The first connection system for modular underwater bio-inspired robots

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***Abstract*—Modularity is a key concept, which has been exploited in a large variety of platforms. This paper gives an overview of the design of an innovative modular underwater robot with bio-inspired electric sense. The system is developed in order to investigate how different morphologies allow to improve the perception of the environment. One critical issue in modular robotics is the design of the docking system between modules. An innovative design to solve this problem is developed and validated. The system uses self-alignment through permanent magnets and a mechanical connection.**

I. INTRODUCTION

This article concerns a novel underwater modular robot. Particular attention is devoted to the description of the docking system, one of the most challenging design problem in modular robotics [1].

The main purpose of the robot is the investigation of the interaction between body morphology and perception. To perform this task the robotic platform is able to swim as an eel-like whole entity or may split into several single agents and reassemble. Both morphologies are able to perceive the environment by means of a bio-inspired "electric sense" [2]. In the eel-like shape the perception is closely linked to the morphology: the bending or twisting of the body change the spatial layout of the electric emitters and receivers, thus modifying the perception. Otherwise, the splitting of the eel-like entity into several single agents permits to increase the perception range of the system.

In the first part of the article an overview of the whole robotic platform is presented. Afterwards the docking system is described in more detail.

II. THE ANGELS ROBOT

The Angels platform is composed by several modules, which are able to connect each other in a serial configuration. Individual and eel-like morphologies are shown in Fig. 1. Each module is 250×120×60 mm and it is neutral buoyant with a weight of 1.2 Kg.

Fig. 2 shows all the mechanical subsystems of a single module. It requires:

- an external shell,
- propellers,
- a buoyancy control.

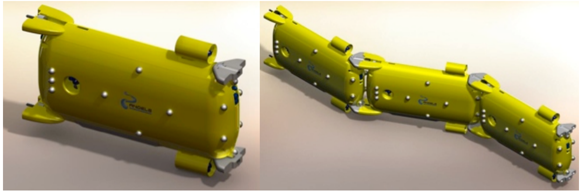

Fig. 1. The ANGELS robot. Trimetric view of a single module and of a three modules serial structure.

With these systems each module is able to move underwater in 3D.

Two other systems are required for the eel-like morphology:

- a docking system,
- an actuator for anguilliform swimming.

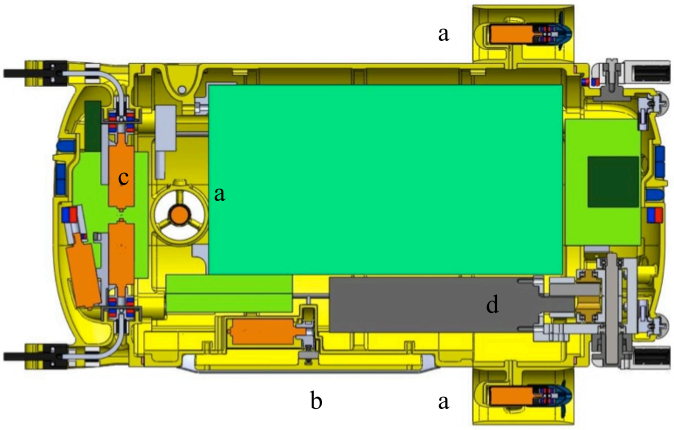

Fig. 2. Longitudinal section of the modules: a. propellers, b. buoyancy system, c. connection system, d. motor for anguilliform swimming.

A. *The External Shell*

All the mechanical systems are hold inside a shell, which is manufactured by rapid prototyping. The shell is divided into three parts: a rear and a frontal shell that are screwed to a middle section. Custom silicone seals between those parts keep the inside of the robot waterproof. An elliptic shape of the frontal and longitudinal sections allows reducing the drag force during the movement in the water. Twenty hemispherical electrodes for electric sense are located in the shell.

B. *The Propellers*

Three propellers (Fig. 3) control the motion of surge, pitch and yaw. The system is designed to be completely waterproof by means of a magnetic coupling that transmits the torque of the motor to the propeller without any mechanical connection. This solution is very convenient for miniature systems where conventional seals are usually not suitable and show a lack of efficiency. The pitch of the propeller is chosen to maximize the efficiency of the whole system (motor, magnetic coupling and propeller), achieving a total efficiency of 7.3%.

Each propeller produces a thrust force up to 0.15 N and a nominal surge velocity of 0.3 m/s.

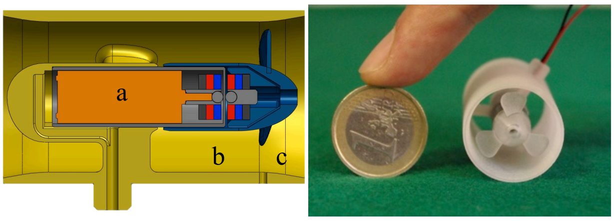

Fig. 3. Longitudinal section of the propeller: a. Dc motor, b. magnetic coupling, c. propeller.

C. *Buoyancy system*

The system (Fig. 4) allows controlling the swimming depth of each module by modifying its total volume. A Dc motor, connected to a cam, moves the bottom part of the shell. A thin silicone membrane guarantees the waterproofness of the connection between the movable part and the shell. Despite the compact design, the system allows a high heave velocity up to 0.1 m/s.

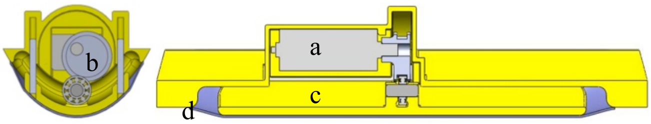

Fig. 4. Cross- and longitudinal sections of the buoyancy system: a. Dc motor, b. cam, c. movable shell, d. silicone membrane.

D. *The Docking system*

The docking system is composed by a permanent magnet and a mechanical system. The former allows the self-alignment between the modules in order to facilitate the docking procedure. The latter consists of two screws, which ensure the mechanical connection between the modules. These systems are described with more details in the next sections.

E. *Anguilliform swimming mechanism*

A lever mechanism (Fig. 5) transmits the movement from the shaft of the motor to a perpendicular shaft with a 1:2 reduction. The second shaft is attached to the connectors, which transmit the movement between the two linked modules.

The advantage of a lever system with respect to a traditional gearbox is a smaller clearance. This feature is very important in a serial structure such as the Angels robot, since the errors in each joint are generating a larger overall error.

The robot is able to swim with a maximum frequency of 0.7 Hz at a velocity of 0.7-body length/second. For a nine modules serial structure this velocity corresponds to 1.6 m/s.

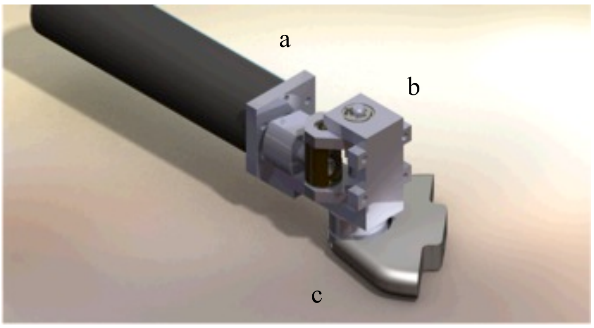

Fig. 5. Isometric view of the actuation system for the anguilliform swimming. The system is composed of: a. brushless motor, b. lever system, c. connector.

III. DOCKING SYSTEM OVERVIEW

The design of the docking system is one of the main issues in swarm robotics [3]. The difficulties are related to:

- alignment of the robots for which an high precision is needed;
- transmission of high and time dependent forces through the connection system;
- necessity of avoiding clearance between the linked robot;
- necessity to transmit data or electrical power.

During the past year many modular robots have been developed with a large variety of docking systems. It is possible to classify these systems in three main categories with specific advantages and disadvantages. It is worth stressing that none of these systems are designed for underwater modular robots.

A. *Electromagnetic connection*

Fracta [4] and the robots developed for the Claytronics project [5] exploit this solution. The main advantage is the possibility to self-align the robots using the magnetic field path that is generated by the electric current. Main drawbacks are a low connection force and a low efficiency of the system, since the activation of the connection requires electrical energy.

B. *Permanent magnet connection*

The permanent magnetic interaction allows self-alignment as well. Moreover, using magnets with high residual induction, it is possible to obtain very strong connection forces without energy spread. The main drawback is related to the “unwanted interaction” between permanent magnets. This problem is mainly caused by the difficulties in modification and control of the shape of the magnetic field lines.

Miche [6] and Telecubes [7] are examples of robotics platforms with permanent magnets connection.

C. *Mechanical connection*

A mechanical connection is the most common solution. Main advantages are versatility and possibility of high forces transmission. The main drawback is the requirement of high precision alignment for the connection. This is usually achieved with dedicated control algorithms and sensors [8]. Examples of mechanical connections are in I-cube [9], Conro [10], ATRON [11] or Amour AUV [12].

The main characteristics of the three categories of connection systems are summarized in table 1.

	Electromagnetic	Magnetic	Mechanical
Advantages	Self alignment	Self alignment	High forces
Disadvantages	Low forces High energy consumption	Unwanted interaction	High precision alignment

Table 1. Main features of connection systems

IV. AN HYBRID SOLUTION FOR DOCKING

Taking into account the previous considerations and also the underwater application, Angels modules have been equipped by an hybrid connection system. This approach permits to exploit the advantages of both the permanent magnet and the mechanical solutions.

The key idea is to use small magnets to self-align the robots. Despite the weak intensity of the magnetic fields it is possible to move in the water the robots at a reasonable velocity. On the other hand, the smallness of the magnets permits to avoid the unwanted interactions that are typical for the permanent magnets connection systems.

However, small magnets produce inadequate connection forces, so it is necessary to introduce a mechanical system to link together the modules during the anguilliform swimming. Obviously, the mechanical connection procedure is simplified by the fact that the magnets already align the robots.

A. *Magnetic alignment system*

As shown in Fig. 6, two magnets, one in front and the other in the back, equip the robot. The rear magnet is movable, in order to control the attractive and repulsive configuration. Both magnets are cylindrical and have a diametral magnetization (N48); the diameter is 6 mm and the length is 5 mm.

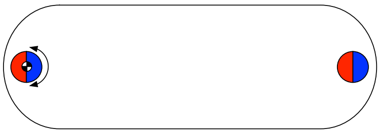

Fig. 6. Top view of the module. There is a fixed magnet in front of the robot and a movable magnet in the back

In order to evaluate the performances of the system it is possible to compare the force of the propellers with the one produced by the magnetic system. The latter is evaluated by using FEM analysis.

As a result of the simulation (Fig. 7) in the attractive configuration, it is possible to identify an attraction region, of roughly a circular form with radius 70 mm and angle 80°.

Moreover, the simulation (Fig. 8) in the repulsive configuration demonstrates that is always possible to avoid unwanted attraction by means of the propellers.

The alignment of the robots requires two steps:

- during the first step one robot is driven into the attraction region of another one using the electric sense. This phase involves control algorithms, motion of the propellers and feed-back from electrodes;
- after the robot reaches the attraction region, the alignment is automatically obtained without any action of the propellers. This also means that it is not required any specific control system or sensor in the last step of the alignment.

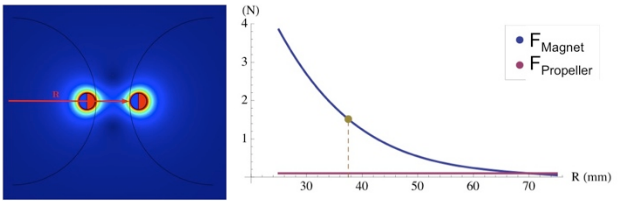

Fig. 7. FEM analysis of the magnetic repulsive force VS the distance (R) between the modules. The magnetic force is compared with the maximum thrust produced by the propeller. This allows estimating a maximum attraction distance of 70 mm.

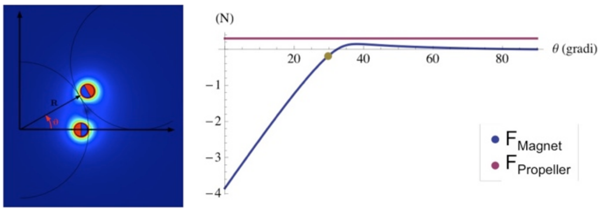

Fig. 8. FEM analysis of the magnetic repulsive force VS the angular position (θ) of the modules. A positive value of the magnetic interaction means attraction between the modules. Since the thrust of the propeller is always greater than the magnetic force, no unwanted interaction could occur.

B. *Mechanical connection system*

The mechanical connection acts when the robots are already aligned by the magnetic interaction. The system is designed to transfer the connection force and torque required during the anguilliform swimming.

The system should respect two main constrains:

- no metallic components in contact with water, in order to avoid interference with electric sense perception;
- no clearance between the connected robots.

Both constrains are respected trough mechanical connection with screws:

- nylon screws are used in order to avoid metal. Despite that, the connection can still transmit a force up to 30 N and a torque up to 2 N/m;

- during the docking the screws and the connectors are tighten up, in order to avoid any possible clearance between the two modules.

The final design of the connection system is shown in Fig. 9. In the rear shell, two screws tighten up the connectors in the front part of the robot that needs to be docked. The upper connector is free to rotate, while the lower one is controlled directly by the motor for the anguilliform swimming.

A DC motor rotates each screw and the required torque is transmitted from the inside to the outside of the robot trough a magnetic coupling. This solution guarantees a complete waterproofness. The external magnets are coated with epoxy in order to respect design constraints. A flexible silicone shaft connects the screw with the outside part of the magnetic gear. A custom axial bearing with polymeric sphere is designed in order to reduce stick-slip when unscrewing.

In order to compensate a possible angular misalignment between the robots along the tilt axis, compliant nuts are introduced in the frontal connectors. This behavior is achieved by means of two magnets that act like a mechanical spring.

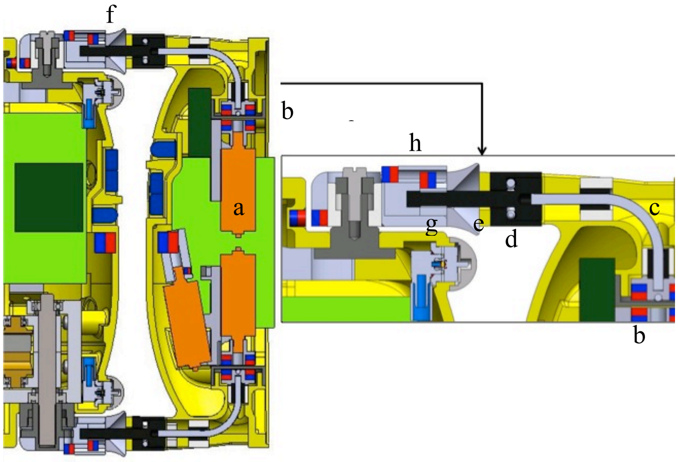

Fig. 9. Longitudinal section of the docking system. The rear shell holds: a. motor, b. magnetic coupling, c. flexible shaft, d. axial bearings and e. screw. The frontal shell holds: f. connector, g. nut and h. magnets.

V. EXPERIMENTAL VALIDATION

The working principle and the design of the connection system has been validated trough a large variety of tests (Fig. 10). At the moment the docking is performed with prototype robots controlled via Wi-Fi transmission near the water surface.

The propellers move the rear part of one robot for approaching the front of a second one. When the first module enters the attraction region (Fig. 10a), the propellers are turned off and both robots are attracted (Fig. 10b) together and subsequently aligned (Fig. 10c) by the magnetic interaction. After the alignment is performed, the screws can penetrate into the frontal connectors of the second module. The two compliant nuts are pushed back and the two screws are turned on until they are tightened up. Finally the modules are connected together and ready to swim like an eel (Fig. 10d).

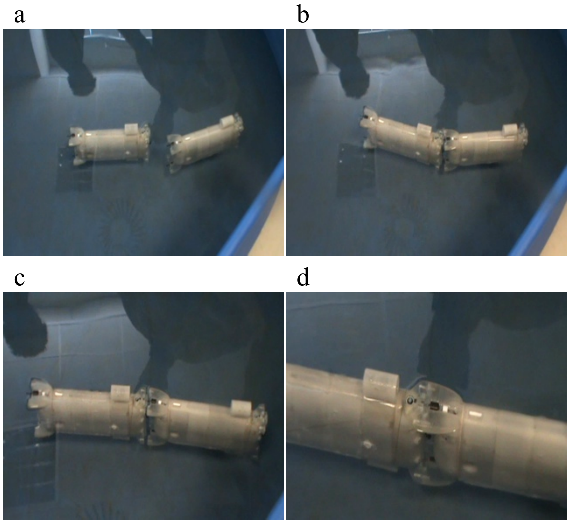

Fig. 10 Experimental validation of the docking systems.

VI. CONCLUSIONS

A first reconfigurable underwater robot with an innovative docking system is presented. The hybrid design of the system exploits weak magnetic interaction to self align the robots and a strong mechanical connection to link the robots together. This solution allows to simplify one of the most critical features of modular robotics.

Wide range of tests has been performed which validated both the working principle and the design of the docking system. Future work will be focused on the integration of the electric sense to reach autonomously the attraction region of the robots.

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