unit passes through Jeff's bow, it has a different design compared to the stern propulsion units.

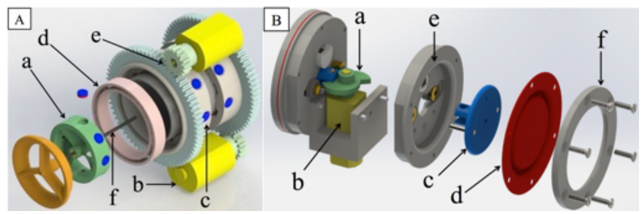

Figure 8. For sake of clarity, the images propose a partially exploded view of the systems. Fig. 8A shows the bow thruster assembly and exploded components. Fig. 8B shows the buoyancy assembly and exploded components.

As shown in Fig. 8A, the system is composed of two contra rotating propellers (a) each one driven by its own DC motor (b) (N20 DC Motor from Gizmo's zone). Like the previous design, torque is transmitted with two series of magnets that couple the two external propellers with two rings (c) inside Jeff's shell. Each ring is constrained with a thin section radial ball bearing (d) and it is connected to the motor with a pair of spur gears with a reduction ratio of 16:70 (e). In this case, a stabilization system is not required since the two propellers are constrained to rotate around a 1 mm shaft (f).

IV. BUOYANCY SYSTEM

Jeff is equipped with a buoyancy system (Fig. 8B) in order to actively control its depth.

A cam (a) converts the rotational motion of a DC motor (Precision Microdrives 212-117)(b) into a translation of two pistons (c), one on each side of the robot. The cam has a linear profile, it can rotate at 90° and allows to move the two pistons ±2 mm. By controlling the position of the piston the overall volume of the robot is modified, thus the buoyancy is controlled. The waterproofness of the system is guaranteed by means of rolling diaphragms (d), a durable, flexible membrane shaped like a top hat with the peak of the hat fastened to the end of the piston and the brim clamped to the piston housing (e) and tightened with six screws on a flange (f). Inside the cylinder, the rolling diaphragm forms a continuous seal between the piston head and cylinder wall. When the piston is moving, the rolling diaphragm rolls along the cylinder walls. Compared to conventional sealing solutions, rolling diaphragms have the advantage to be almost frictionless and watertight. The system generates a buoyancy force of ± 2 g that corresponds to a steady vertical velocity of 0.08 m/s. Because Jeff is conceived for experiments in swimming pools, in order to reduce costs, the buoyancy system is designed for a maximum depth of 3 m.

V. DOCKING SYSTEM

Since the operative life of AUVs during missions is mostly constrained by energy and data storage limitations, the CoCoRo swarm includes a floating station equipped with a submerged docking station that can exchange information and charge the AUV's batteries. The floating station can carry a large battery payload that can be potentially refilled with energy scavenged from sun or wind and can easily communicate with a remote operator that can update the AUV's mission. Similarly to the work presented by some of the authors in [11] the docking station and the AUVs are equipped with magnets that provide passive alignment at short range (i.e. one AUV's body-length). When the robot enters in the attraction region generated by the magnet of the docking station, the robot is attracted and passively driven for a successful connection. Hence, this system is able to reduce both complexity and precision required by the docking control algorithms [16] and sensors. Indeed, part of the "computation and perception" required for guidance and alignment is passively performed by the magnetic interaction.

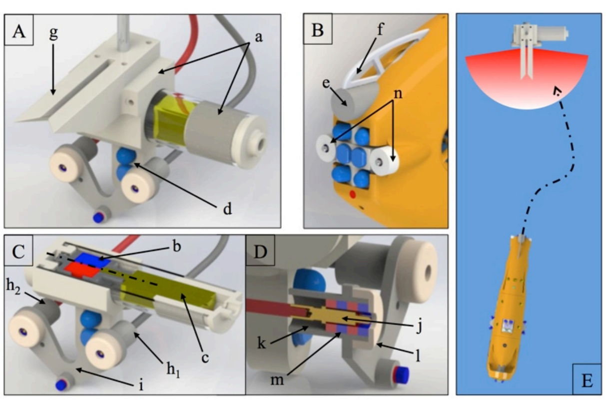

Figure 9. The figure shows the 3D models of the docking station and of Jeff's nose.

As shown in Fig. 9, the docking station is composed of a waterproof case (a) that contains a rotating magnet (b) and a DC motor (c). The magnet is diametrically magnetized and it can be actively oriented by the DC motor. When Jeff needs to be docked, the magnet is oriented in an attractive configuration with respect to the magnet which is located in Jeff's nose (e). When recharging is completed, the magnet in the docking station is rotated at 180°. This generates a repulsive force that disengages the AUV with no contribution from the propellers.

A probe (f) and drogue (g) system provides the final and precise positioning that is required for a successful electrical connection. The charging station is equipped with two electrical connectors (h1 and h2) that are inserted inside a "floating" frame (i). The frame is connected with cables (not shown in Fig. 9) to the charging station in order to passively compensate for possible oscillations of the AUV caused by waves.

The working principle of this system is based on the so called attraction region, which can be defined as the space where an AUV has to enter in order to be passively aligned for a successful connection with the docking station (illustration in Fig. 9E). The shape and the dimension of the attraction region are a function of: i. the alignment forces generated by the magnets; ii. the dynamic behavior of the AUV, which is a function of its inertial properties and shape; iii. the geometrical compliancy of the probe and drogue system. The attraction region can be estimated by numerically calculating the trajectory of the AUV under the effect of the magnetic attraction of the docking station. The case study presented here, concerns the connection between an AUV and a fixed docking station assuming that: i. the AUV moves in the horizontal plane (this study is valid if the AUV is kept at the same depth of the docking station by means of a closed loop depth control or if the connection is performed at surface); ii. the magnetic interaction is evaluated by approximating the permanent magnets as magnetic dipoles; iii. the docking station is fixed and it is composed of a conical indentation, which acts as a drogue element, while the AUV is equipped with a spiky probe.

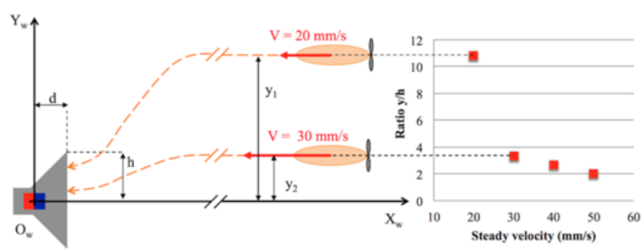

Figure 10. The graph shows the gain of misalignment that can be compensated if Jeff is frontally approaching the docking station with different steady velocity in the range of 20-50 mm/s. Considering the length of Jeff, this velocity corresponds to 0.8-2 BL/s (Body-Length/second).

As shown in Fig. 10, Jeff is assumed to approach the docking station parallel to the Xw axis, starting from an initial distance where the magnetic interaction can be neglected. The AUV moves at a steady velocity by means of a propulsion force generated by the propeller, which is kept constant during the simulation (no active alignment techniques are considered). The probe of the fixed docking cone can compensate a misalignment along the Yw axis of ±h (6 mm). The simulation aims at evaluating the previously defined attraction region, hence the maximum distance y of the AUV from Xw that the magnetic attraction can compensate to guarantee a successful probe and drogue match. Considering Jeff's main parameters, the results of the simulation are shown in Fig. 10, where the y/h ratio is plotted as a function of the initial steady velocity of the AUV. As expected, the proposed system amplifies the misalignment that can be successfully compensated by the geometrical properties of the docking system. However, alignment capabilities are strongly affected by the dynamics (initial steady velocity) of the AUV.

VI. Sensing and communication

Jeff is equipped with BlueLight communication and sensing devices on its six sides (h in Fig. 2). Each BlueLight unit comprises four blue LEDs [5] that ensure high penetration in the water: a pair of long range (1 m), narrow-beam (60°) LEDs and a pair of low intensity (0.5 m), wide-beam (120°) LEDs. Each unit is also equipped with two photodiodes, one for communication and the other to detect and measure the distance from obstacles. In addition Jeff is equipped with 14 electrodes that are used as potential field sensors for communication and localization [12][13] within a range of 250-500mm.

In addition, Jeff is equipped with an acoustic sensing system, which is used in order to constrain the swarm in a desired region. Indeed, the floating station generates an acoustic virtual fence that limits AUV's movements. The floating station emits an acoustic signal at the frequency of 5 kHz, which is received by a microphone located on the top of Jeff's shell (l in Fig. 2). If the sound perceived by Jeff decreases under a threshold, the AUV swims back following the sound gradient. The acoustic system is designed to create a virtual confinement up to 10 m from the floating station. Furthermore, each robot is equipped with two loudspeakers (j), one for each side. Their use for localization and communication (range of 0.5-1 m) is currently under investigation.

VII. Conclusion

This paper presents Jeff, a miniature AUV that has been conceived to perform affordable swarm experiments in confined underwater environments. To take full advantage of the swarm behavior, Jeff is capable of 3D swimming, local sensing and communication from multiple directions. Due to the lack of off the shelf components for miniaturized AUVs, Jeff's main systems are custom designed. Those are conceived to be both watertight and energetically efficient thanks to miniaturized magnetic couplings for the propellers and rolling diaphragms for the buoyancy system. Extended operations are ensured by Jeff's docking capabilities. Docking is based on permanents magnets, a solution that ensures a short-range, passive and precise connection between Jeff and the submersed docking station.

Future work mainly involves the implementation of cognitions and awareness generating algorithms in order to perform autonomous swarm experiments. Docking will also become fully autonomous thanks to tailored control algorithms integrated with the passive magnetic alignment.

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