Concept Design and Simulation of a Water Proofing Modular Robot for Amphibious Locomotion

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***Abstract*— This paper will introduce a novel adaptive modular robot for amphibious locomotion research. First, an overview of modular robotic research is given systematically. In this project, we concentrate on designing a new kind of modular robot with a central part and adaptable covers, so to build different configurations. The assemble prototypes could be used for bio-inspired locomotion research not only on ground, but also in water. The modular design, interfaces, and different configurations will be presented throughout. After that, related simulations including locomotion and swimming are shown to confirm the concept and principle. In the end, a conclusion is given and future work is outlined.**

***Keywords*— Modular robot, water proof, amphibious locomotion, system design**

I. INTRODUCTION

The last few years have witnessed a strong and increasing interest in modular robotic technology for different applications [1] [2]. Modular robots normally consist of several modules with uniform docking interfaces that allow the transfer of mechanical forces and moments, electrical power and communication throughout the whole robot. Furthermore, the modular approach enables robots to reconfigure, which is very essential for tasks which are difficult for a fixed-shape robot [3]. It also makes the mobile robotic system versatile [4], cost-effective [5] [6] and fast to prototype [7], so that new configurations of different robots can be built fast and easily for the exploration, testing and analysis of new ideas.

The first modular robot concept was introduced in 1980 [8]. After that, many research projects on modular robots were implemented worldwide, most of them in the U.S.A. and Japan. The modular approach offers many advantages to the design of a multi-functional mobile robot. According to an existing classification of modular robots, they fall into two groups: lattice and chain robots [1]. The former kind arranges modules to form a grid, just like atoms forming complex 3D molecules or solids. The latter structures are composed of chains of modules. They are suitable for locomotion and manipulation since the modular chains are like legs or arms. In [9], 1D, 2D and 3D chain robots are classified according to their topology. They can adopt different shapes to pass though tubes, grasp objects and move in rough terrain. However, the pitch-connecting robots can only move forward or backward. Their movements can be generated by waves that travel through the body of the robot from tail to head. M-TRAN [10] and YaMor [11] are similar prototypes that connect in a pitch-pitch way.

Another kind of modular robot features yaw-connections. All the joints rotate around the yaw axes. A lot of research has been done on this kind of robots. They were first studied by Hirose [12] who developed the Active Cord Mechanism. Recently, his group has developed new versions of this [13]. S. Ma et al. in Japan [14] and their Chinese colleagues at the Robotics Laboratory of the Shenyang Institute of Automation have also developed their own yaw-connecting robot and studied its creeping motion on a plane and on a slope [15].

Based on the cooperation with Dr. Juan González-Gómez in Spain, we have been working on modular robot project from 2006. There are two focuses in our team. First, we concentrate on developing a cost-efficient robust modular robotic system that meets the requirements of flexibility, functionality, extensibility, easy handling for educational purposes in our international consortium. Several low-cost flexible modular robotic prototypes have been developed [5] [6] [9]. Second, we have a special interest on biological locomotion research by using Centre Pattern Generators (CPGs) [16]. On this topic, different locomotion gaits have been investigated.

Currently, in the literature, Salamandra robotica [17] was presented at the Biologically Inspired Robotics Group (BIRG) of the Ecole Polytechnique Federale de Lausanne (EPFL). The robot consists of several homogeneous modules and can connect normally in a yaw-yaw way. Four legs are added on the body part in order to provide the movement on the group. The Hirose-Fukushima Robotics Lab in Japan has invented an amphibious snake-like robot called “ACM-R5” for the purpose of performing search and rescue missions such as looking for people trapped in collapsed buildings and other tight spaces [18]. The snake-bot could also help build underground optical fiber infrastructures, and inspect unreachable waterways and sewer systems. Recently, a new snake-like robot based on modular approach was developed for underwater application in Trondheim by researchers from NTNU and SINTEF [19]. Based on the research work, a commercial version, Eelume is proposed as a disruptive technology for subsea inspection, maintenance and repair (IMR) [20]. However, the robot could not move flexibly on the ground.

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There are two reasons for us to pay attention to modular robots for inspired research on amphibious locomotion. First, modular approach enables robots to locomote and reconfigure flexibly, which is very essential for tasks which are difficult for a fixed-shape robot, thus also makes the robotic system versatile, robust. Compared to some famous amphibious robots like ACR5, a low-cost limbless mobile robot will be very promising for researchers to investigate the control realization and behavior state transition during the moving process on different terrains. Secondly, as mentioned in [6], normally biologists use expensive devices to capture, memory and analyze two or three dimensional motion of different animals. Limbless amphibious locomotion is very special in nature, and challenging in robotics. As shown above, there are only very little number of robotic projects worldwide to give efforts on the topic. However, with the development of modular robots technology, the biologists have an alternative. In principle, the experiment using modular robots should be similar to that of using natural creatures if we can implement the bio-inspired control methods which are adopted by snakes moving in water and on the ground. In this way, robotic research could also give support to biological research. This is the main reason why our team want to develop a water proof modular robot.

This paper presents a new application of our low-cost modular robots on bio-inspired research. The paper is organized as follows: Section 2 will introduces the module concept design, connection interface. Some possible robotic configurations and features will be presented in Section 3. After that, the locomotion on the ground and swimming in water will be discussed in details. Related simulations will be given. In the end, future work and conclusions are given.

II. MODULE DESIGN

A. *Requirements*

In order to design an adaptive and water-proof module for locomotion research purpose, we should meet the following basic requirements.

- Provide rotate 90 degrees for pitching and yawing;
- Water proofing feature;
- Eought I/Os for sesnors and actuations;
- Communication with neighbouring modules or centre graphical user interface (GHI);
- With internal space for battery and extra control units;
- Flexible interfaces to build different configurations;
- Low cost.

As a result, a single module should contain the basic compontens including a servo motor, a teensy micro-controller, battery, and special interfaces for communication and interact with other modules. The three major design iterations were implemented in order to meet all requirements. First, the project selected the following compontents for the concept design.

- Servo Motor: MG995 Tower-pro dual ball bearing servo with metal gears. It could provide 8.5 kgf·cm stall torque, 0.2s/60degree operating speed. The working voltage is 4.8 V. The dimension is 54mm long, 48mm high and 20mm thick.
- Microcontroller: we select Teensy 3.1 [21], compatible with Arduino software and libraries and has the following specifications, as shown in Table I.

TABLE I. THE TEENSY 3.1 SPECIFICATIONS

Specification	**Teensy 3.1**
Processor	MK20DX256, 32 bit ARM, Cortex-M4,72 MHz
Flash Memory	262144
RAM Memory	65536
EEPROM	2048
I/O	34, 3.3V, 5V tol
Analog In	21
PWM	12

- Battery: a 5.5 V Lithium Ion Battery with a 2000 mAh capacity from PKCELL. The dimensions of this component are 37 mm x 60 mm x 7 mm. It will provide power to each module on board.
- Waterproof Connectors: two kinds of connectors are selected, are in charge of providing the required inputs, and outputs for sensors and actuators.

The whole design process of the module is shown in Fig 1. From step a to setp c, it is the initial interation which is just for concept design. There are two parts on each module. The right box hosts the motor, controller and battery. The blus part with two arms will provide the connection with the neigbouring modules in a pitch-pitch way. The waterproof is utilized by using a gasket made of garlock which is a series of compressed fiber layer subjected to a high-pressure sheet process.

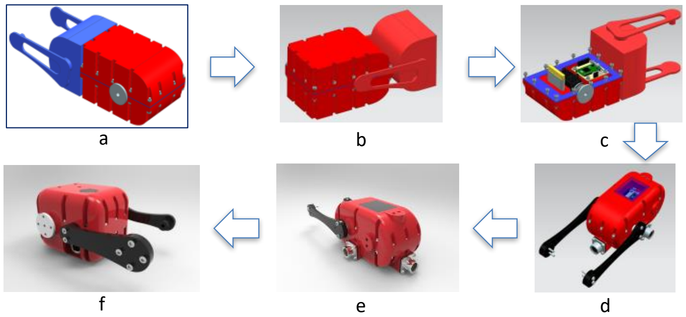


Fig. 1. Three iterations design of new module. a-c the first interations, d-e the second interations, f the last one.

B. *Second interation of design*

For the second iteration, the main focus is on how to integrate the module connection flexiblity. This not only reduces the number of necessary interfaces, but also provides the opportunity to implement different configurations for the internal arrangements of the design. As shown in Fig. 2, the design implements interchangeable arms as the elements in charge of transmitting motion from one module to another. These arms can be connected to two orientations (pitch or yaw) to the next module according to the application requirements.

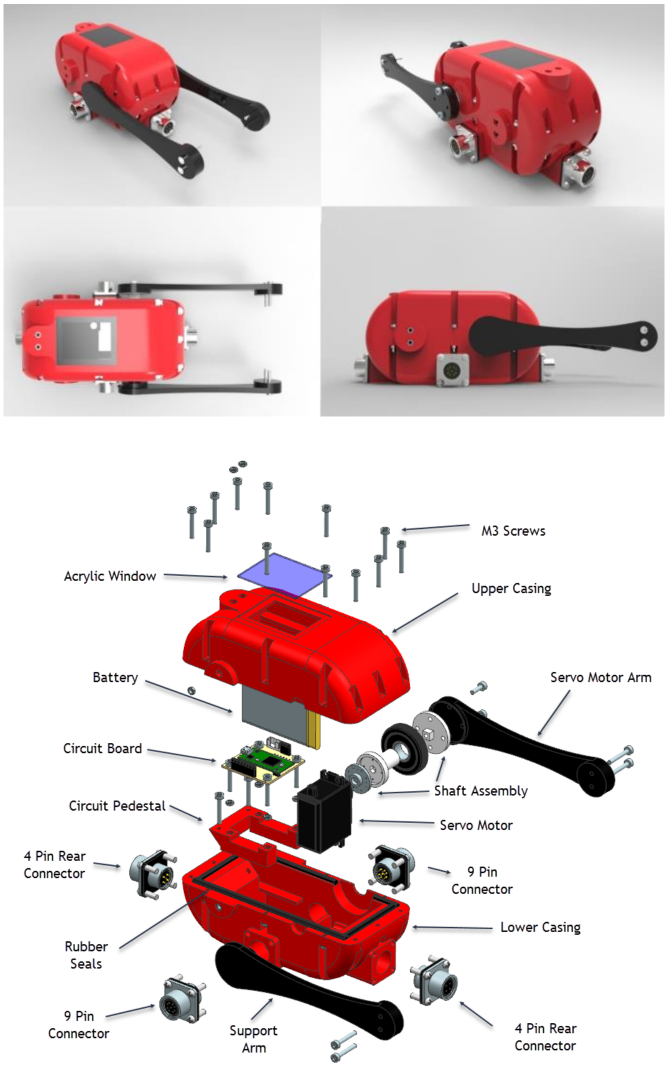


Fig. 2. Improved modular robot design

Compared to the initial design, there are four major changes. The first is related to the implementation of a small window on the top of the module to provide a possilbity of implementing an infrared distance censor if needed, or even a camera. The second is the addition of waterproof ball bearings added to the transmission shaft as opposed to the high-friction dual O-ring arrangement from the first iteration of the design. This will allow a smooth rotation along with the required protection from water. The third is to implement rubber seals as the method of waterproofing mechanism in contrast to the original idea of using gaskets for sealing. The main reason for the change is the simplicity and robustness of the design. Finally, the last is related to use both four and nine pin connectors. 4-pin connector locates at the longitudinal extreme of the module to connect between modules through an additional flexible water-resistant cable. The 9-pin connector is used to connect all signals, located at the both sides of the module for ease of access and installation. All components including controller, motor, and battery are protected by the cover.

C. *Final module design*

There are a lot of important features of this design. However, the main drawback is the dimension. It is 80mm high, 80mm width, and 260mm long with the arms. The total module will be around 1kg, which is much too heavy for locomotion research. As a result, we have the final design as shown in Fig.3.

Compared to the second design, first we reduced the dimenison in the length from 260mm to 145 mm, cutting down 33% of the volumn. Then, the 4-pin connector was removed and replaced by a wired connection between modules. In order to protect wires, the arm consists of a hollow rigid link to house the wires to establish communications between links. The 9-pin connector was designed embedded into an internal position to reduce the size and also to allow a more stable and compact form. On the top and bottom, there are three screw holes to wear some extra covers for shape changing and supporting locomotions. The specification of the module is shown Table II.

Fig. 3. Final design and 3D printed module

TABLE II. NEW MODULE DESIGN SPECIFICATIONS

Items	***Iteration 1***	***Iteration 2***	***Iteration 3***
Main Dimensions (W x H x L mm^3)	80 x 80 x 180	80 x 80 x 150	80 x 80 x 100
Main Waterproofing	Gasket	Rubber Seals	Rubber Seals
Number of Bearings	0	1	2
Compatible with External Covers	No	No	Yes
Additional I/O	No	Yes	Yes
Internal Space	Mid	Max	Min

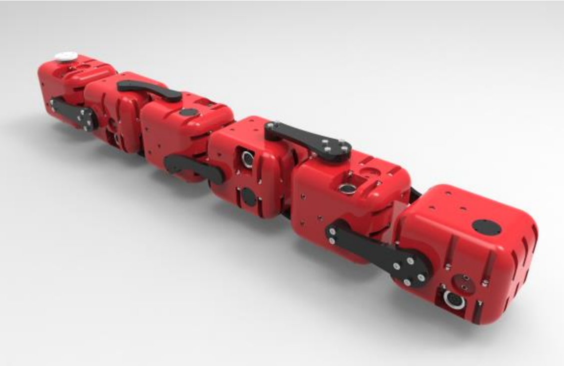
III. DIFFERENT CONFIGURATIONS

A special feature of new modular robot design is configuration flexibility that is offered by using various wearable covers on the central module unit. The single module could be used as a central unit. Two additional interfaces are designed to allow each module to wear different outside covers modifying either the outer shape, or simply providing extra support during the task implementations. In this way, the module will be adaptive for shape changing.

According to the configuration requirements, these additional covers are mounted in a secure way connecting the module from the top and the bottom faces via three screws. In the literature, some similar approaches have been investigated [22]. The Mamba robot could have passive wheels, propulsion unit, motorized legs or tail on the basic module. After assembling, the robot is still in the same chain configuration, while with different locomotion capabilities. Many extra units are with independent actuation. In principle, they are real functional modules, rather than extra attachments. That is the main different between Mamba project and our intention. All different covers are complete passive, and provide configuration possibilities. There are two advantages of utilizing this idea. It will give all students and researchers flexibility to propose their innovation and configurations to build mobile robots. By using 3D printing, the covers could be easily designed and manufactured in a low cost. In the following section, we will just show three on-going cases in our lab.

A. Limbless configuration for amphibious locomotion

The first case is to show the limbless snake-like configuration for locomotion in various environments. The modules are connected in pitching and yawing way alternatively. The limbless configuration is shown in Fig. 4, with and without covers.



(a) Without covers

(b) With covers

Fig. 4 Catepillar configuration.

The render just shows the principle. Therefore, different numbers of modules are presented in the figure. In principle, the modular robot with this configuration could implement linear movement, turning, rotation, sideway walking, and rolling movement. Only 3 modules without any covers will be enough to generate all gaits [23]. This configuration is very stable since the bottom is flat. In order to have a good performance, the bottom should provide enough friction to generate the movements. Fig. 5 shows how to install a cover on the central module. After assembling, the robot will have more robust, strong and owning better friction efficiency.

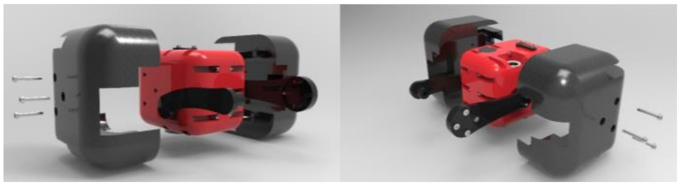


Fig. 5 Cover assemble

B. Fish-like robot configuration

According the biological study on fish, it is possible to use a similar configuration to resemble a fish-like structure [24, 25]. Each module can yaw -90 to 90 degrees. The wearable covers will simulate the hydrodynamics of fish and realize the swimming more effective, as shown in Fig. 6. It shows in total 5 core modules with three different types of covers on the robot, including the front one as an arrowhead, three body segments, and the last module simulating a back fin. Currently, we are still working on designing the biological cover to offer the better swimming hydrodynamic property. Even two extra breast fins are considered to install on the bottom of head cover to have a better swimming performance.

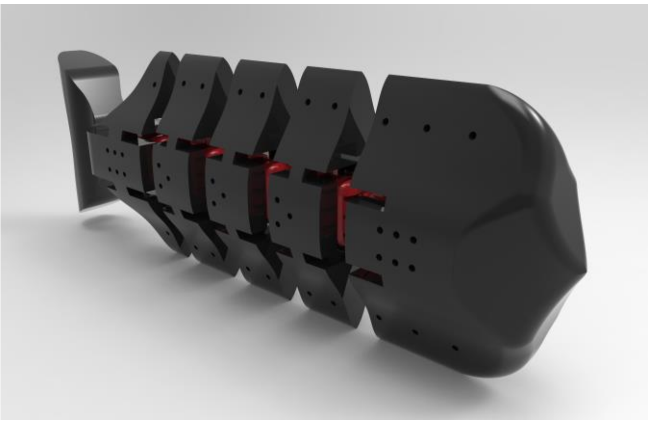


Fig. 6 Fish-like configuration

The wearable covers enable the modular robot various configurations flexibly and easily. It not only changes the shapes and structures of the configuration, but also provides extra functionality.

IV. SIMULATIONS AND VERIFICATIONS

A. *Simulation environment*

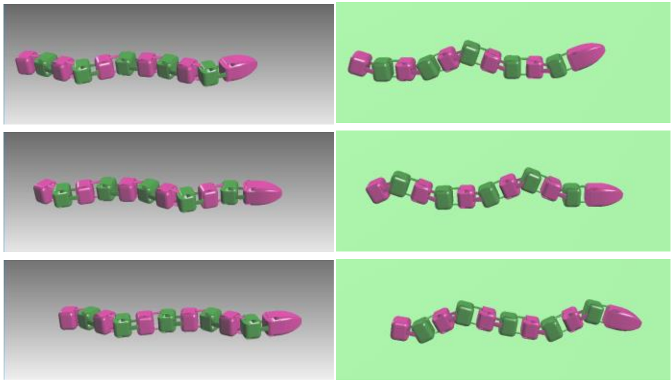
To verify the concept design of the modular robot, several simulations were executed in the AgX dynamics software—a commercial physical engine with hydrodynamics capability [26]. To keep consistent with the real world, the gravity, the water density, and the friction coefficient were set to -9.81 m/s^2, 1000 kg/m^3 and 0.6 respectively. The designed module density was set to 970 kg/m^3, so that the module can float on the water surface. A pitch-yaw connected modular robot with covers to adapt to amphibious locomotion was utilized as the testbed basis, as shown in Fig. 4b.

B. *Amphibious locomotion simulations*

Two groups of simulations were studied: the first one for swimming in the water while the other for the locomotion on the land. Both groups generate body waves for propulsion by using the sine generator [27]:

$$\theta_i(t) = A\sin(\frac{2\pi}{T}t + i\cdot\varphi) + O$$

where θ is the bending angle of the module; *i* is the index of the module; A, T, φ and O are the parameters for controlling the amplitude, the period, the phase difference and the offset of the generator, respectively. Fig. 7 illustrates an example of the two groups of simulations using 11 modules with covers. Note that for simplicity, the modules in green color are fixed to zero value during the simulation. Because of the covers, both types of locomotion performed well as we expected.



(a) Swimming in water (b) Linear movement on land

Fig. 7 Snapshots of amphibious locomotion with 11 modules eployed with covers, using control parameters A=45.0, T=1.0, φ=2.1 and O = 0.0.

In the simulation, how the covers takes effect on the amphibious locomotion in terms of speed was tested. We took the same parameters as listed in Fig. 7, but varied the number of modules with/without covers. Fig. 8 shows the result for swimming in the water. With the growth of module number, the swimming speed decreases. This may result from the lower propulsion force due to the increased drag force during body undulation. Another interesting finding is that the employment of the covers increases the swimming in the water compared to the group without covers. This is because the covers provide a smooth surface that creates less water resistance as the robot swims, whereas the regular design of the module that has several irregular patterns and a much more complex outer geometry increases the resistance of water and leads to a lower speed.

Fig. 9 illustrates the result of the linear locomotion on land. As the number of modules increases, there are more modules in contact with the ground during the movement. Consequently, more friction is generated for propulsion, leading to the increase of the locomotive speed. However, the speed incremental slows down gradually and almost equals to zero when the number of module involved in the locomotion is up to 12. This is because when there is enough friction for propulsion and no sliding happens, the main factors that affect the locomotive speed are only related to control parameters of the sine generators, including the amplitude, the period, the phase difference and the offset. In this case, these parameters are not changed during the simulation, and therefore the speed converges to a constant.

Through the simulation results, the effectiveness of the design of the module together with its cover for amphibious locomotion is verified.

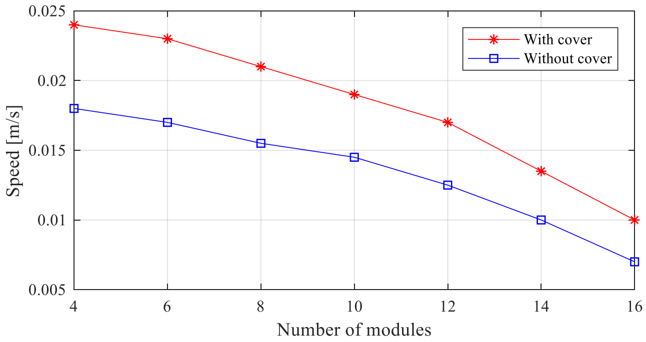


Fig. 8 Swimming speed variation with respect to the number of modules.

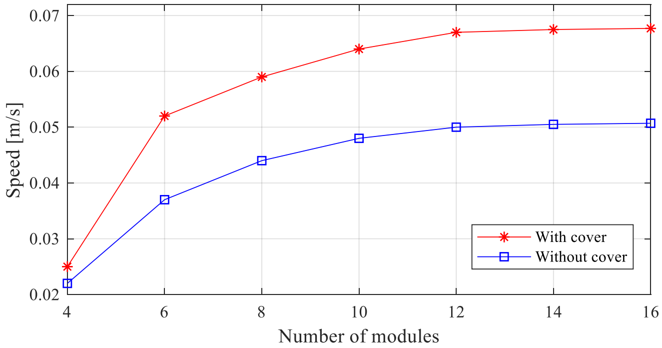


Fig. 9 Speed variation of linear movement on land with respect to the number of modules.

V. CONCLUSIONS AND FUTURE WORK

This paper presented a new water proofing modular robot design which has the following features. First, the module could provide flexibile connection interface with neigbouring modules, so to build different configuration easily. Second, the module meets the water proofing requirements for amphibious locomotion research. Third, the module could be used as a central unit to build different kinds of mobile robots with the help of wearing different supporting covers. Three interations of design have been implemented and concluded the current solution. The single module has been produced and tested in the lab. Related simulation of snake-like amphibious locomotion has been investigated to confirm the idea.

Currently, we just do a first step on amphibious locomotion research. As we mentioned before [6], as a new application of modular robot research, it will provide an alternative and makes the bio-inspired research relatively easy.

According to the experimental results we are working on the further elaborate testing in order to find the optimized parameters for swimming and locomotion control on the ground. Meanwhile in order to move in different gaits on surfaces of various materials, we are starting to focus on control transitions based on sensor fusion. The other topic in our lab will be on the different configurations and locomotion realization. This new modular prototype will enhance the system capability for future research remarkably.

VI. ACKNOWLEDGMENTS

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