Bio-inspired Underwater Robot with Reconfigurable and Detachable Swimming Modules

Santhosh Ravichandran
Center for Nondestructive Evaluation, Indian Institute of Technology Madras
Chennai, TamilNadu 600036
santhosh11dec@gmail.com

Akhil B. Arackal*
Muthoot Institute of Technology And Science
Puthencruz, Kerala 682308
abarackal@gmail.com

Aniket S. Mazumdar †
Center for Nondestructive Evaluation, Indian Institute of Technology Madras
Chennai, TamilNadu 600036
aniket.smazumdar@gmail.com

Jaya Sai Kiran P
Center for Nondestructive Evaluation, Indian Institute of Technology Madras
Chennai, TamilNadu 600036
saikiranp321@gmail.com

Prabhu Rajagopal
Associate Professor, Center for Nondestructive Evaluation, Indian Institute of Technology Madras
Chennai, TamilNadu 600036
prajagopal@iitm.ac.in

ABSTRACT

Maneuverability and propulsive efficiency are of much interest in autonomous underwater robots. In this paper, we present a novel underwater robot design with two reconfigurable and detachable swimming modules that would be capable of offering both maneuverability and propulsive efficiency. They are also capable of reconfiguring automatically to take two different orientations favoring reduced drag in the swimming direction. A key feature of this design is that the reconfigurability is achieved without additional actuators - helpful in the development of autonomous swarm robots with good maneuverability and efficiency.

KEYWORDS

Bio-inspired underwater robots; swarm robots; re-configurable robots.

ACM Reference format:
Santhosh Ravichandran, Akhil B. Arackal, Aniket S. Mazumdar, Jaya Sai Kiran P, and Prabhu Rajagopal. 2017. Bio-inspired Underwater Robot with Reconfigurable and Detachable Swimming Modules. In *Proceedings of AIR '17, New Delhi, India, June 28-July 2, 2017,* 6 pages.
https://doi.org/10.1145/3132446.3134875

*This author worked on this project as an intern in the Department of Mechanical Engineering at Indian Institute of Technology Madras.
†This author worked on this project as an intern in the Department of Mechanical Engineering at Indian Institute of Technology Madras.

AIR '17, June 28-July 2, 2017, New Delhi, India

ACM ISBN 978-1-4503-5294-9/17/06…$15.00
https://doi.org/10.1145/3132446.3134875

1 INTRODUCTION

Underwater robotic technologies have been explored widely in recent years with applications ranging from simple observation to complicated work class operations such as trenching and cable laying [1][2]. In particular, there is an increased interest in observation level operations and light work class missions such as sample collections and environmental monitoring [3][4]. In these applications, the underwater robot would carry a camera or other simple data acquisition, and should have good maneuverability, propulsive efficiency, and stealth if used for defence and military applications. Bio-inspired underwater robots with flapping fins could have good maneuverability [5], propulsive efficiency [6] and stealth capabilities compared to conventional underwater robots [7]. Labriform [8] inspired underwater robots could exhibit good maneuverability. Although high propulsive efficiency can be optimized by careful design of the bio-inspired propulsion system [9], it can also be improved by reducing the fluid drag on the underwater vehicle through vehicle design.

In this paper, we present a novel underwater vehicle design consisting of a body with two separable and reconfigurable swimming modules. Here, by 'reconfigurable', we mean that the swimming module is capable of taking two stable orientations depending on the direction of motion by shifting its center of gravity (CG) without the need for dedicated actuators. Each swimming module has two bio-inspired flapping fins on two sets of 2 Degree of Freedom (DOF) serial links actuated by a total of four servo motors per module allowing good maneuverability. The details of this design and the structure of the overall vehicle are discussed in Section 2. The reconfigurability allows for reduced drag in the direction of motion, which is explained in Section 2.2. The primary motivation for separable swimming modules is to shift the majority of power-supply, processing equipment and other common payloads to the main body and only have important sensors and propulsive actuators on the swimming modules. Such detachable swimming modules also allow the capability of inspecting tight spaces that the overall vehicle may not be able to reach. This allows for a swarm of light swimming modules with a common power supply or processing

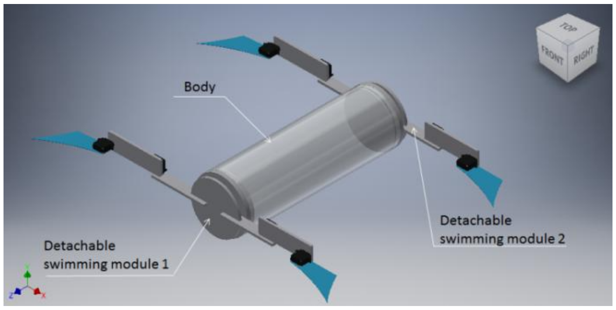


Figure 1: Illustration of the overall robot design with detachable and reconfigurable swimming modules.

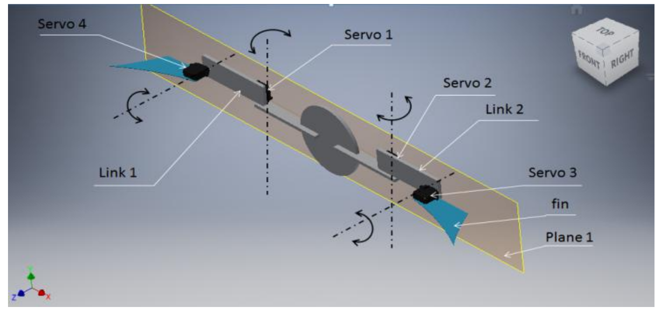


Figure 2: Diagram illustrating the swimming module. The curved arrows show range of motion of the servos.

module. Therefore, these swimming modules, although separable, are connected to the main body through tethers for power supply and control signals (electronic hardware and software is presented in Section 2.3). Discussion on the potential applications of the design is given in Section 3, presented together with test results.

2 VEHICLE DESIGN

In this section, the details of the design of our labriform-inspired underwater robot with detachable swimming modules are discussed. Two of these detachable, reconfigurable swimming modules along with the main body constitute the entire vehicle (see Figure 1). The reconfigurable swimming modules consist of flapping fins at the end of a two (revolute) jointed arm assembly. These modules can stay attached to the main body and provide propulsion to the entire vehicle and also detach to swim by themselves. In addition to this, they can also assume two configurations, resulting in reduced drag in the direction of motion. All these parts - the main body and the detachable swimming modules are neutrally buoyant. This vehicle, in its undetached form resembles the Aqua robot in [10]: however, their design does not incorporate features of detachability and reconfigurability.

2.1 Main Body and Attachment/Re-attachment Mechanism of the Swimming Modules

The main body of the vehicle is made of a cylindrical acrylic tube closed at both ends and sealed with O-rings (see Figure 1). Acrylic, being transparent, makes fault and leak detection easier, in addition to being strong enough for withstanding hydrostatic pressures in shallow waters (depths less than 2 m in our case). This module houses power supply related components and other major electronics (see section 2.3 for more details on electronic hardware and software).

The two swimming modules stay normally attached to the end caps at both ends of the body. A set of electrical wires passes from the body to the swimming modules to supply power and send signals to the four servo motors. The challenge is to spool this set of electrical wires when the swimming modules are attaching to the body and to spool during separation. We solve this by spooling a thin nylon wire which passes through rings placed equidistant throughout the length of the set of electrical wires. The spooling of this nylon wire is actuated through a servo motor mounted on the end cap of the body. As a result, when the nylon wire is spooled, it also pulls the set of electrical wires, which by themselves fold and settle between the swimming module and end cap.

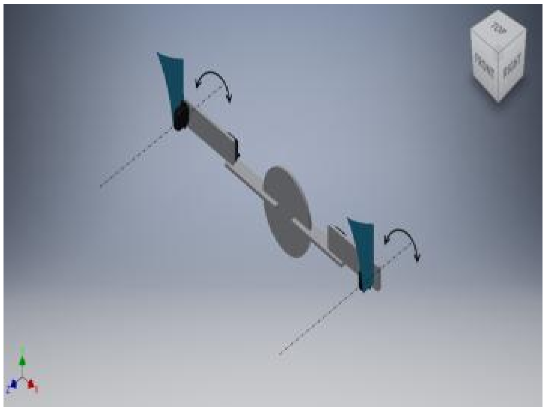
2.2 Reconfigurable swimming modules

Each of the two detachable, reconfigurable swimming modules consists of two arms (Figure 2) with revolute joints. These revolute joints are individually actuated by servo motors (PowerHD 6001HB [11]) with a range of motion limited to 180 degrees (Figure 2). With the given restriction on the range of angular movement, the position of servo motors was designed such that the flapping can be done in any direction to generate thrust in the module.

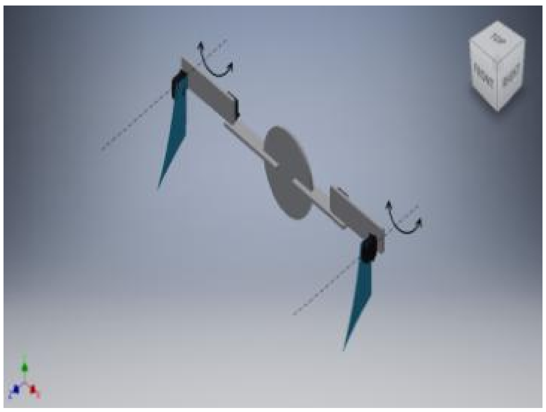
The default or first configuration of these modules is as shown in Figure 2 and the second configuration is shown in Figure 3 (c). In the first configuration, the robot can move in any direction in plane 1 (Figure 2) by flapping servo 3 and 4 in the desired direction. See for example, Figure 3 (a) and (b) where servo 3 and 4 are shown in their positions for flapping up or down for depth control. However, to move forward, servo 1 and servo 2 have to rotate 90 degrees backwards (See top right corner of Figure 2 for sense of direction) to allow servo 3 and servo 4 to flap backwards. This causes a shift in the center of gravity, which makes the robot go to the second configuration (see Figure 3 (c), Figure 4). We observe that in this second configuration, the robot is free to move in any direction in plane 2 (see Figure 3 (c)). Incidentally, these changes in configuration also results in an advantage that the module will always be moving in the direction with the least frontal area, thus experiencing least drag. In the first configuration, the robot is free to swim in plane 1 (Figure 2) and in the second configuration, the robot is capable to swim in plane 2 (Figure 3 (c)), both experiencing least drag in the direction of motion. If the robot was made to move forward in the first configuration, it would have to encounter the drag of the vertical flat circular plate of the module.

On the other hand, when it reconfigures, the flat circular plate becomes horizontal, reducing the frontal area and hence reducing drag while moving forward.

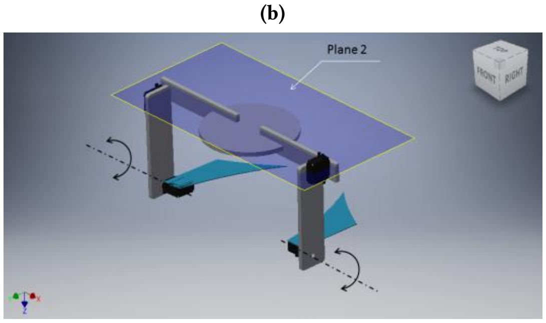
The challenge in achieving these two configurations is the difficulty in achieving stability in both. The position of the center of buoyancy and center of gravity should be carefully designed. Our approach is as follows, we designed the vehicle with the initial priority of mounting the servo motors in favorable orientations as mentioned earlier in this section. The first configuration (Figure 4



(a)

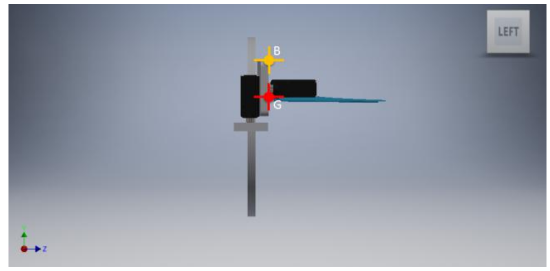


(b)

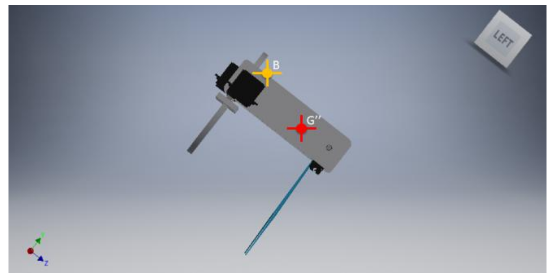


(c)

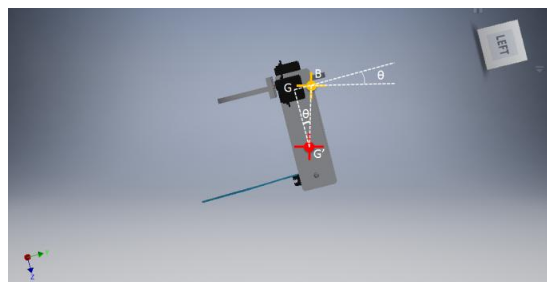
Figure 3: Illustration of the two configurations of the swimming modules, (a) and (b) show first configuration where, (a) shows the positions of servos 3 and 4 during upwards motion in first configuration. (b) shows the positions of servos 3 and 4 during downwards motion in first configuration, and (c) shows the positions of servos during forward motion in second configuration.



(a)



(b)



(c)

Figure 4: Left side view of the swimming module showing transformation from first configuration to the second. (a) shows the side view of the first configuration (Figure 2), in which the center of gravity G, is below the center of buoyancy B, making it stable. (b) shows servos 1 and 2 in the actuated position, thereby shifting the center of gravity and initiating transformation to the second configuration. (c) shows the stable second configuration after transformation. Note that the buoyancy foams are not shown in these images.

(a)) was taken and corresponding position of center of gravity was determined. Buoyancy material was added to the module until the center of buoyancy was above the center of gravity by a certain distance GB (Figure 4). Polystyrene sheets were added to obtain the required buoyancy and location of center of buoyancy. However, any other commercial buoyancy foams can be used if the robot is intended to operate at higher depths. The distance GB almost remains the same in the second configuration also (Figure 4 (c)), as the servos 1 and 2 rotate the majority of mass about their axis, shifting the center of gravity mostly along GG’ (Figure 4 (c)). The servos are placed above the horizontal mid-plane of the first configuration and thus the center of gravity positioned near the center of buoyancy. This happens as servos with their attachments constitute majority of the mass in these modules. It is also assumed that the center of buoyancy does not shift by much between the two configurations, as most of the buoyancy foam materials, constituting for majority of buoyancy of the modules were placed near B as shown in Figure 4 (a) and also considering that servo motors do not contribute much to buoyancy.

In the second configuration, the arm lengths - lengths of links 1 and 2, see Figure 2, play a crucial role as this length determines the vertical distance between the center of gravity and the center of buoyancy GG'. To maintain the body of the module near horizontal position, i.e., pitching angle θ (Figure 4 (c)) - less than say five degrees, the following relation has to be satisfied,

$$GG' \cong \frac{GB}{tan(\theta)} \tag{1}$$

For a pitching angle of less than five degrees, GG' $\geq$ 0.2 GB (assuming that for small angles of θ, tan $\theta \sim \theta$). So, the length of the arm should be such that the distance GG' is greater than this value. The value of GB itself can be chosen according to the amount of stability desired in the first configuration. A greater value of GB will lead to greater stability and vice versa. A higher value however, could result in the need for a bigger arm, which may not be desirable.

2.3 Electronic hardware and software

The electrical components used in this vehicle are: AC to DC power supply converter, Raspberry Pi 3 model B [12] and an Arduino Uno [13], all placed inside the sealed acrylic body. The vehicle is powered by the AC to DC power supply converter, which gets 220V AC Voltage as input through a tether from the off-board station and gives 5V DC (up to 20A) as output to the circuit.

The robot is controlled by an off-board laptop computer through an Ethernet communication with the Raspberry Pi on the robot via router. We have adopted a multi-process software paradigm that uses Lightweight Communications and Marshalling (LCM) [14], an open-source inter-process communication library. Thus, the commands from the joystick are received by the laptop computer with a python script, which then serializes and sends it to the Raspberry Pi with LCM through the Ethernet connection.

Onboard, the Raspberry Pi communicates with the Arduino through USB-serial communication. The servos are connected to the Arduino, which is programmed to receive the serial data from the Raspberry pi and controls the servo motors positions as directed by the serial data.

To summarize, the vehicle technical specifications are listed in Table 1.

Table 1: Technical specifications of the vehicle

Mass	Swimming module	600 g
	Main body	3.5 kg
Buoyancy		Adjusted for near neutral buoyancy - about 4.1 kg
Forward speed (swimming modules)		0.05 m/s
Dimensions (bounding box)	Main body	ϕ140 x 225 mm
	Swimming module	470 x 140 x 60 mm
Degrees of motion		Five - surge, heave, sway, yaw and roll.
Actuator specifications		Four servo motors per swimming module.
Electronic hardware		Raspberry Pi 3 model B and Arduino Uno.
Communications		Lightweight Communications and Marshalling (LCM).

3 RESULTS AND DISCUSSIONS

The aim was to design and develop a robot with detachable/re-attachable, and reconfigurable swimming modules. The vehicle was developed and tested for these capabilities in a 1.4m x 1.4m x 0.7m tank, filled with water for about 0.6m depth. The features to be tested are its capability to detach/ reattach, reconfigure and to swim.

3.1 Attachment and detachment

As described earlier, a thin nylon cable is used to pull and manage the electrical cables of the swimming modules. Once the servo for the nylon spooling mechanism starts to rotate, the module is pulled back towards the body and the set of electrical cables are also bent and automatically packed in the process. Figure 5 presents snapshots showing the attachment process. It can be seen that the two sets of electrical cables are automatically packed in between the swimming module and end cap of the body. Although this was successful, the use of a single set of electrical cables could have made the packing more effective. Detachment process is similar, where the spooling mechanism rotates in the opposite direction to un-spool the wires to allow the swimming module to swim away.

3.2 Reconfigurability of the swimming modules

The swimming modules, as explained in section 2.2, are capable of maintaining two stable configurations depending on the direction of motion. Figure 6 and Figure 7 present snapshots from live operation showing the transition from one configuration to the other.

Figure 6 shows that the module leans backwards during its transformation (see Figure 6 (c)-(d)). This is believed to be because of the drag and added mass on links 1 and 2 of the module which is swept forward during the motion. These forces causes a moment on the module as the links are attached at an offset from the horizontal mid-plane of the module. As discussed in section 2.2, this offset helps in maintaining the center of gravity above this mid-plane and close to the center of buoyancy.

Figure 7 presents the transition from the second configuration to the first configuration, also shows the module leaning downwards during the initial stages of the transformation. This is also believed to be because of the same reason as discussed above: the drag and added mass due to the links 1 and 2 (Figure 2) moving upwards, creates a moment on the module forcing it to pitch down until the movement of the link stops.

This intermediate motion during the transition can be avoided with links of lower drag along its direction of movement. The links 1 and 2 were rectangular acrylic plates of size 0.14m x 0.04m x

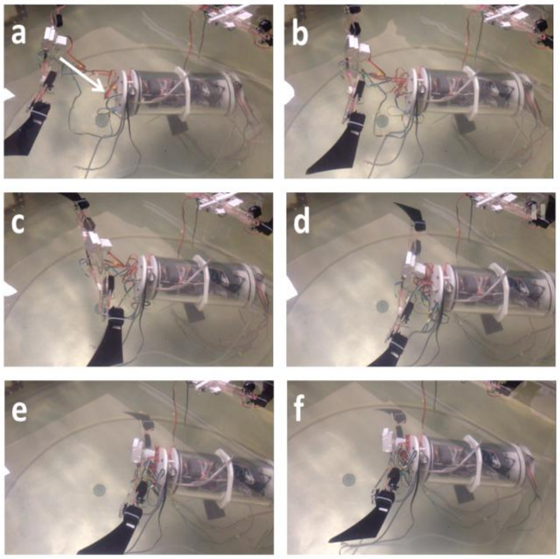


Figure 5: Snapshots showing the sequence of images during the attachment process. It can be seen that the swimming module (on the top left corner of the first image) approaches and successfully attaches with the body.

0.006m with the 0.14m x 0.04m side facing the direction of motion (see Figure 6 and 7), hence these forces. These dimensions were chosen to meet the strength requirements of the design.

3.3 Swimming

The swimming modules can swim in two planes. Flapping in plane 1 (Figure 2) in the first configuration will be used mostly for heave and sway control. Whereas, flapping in plane 2 (Figure 3 (c)) of second configuration is mostly used for yaw and surge control. This type of reconfiguration reduces effective drag in the swimming direction and hence could increase the swimming speed for the same amount of thrust. Increased speed also implies improved propulsive efficiency since propulsive efficiency is defined as,

$$\eta = \frac{FU}{P} \tag{2}$$

Where F is the average thrust force, U is the forward velocity of the vehicle and P is the power input for propulsion.

Out of phase flapping is desired in most cases to reduce the module's oscillation. This type of flapping yielded 0.05 m/s of forward swimming speed in fresh water. Salt water speed is not measured due to the limitation of scope of this paper. Also, the experimental evidences of improved propulsive efficiencies are held for the future as the scope of this paper is only to introduce and prove feasibility of the concept of this design.

These modules could also swim into tighter spaces where the entire vehicle cannot reach. Although the swimming module presented here is large, careful design considering equation (1) could result to smaller modules. Another possible application of these types of robots is in cases demanding station keeping abilities. The two modules can detach from the main body and swim to a suitable

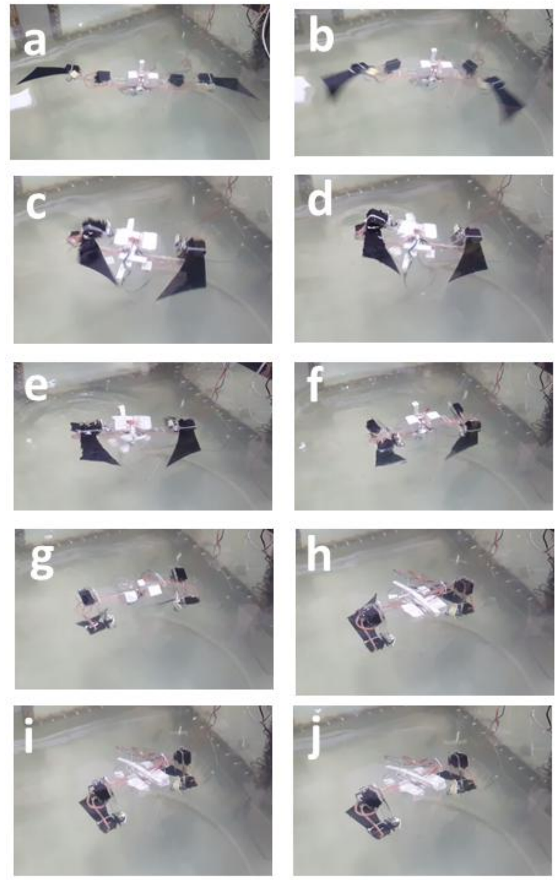


Figure 6: Snapshots showing the sequence of images during the transformation from the first configuration to the second configuration; the module leans back during the initial stages of transformation ((c)-(d)) and starts again to lean down from (e) to (i), and settles with the second configuration at (j).

substrate and clamp themselves onto it. Since the main body is still tethered to these modules, it remains in that location, provided that the tether is strong enough to withstand the tension. This eliminates the need for complex station keeping control algorithms as in conventional underwater robots which often senses the ocean current and applies thruster controls to remain at a certain location. Not only is this power consuming, but also complex and utilizes more computational resources. The concept for station keeping implemented in our design presented here was inspired by the work of Asano et al. in [15] where they use a launchable hook for a robot to climb trees.

4 CONCLUSIONS

The design and development of a novel bio-inspired underwater robot with detachable, reconfigurable modules was discussed. The method of using reconfigurability to reduce drag without compensating maneuverability remains un-explored in bio-inspired underwater robotics. Here, we have presented this novel concept

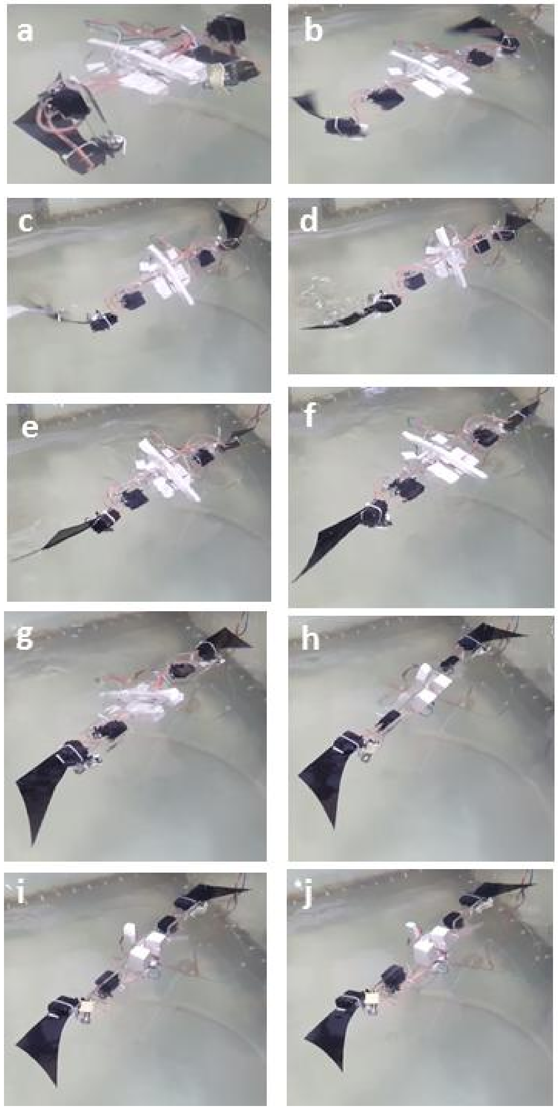


Figure 7: Snapshots showing the sequence of images during the transformation from the second configuration to the first configuration; the module leans down during the initial stages of transformation ((c)-(d)) and starts again to go upright from (e) to (i), and settles with the first configuration at (j).

and proved it with a prototype. The design challenges and the analytical analysis required to achieve reconfigurability in this design were discussed. Some notable design challenges were the management of electrical cables passing to the detachable modules and the ability to maintain two stable configurations. Our solutions and results to such challenges were presented. Although only the basic vehicle platform with the aforementioned capabilities were discussed in this paper, future work will focus on quantifying the ability of such robots to perform tasks such as station keeping and ability to maneuver in tight spaces. The results of station keeping claims are not presented as it requires research on the design of a suitable anchoring device on the modules. This is also planned to be a part of our future work. The effects of the shape of the fins used for flapping also were not discussed. Further work is also to be directed towards the study of the effects of flapping phase difference of the two individual arms of these modules on the thrust production.

REFERENCES

[1] G. Antonelli, *Underwater Robots.* Springer Publishing Company, Incorporated, 3rd ed., 2013.

[2] T. V. Di and A. Rodighiero, "Underwater vehicle for laying underground cables and pipelines," Dec 1974. US Patent No. 3,857,250.

[3] M. Dunbabin and L. Marques, "Robots for environmental monitoring: Significant advancements and applications," *IEEE Robotics and Automation Magazine*, vol. 19, no. 1, pp. 24–39, 2012.

[4] I. C. Robbins, G. J. Kirkpatrick, S. M. Blackwell, J. Hillier, C. A. Knight, and M. A. Moline, "Improved monitoring of HABs using autonomous underwater vehicles (AUV)," *Harmful Algae*, vol. 5, pp. 749–761, Dec 2006.

[5] J. L. Tangorra, S. N. Davidson, I. W. Hunter, P. G. A. Madden, G. V. Lauder, H. Dong, M. Bozkurttas, and R. Mittal, "The development of a biologically inspired propulsor for unmanned underwater vehicles," *IEEE Journal of Oceanic Engineering*, vol. 32, no. 3, pp. 533–550, 2007.

[6] R. Du, Z. Li, K. Youcef-Toumi, and P. Valdivia y Alvarado, *Robot Fish: Bio-inspired Fishlike Underwater Robots.* 2015.

[7] P. R. Bandyopadhyay, "Maneuvering hydrodynamics of fish and small underwater vehicles.," *Integrative and comparative biology*, vol. 42, no. 1, pp. 102–117, 2002.

[8] C. Lindsey, "Form, function, and locomotory habits in fish," *Fish physiology*, vol. 7, 1978.

[9] I. Borazjani and F. Sotiropoulos, "On the role of form and kinematics on the hydrodynamics of self-propelled body/caudal fin swimming.," *The Journal of experimental biology*, vol. 213, no. 1, pp. 89–107, 2010.

[10] C. Georgiades, A. German, A. Hogue, Hui Liu, C. Prahacs, A. Ripsman, R. Sim, L.-A. Torres, Pifu Zhang, M. Buehler, G. Dudek, M. Jenkin, and E. Milios, "AQUA: an aquatic walking robot," in *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566)*, vol. 4, pp. 3525–3531, IEEE.

[11] ""PowerHD 6001HB", HuiDa RC International INC, [Online]. Available: http://www.chd.hk/Product_Detail.aspx?id=38. [Accessed: 10-Sep-2016],"

[12] "Raspberry Pi 3 Model B, [Online]. Available: https://www.raspberrypi.org/products/raspberry-pi-3-model-b/. [Accessed: 10-Sep-2016]."

[13] "Arduino UNO, Arduino 2016. [Online]. Available: https://www.arduino.cc/en/Main/ArduinoBoardUno. [Accessed: 10-Sep-2016]."

[14] A. S. Huang, E. Olson, and D. C. Moore, "LCM: Lightweight Communications and Marshalling," 2010.

[15] N. Asano, H. Nakamoto, T. Hagiwara, and S. Hirose, "Tethered Detachable Hook for the Spiderman Locomotion (Design of the Hook and Its Launching Winch) BT - Field and Service Robotics: Results of the 7th International Conference," pp. 25–34, Berlin, Heidelberg: Springer Berlin Heidelberg, 2010.