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Article

Design and Implementation of a Quadruped Amphibious Robot Using Duck Feet

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Abstract: Roaming complexity in terrains and unexpected environments poses significant difficulties in robotic exploration of an area. In a broader sense, robots have to face two common tasks during exploration namely walking on the drylands and swimming through the water. This research aims to design and develop an amphibious robot, which incorporates webbed duck feet design to walk on different terrains, swim in water and tackle obstructions on its way. The designed robot is compact and easy-to-use and also has the abilities to work autonomously. Such a mechanism is implemented by designing a novel robotic webbed foot consisting of two hinged plates. Due to the design, the webbed feet are able to open and close with the help of water pressure. The Klann linkage has been used to convert rotational motion to walking and swimming as an animal's gait. Because of its amphibian nature, the designed robot can be used for exploring the tight caves, closed spaces and moving on uneven challenging terrains such as sand, mud or water.

The presented model and design of the amphibious robot has been inspired by the working principle of duck feet. The propulsion generated through this feet system has been observed to be better and more controlled then the initial design and prototype of designed duck feet robot reported in [1]. The direction of movement can be managed, and the speed can be controlled using a larger contact area with water. Since duck is able to roam on both land and water, their feet movement during walking and swimming is adopted in designing the robot's four legs. Klann linkage is used to mimic such duck feet motion and the control mechanism of the feet is driven by DC motors and DC servo motors which are governed by an Arduino microcontroller. The robot is capable of sensing the presence of water through conductive sensors and detects obstacles using ultrasonic sensor while walking. Due to its amphibian nature and other features in movement, the robot is capable of traversing diversified terrains. It is envisaged that the proposed design will be appreciated in the industry to design amphibious robots in near future.

Keywords: amphibious robot; duck feet; quadruped; Klann linkage; webbed feet

1. Introduction

Nature-inspired robots are defining new applications as well as reviving previously abandoned explorative missions. Such exploration tasks are widely done by robots in the area where human presence is risky or impossible; such as tight caves or deep oceans or a new planet with unknown rough terrain.

During the exploration in an unknown environment, robots can experience different terrains, obstructions, and water. The robot should be capable of moving on all such terrains effectively and continue its task. Ducks are one of a variety of animal which has webbed feet. They move through water by paddling their feet back and forth. However, this alone does not justify their efficiency when moving through the water. By observing the duck anatomy, it can be seen that the duck has webbed feet where toes are attached by folds of skin. The objective of this research is to design and develop a

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prototype which will mimic the webbed feet of the duck, and, consequently, is capable of roaming in diversified terrains with acceptable efficiency and effectiveness.

2. Literature review

There are several commercially available amphibious robots, which use different methods to move around on land and in water. Many robots such as quadruped robots, snake robots, and bi-pedal robots were designed with inspiration from animal morphologies. S. B. A. Kashem et al., [1] and Tuan Dai et al., [2] observed the duck's movement underwater and found that the feet movement could be divided into two phases: stroking forward and backward phases. The backward stroking motion drives the duck body through the reacting force from the water (the duck feet fully open to maximize the contact area with water during back stroking). In the forward motion, the feet fully contract to minimize the contact area with water. Tuan Dai [2] has also designed a structure of an underwater vehicle with a biomimetic propulsion mechanism. It included the body, steering engines, and propulsion mechanisms. Initially, the fins at the propulsions mechanism would be fully closed. With the swinging of the shaft, it would gradually open due to force from the water. This will give the fins enough thrust to move forward in the water. In the second phase, the fins contract due to the pressure of water from the opposite side, reducing the contact area with it. With the shaft's swinging movement, the vehicle has enough force to move forward. This design has a limitation of only moving in water, and not being functional on land as a terrestrial robot. A. J. Ijspeert [3] has conducted an extensive review of locomotion control in animals and robots. Several amphibious robots have been designed and tested in recent years. Amoeba II has been designed by Li, et al. [4] which is a transformable amphibious robot. The actuation system of this robot contains four main elements. Each element comprises of a water-jet propeller, two servo motors, and a stainless-steel stand. Water-jet propellers actuate the robot when underwater. This design has its limitations, as it uses different mechanisms for movement in land and water. FroBot [5] is a novel amphibious robot which consists of dual-swing-legs propulsion mechanism. Yu, et al. [6] developed a Bio-inspired Amphibious Robot named as AmphiRobot which is capable of Multimodal Motion. Hyung-Jung, et al. [7] have designed a turtle-like robot having a soft-morphine turtle flipper using a smart soft composite (SSC) structure. A crab-like robot has been created by Chen, et al. [8]. A squid-like Underwater Robot with Two Undulating Side Fins has been constructed and tested by Rahman, et al. [9]. This robot was designed based on the Median and Paired Fin (MPF) movement, which uses the undulating side fin for propulsion mimicking the squid. Although this robot moves slowly, it is preferred in applications where stealth is required, as in experimentations where it is important to keep the surrounding undisturbed.

Salamandra Robotica II, an advanced version of Salamandra Robotica I, is a salamander-inspired robot. This robot, designed by Crespi, et al. [10], can swim in water as well as walk on land. The robot has an actuated spine and four legs which allow it to walk in the ground and anguilliform swimming in water. This robot has disadvantages of going slow and more chances of problems in hinge joints.

In the legged system design, numerous biological locomotors are analyzed and adapted. Animal locomotion and their walking patterns are widely researched with high interest in their complexity, flexibility, and energy efficiency. The task of designing and developing a legged robot also requires a thorough optimization and cost analysis. The design must be made by taking performance, function, and maneuverability into consideration.

As compared to wheel-based robots, legged robots have some advantages on rough terrains, Silva and Machado [11]. In terms of speed and energy consumption, the wheeled robot is far superior to the legged robot. However, many researchers are designing improved legged robots with enhanced performance. Raibert, et al. [12] designed Big Dog which has four legs and quite effective in performing various locomotion and logistical tasks. Lokhande and Emche [13] have designed a walking robot, which follows the locomotion of a spider and utilizes the Klann linkage mechanism. Similarly, Zhang and Kimura [14] fabricated a quadropod robot named Rush using legged mechanism imitation of animal movement for their robots. Their mechanism is complex and uses

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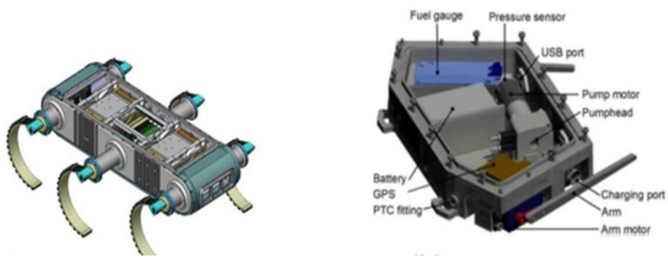
numerous sensors to help the robot walk. However, all of these robots are designed for land-based terrains only and are not amphibious in nature.

In this research, Klann linkage has been used for the leg mechanism design. Sheba, et al. [15] suggested putting actuators among the connections of Klann linkage to perform better in walking mode. However, such intricate linkage is expensive and not necessary in prototype design. Thus, the fundamental Klann linkage is adopted in this project. The foot design of the robot is inspired by the biological webbed foot design of a duck.

Ducks belong to the Amphibian category of animals that can travel both on land and water. They move through water by paddling their feet back and forth. However, this alone does not justify their efficiency when moving through water. By looking at the anatomy of a duck, it can be observed that the feet of a duck are webbed meaning the toes are connected by folds of skin. This provides a more efficient transfer of force when moving through water.

Ribak, et al. [16] explained in their research that the maximum propulsive force is generated when the robots' feet are swept backward in the water.

When in water, the robot moved using the drag-based swimming. The mechanism proposed by Li, et al. [17], is not feasible for the proposed model since the spherical robot has two different mechanisms for locomotion. The swimming mechanism of the robot designed by Dhull, et al. [18] Dudek, et al. [19], and by Liang, et al. [20] were somewhat similar compared to the robot developed in this paper. Figure 1 shows the Aqua and Aquapod robot. The basic difference is that they have utilized rotational arms to move their robot through water and land. Whereas, the presented robot in this paper has been designed using a proper legged mechanism, which can support swimming and suitable walking phenomena. The initial design and prototype of designed duck feet robot is reported in [1] and some modification had been done in [21-26]. In this manuscript, the final design, layout of the electrical circuit, the final prototype with dimensions and testing results have been provided. The propulsion generated through the feet system is better and more controlled than the initial designs. The direction of movement can be managed, and the speed can be controlled using a larger contact area with water.



(a) (b)

Figure 1. (a) Aqua robot and (b) Aquapod Robot.

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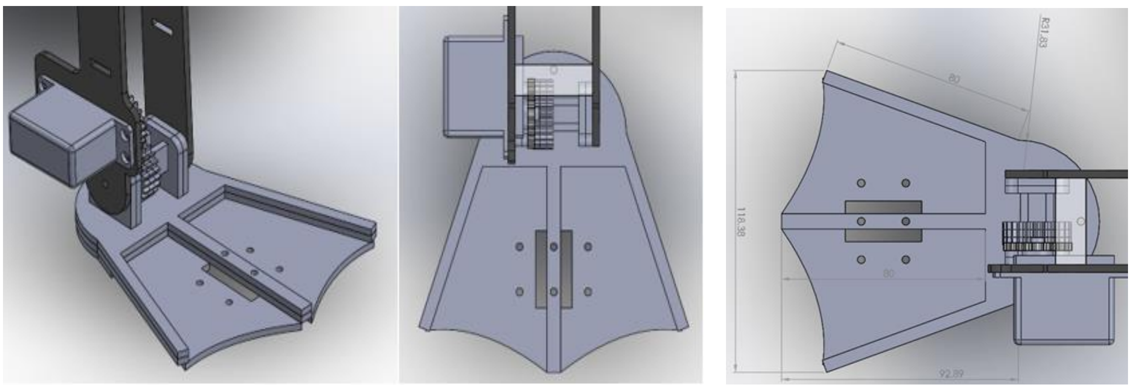
3. Design and Methodology

3.1. Mechanical Design

The design of the duck feet was completed in SolidWorks software environment first. To check the validity of the design, simulation has been conducted. The linkage and the whole body were simultaneously simulated. The feet were engineered to have webbed formation mimicking duck feet as shown in Figure 2. The figure shows the design from various viewpoints and annotated for the dimensions.

By the aid of two hinges, the two flaps were linked to the bottom of the foot. For walking and swimming purposes, the foot base was made such that it provided a large contact area, to provide stability while standing, and to push forward in the water. The feet were connected to the respected Klan linkage. The angle of the foot can be changed by the high torque servo motor as shown in Figure 3. The feet angle in walking and swimming mode are 0° and 80° and the angle remain fixed during the feet movement.

This design of the duck feet has provision for the duck to walk without falling over during the walking mode. To achieve the structure stability, the robot was converted to a quad pod by adding four identical feet to the robot's body. The feet were set in such a way that at any given time two feet always remain in contact with the ground. During swimming in the water, four feet can go forward and backward at the same time to maximize the speed. In swim mode both motors went back and forward at the same time since the robot were moving faster than the both motors went back and forward at the different time. It has been observed during the practical test. No data were recorded as the main focus was the leg design. The flaps of the foot close automatically when pushing back to maximize the contact area with water as shown in Figure 4(a). This helps to push the maximum amount of water in the backward direction which helps the robot move forward. On the other hand, when feet move forward, the flaps open automatically to minimize the force required by the motors since the feet are obstructing less water as presented in Figure 4(b).



(**a**) (**b**) (**c**)

Figure 2. Feet design. (a) Isometric view (b) Top view (c) Top view with dimensions.

Figure 5 shows the interconnected joint movements in the overall foot/leg assembly. This is shown with the help of the trace path of the Klan linkage and shows various joint elements in terms of their displaced positions with respect to the various positions during the walking/swimming movements. The actual design dimensions are also illustrated in the figure. The vertical distance covered by this linkage is approximately 3 cm whereas the horizontal distance is approximately 7.5 cm, which has been shown graphically in Figure 6.

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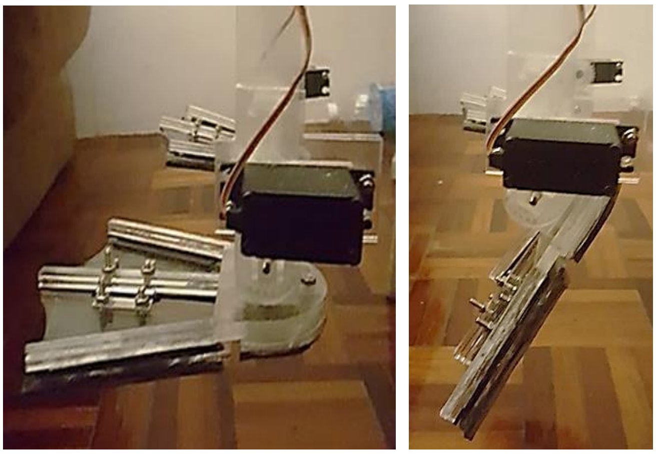
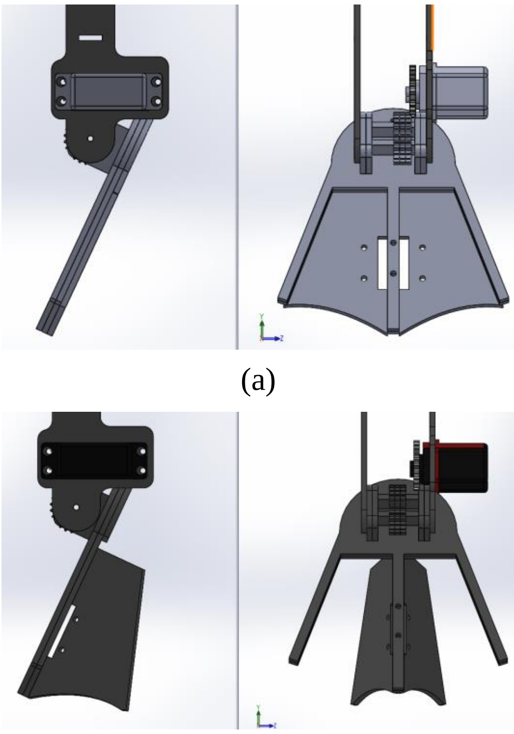


(a) (b)

Figure 3. Foot orientation during (a) walking mode and (b) swimming mode



(a)

(b)

Figure 4. Duck feet position during (a) Backward motion, (b) Forward motion.

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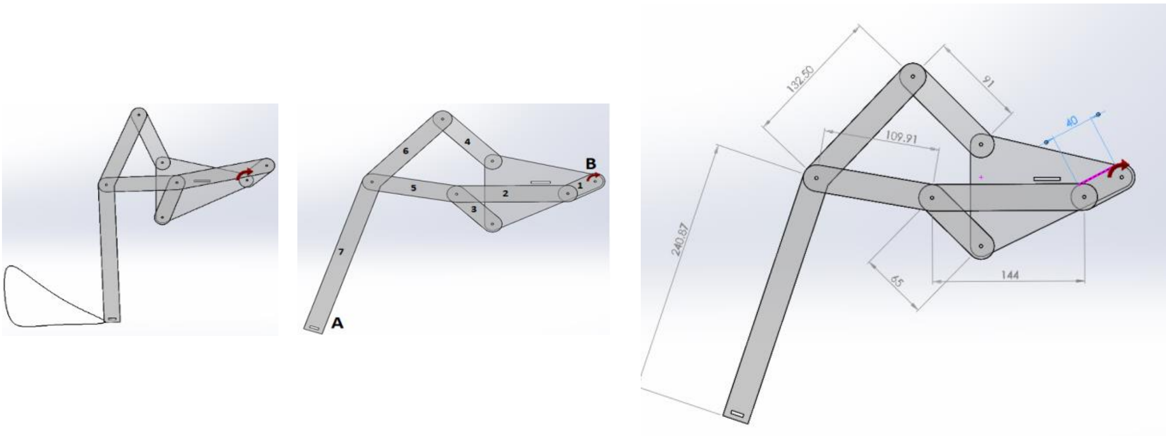
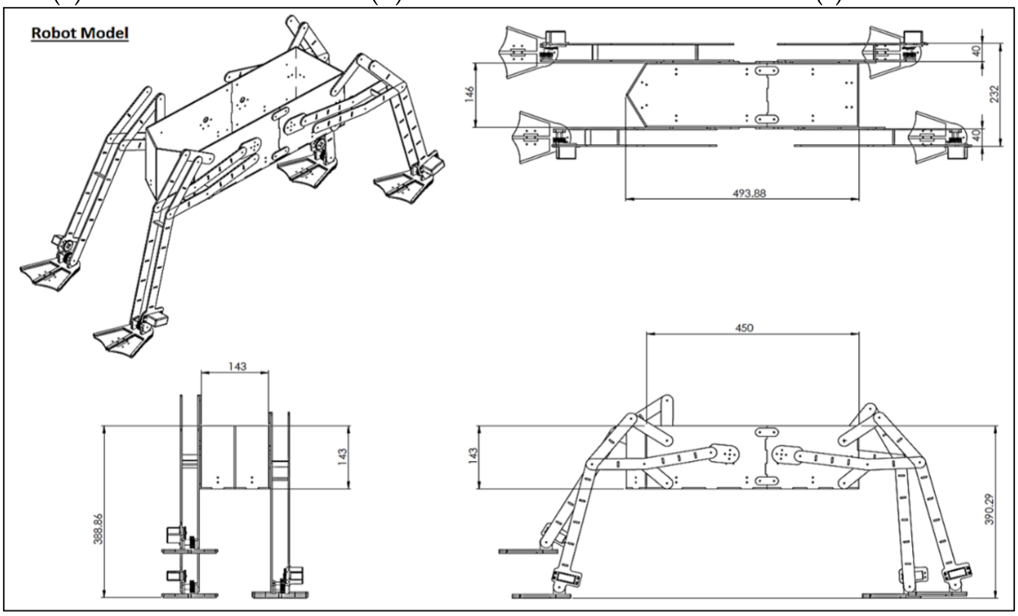
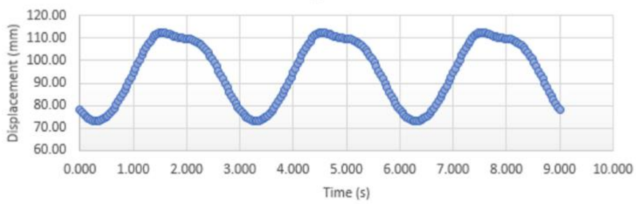


(a) (b) (c)

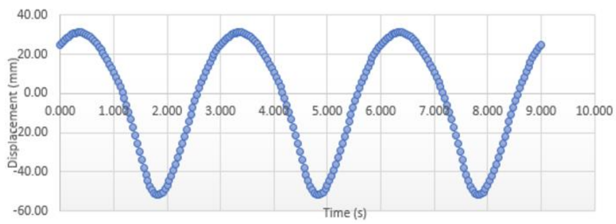


(d)

Figure 5. Trace the path of the Klan linkage foot (a) closed position (b) Extended position (c) Linkage with dimension (d) The actual design dimensions of the robot.



(a)



(b)

Figure 6. (a) Vertical displacement; (b) Horizontal displacement.

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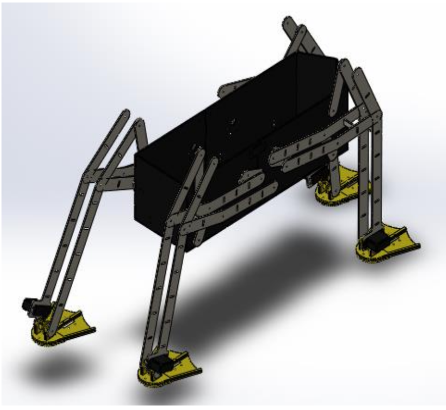
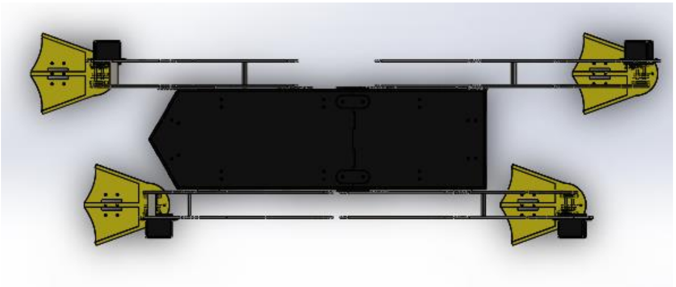


(a)



(b)

Figure 7. (a) Full model isometric view, (b) Full model top view

The full model isometric view and top view have been shown in Figure 7 (a) and (b) respectively. The drag force is the force opposing the movement of the robot in water. The force being applied on the feet by the water, is the force robot will face, which will make it move forward.

The drag force applied on the feet was calculated with the following formula.

$$F_D = \frac{1}{2} \varrho v^2 C_D A$$

Where,

- ρ is the density of the fluid
- v is the velocity of the object
- C_D is the drag coefficient
- A is the area of the object

Based on motor speed[1], the velocity of the feet was computed as 0.03125 m/s. The density of water is 1000 kg/m3, and the Drag coefficient was calculated approximately.

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The area was computed with the aid of Solidworks as shown in Figure 8.

Figure 8: Surface area of Feet bottom (a) and Flap (b)

Mass properties of Feet Bottom part
Configuration: Default
Coordinate system: -- default --

Density = 0.00 grams per cubic millimeter

Mass = 11.89 grams

Volume = 9908.87 cubic millimeters

Surface area = 8948.50 square millimeters

Center of mass: (millimeters)
X = 0.00
Y = 1.50
Z = 12.47

(a)

Mass properties of FLAP
Configuration: Default
Coordinate system: -- default --

Density = 0.00 grams per cubic millimeter

Mass = 9.82 grams

Volume = 8182.85 cubic millimeters

Surface area = 6246.74 square millimeters

Center of mass: (millimeters)
X = 21.47
Y = 1.50
Z = 37.51

(b)

As there are two flaps and a foot bottom for each foot, pushing the water at a moment, the total theoretical surface area is

$$\mathbf{0.00895+0.00625+0.00625=0.02145\ m^2}$$

$$\mathbf{0.02145 \times 2\ feet=0.0429\ m^2}$$

The drag force becomes

$$\mathbf{F_D= \frac{1}{2}(1000)(0.03125)^2(1)(0.0429)=0.0209\ N}$$

So, the force being applied on the robot from water is 0.01341 newtons.

Now the acceleration of the robot was calculated as:

The mass was taken from Solidworks as in Figure 9.

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Therefore, acceleration is

$$\mathbf{a= \frac{F}{m} = \frac{0.0209}{1.89\ kg} = 11.06 \times 10^{-3}\ m/s^2}$$

Robot will move with the acceleration of 0.01106 m/s^2

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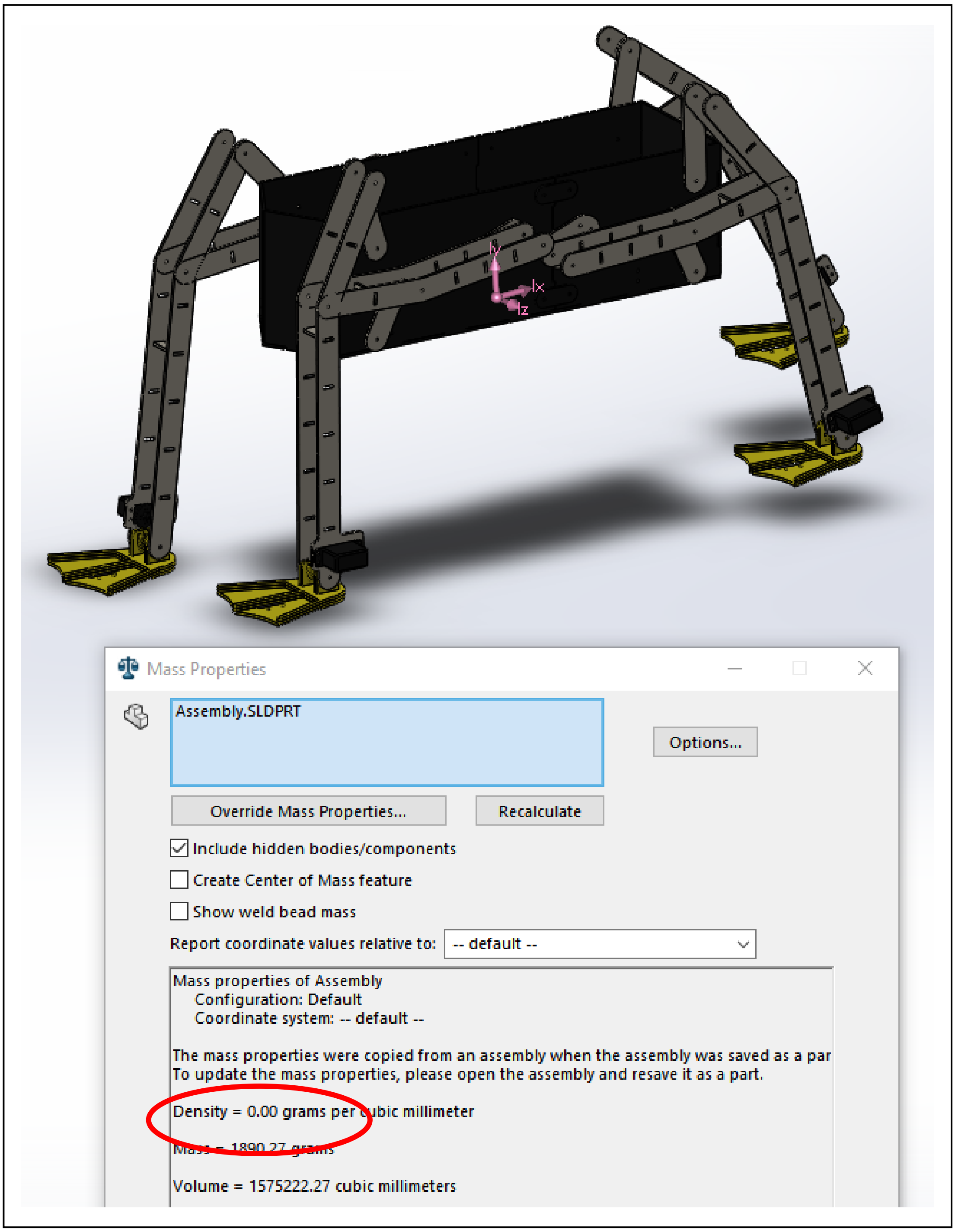

Figure 9: Mass properties of the robot

3.2. Electrical Design

To design the appropriate functions of the robot, several combinations of sensors and actuators have been designed. Arduino Mega microcontroller has been used to control these sensing/actuating components. The selection of the actuators is specifically important since the whole body of the robot stands on these. Figure 9 shows various components used in the design.

Waterproof EMAX ES3005 servo motors are used to design the robot due to their high torque and low-speed capability. They have a speed of 0.14 s/60° and a torque of 12 kg.cm. These servo motors perform the main job of changing the mode from walking to swimming and vice versa. In addition to that, servo motors provide the forward motions. Four servos were used in a coordinated manner, one on each foot.

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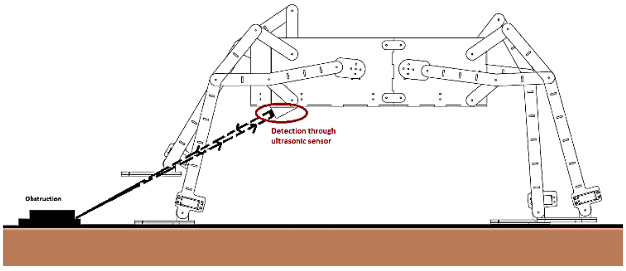
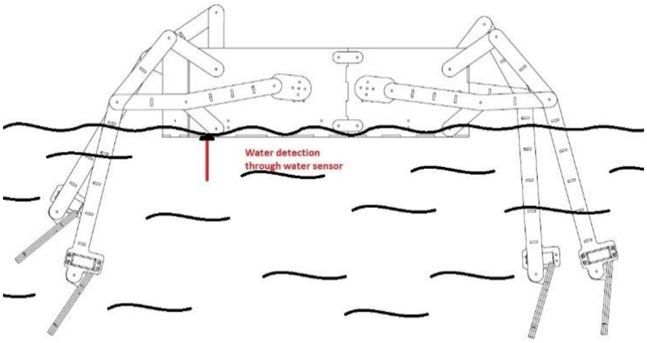


(a)



(b)

Figure 10: (a) Obstruction detection through ultrasonic sensor (b) Water sensor to sense presence of water

Apart from servo motors, Mybotic DC gear motor JGB37 was used to control the linkage of the forward movement. It has a speed of 30 rpm and rated load torque of 25 kg.cm. Every foot is fixed with one DC motor which is paired with Hall effect sensor (built-in with motor) for feedback position, to control the leg movement, and to avoid any desynchronizing.

JSN-SR04T waterproof ultrasonic sensor (range of up to 4.5 m), and water sensor are used in this robot as shown in figure 10(a) and (b) respectively. The ultrasonic sensor is used to detect any obstacle in front so that the robot can avoid it. In addition to that, it measures the water depth to perform switching from walking to swimming. Water sensor is used to detect the presence of water. Whenever the presence of water is detected with sufficient depth for swimming, the robot instantaneously switches from walking to swimming mode.

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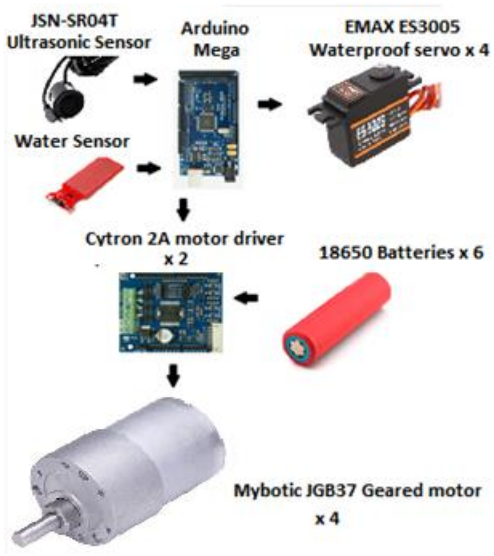

Figure 11. Electrical components used in the design.

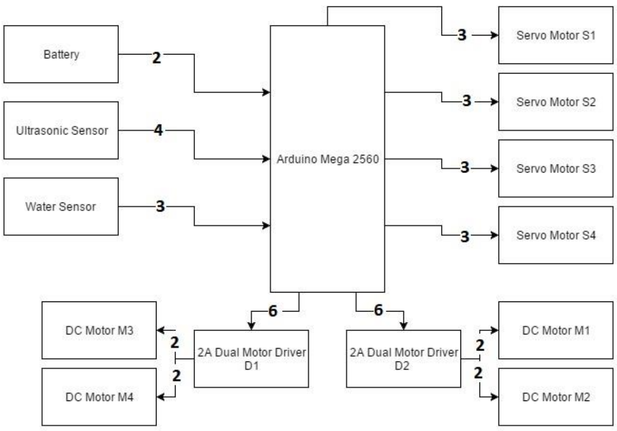

Figure 12. Block diagram showing the Electrical connection layout.

For the power supply, compact and efficient 18,650 Lithium-ion batteries have been used which are high capacity rechargeable batteries. These batteries have a rated capacity of 3800 mAh, and provide 3.7 V. Such batteries were highly suitable for this project due to their compact nature, and hence total 6 batteries were used, two parallel banks of three series connected batteries, in order to get the combined voltage of 11.1 V with the enhanced current. Figure 11 illustrates the internal connections of the electrical components detailed above. The same block diagram is converted into a circuit layout in Figure 12. Finally, Figure 13 depicts the complete design of the operational circuit board.

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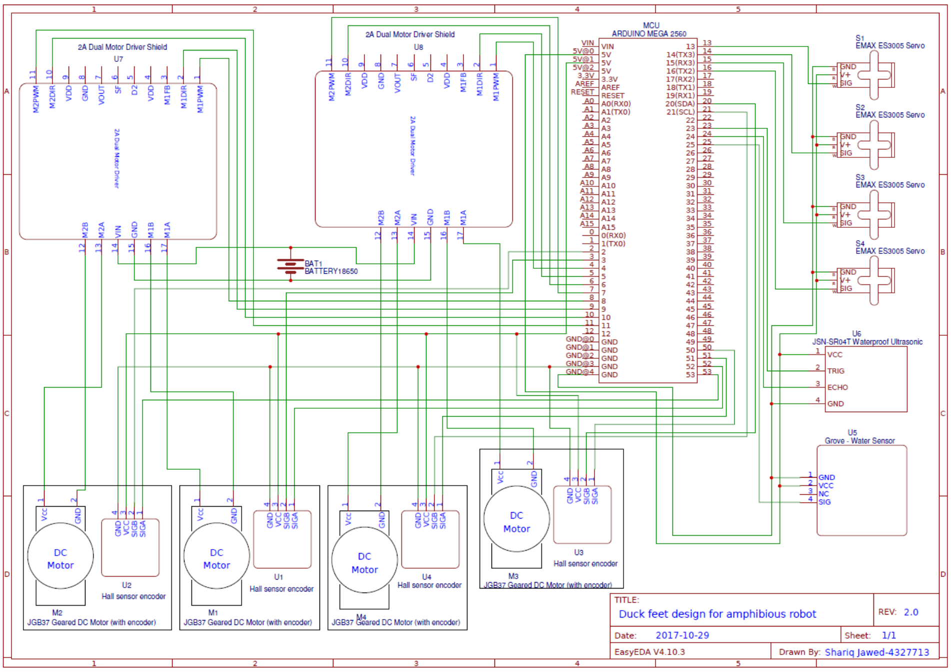

Figure 13. Detail circuit diagram of the overall system.

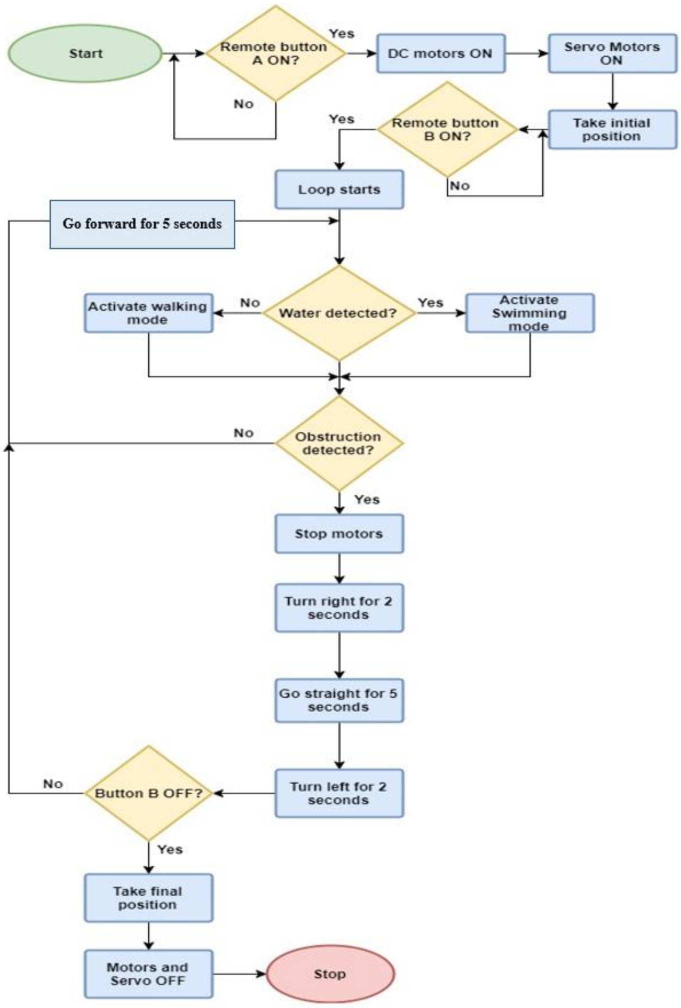

Figure 14. Program Flow.

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3.3. Program Flow

The completed robot was first tested for basic functionalities and manouvers. The flowchart for the program that performed these tests is shown in Figure 14. The robot was activated and took the initial position once the remote button A was pressed. Once the remote button B was turned ON, the water sensors check the presence of water and activate swimming mode if water is present otherwise activate the walking mode. In the next step, the ultrasonic sensor detects any obstacles within the measurement range in front of the robot as it starts to move. With no obstacle is detected, the robot moves forward for 5 seconds and runs the loop again. In the case where the obstacle is detected in the path, the robot will turn right for 2 seconds and go straight for 5 seconds then turn left for 2 seconds. Once the turns are done, the robot will continue to go forward for 5 seconds and repeat the loop as long as the remote button B is in the ON state. The robot will take the final position and turn off when the button B is in the OFF state. B button of the remote control has been used as an emergency switch to avoid any hazardous situation. For safe handling of an autonomous robot, an emergency shut down switch is important. To turn right during swimming mode, the left motors rotate with maximum power and right motors get zero power. On the occasion of turning right during the walking mode the left motors rotate with maximum power and right motors get 60% percent power to keep the robot stable.

4. Discussion and Results

The prototype was designed considering the balancing issue of the robot. The weight distribution of the robot was carefully done and batteries were installed on the upper deck of the robot's body to allow easy recharge or swap. The completed prototype's isometric and top views are shown in Figure 15.

The robot is capable of moving approximately 7.5 cm horizontally per rotation of the motor. The no-load speed and full load speed is 30 rpm and around 25 rpm respectively. As a full 360° rotation with load takes 2.4 seconds by the motor, the velocity of each leg becomes 0.03125 m/s. In one minute, the robot was able to travel about 1.9 meters with continuous velocity.

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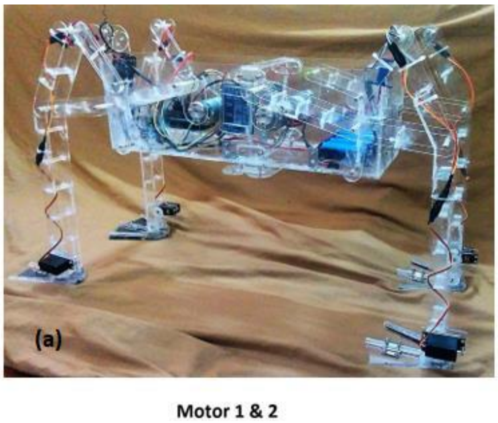
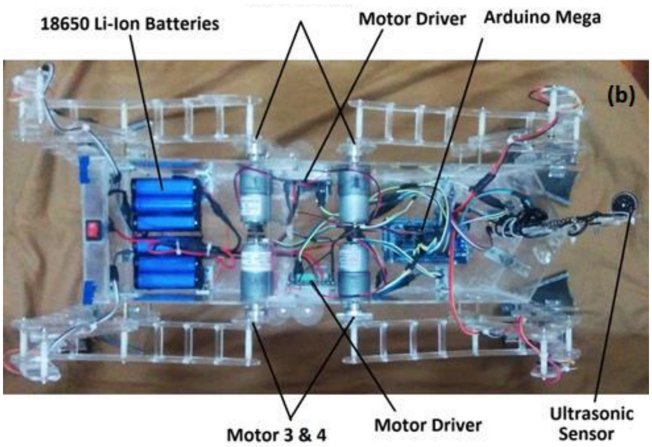


(a)



(b)

Figure 15. Completed Prototype of the Robot (a) Isometric layout of the prototype (b) top view of the design.

When the water sensor, attached under the body of the robot, detects the presence of water, it provides the necessary signal to the controller. The controller sends the activation signal to the actuator attached to the legs to rotate and change the legs positions from walking to swimming mode. The time the water reaches the water sensor (body level), the robot starts floating. This makes it safe to move the legs in swimming mode without hitting the ground.

The robot also has the option to detect an obstacle (shown in Figure 16) using an ultrasonic sensor which is attached to the front of the body (shown in Figure 10(a)). According to design, the robot will automatically stop for a second when it detects an obstacle 20 cm away. Then the robot will turn right for 2 seconds and go straight for 5 seconds. Then it turns left for 2 seconds, thus avoiding the obstacle. Once the turns are done, the robot will continue to go forward for 5 seconds and repeat the loop as long as the remote button B is in the ON state.

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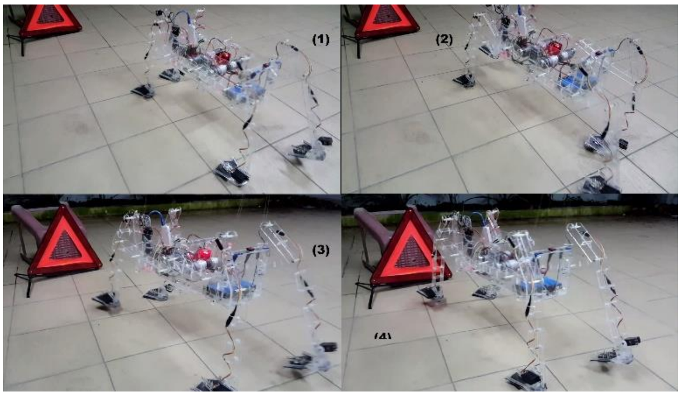

Figure 16. Obstruction Detection by the prototype.

4.1. Walking test

The walking functionality of the robot was tested on land, and the synchronization of leg movement was observed. It was noted, that by using the hall effect sensors to control the speed of the robot, the legs were synchronized, and did not deviate from their positions with time. The robot walking is shown in Figure 17 while the motor coordination is shown in Figure 18. The video of these tests can be seen at https://youtu.be/du9R-pkJYzc.

4.2. Swimming test

The robot was tested in water to observe its movement and speed. It moved slowly compared to the walking mode. To improve the speed under the water, the foot surface area can be increased to surge-up the force exerted by them. Figure 19 shows a swimming test and Figure 20 depicts the flap opening and closing while swimming. The video of swimming tests can be seen at https://youtu.be/KjaWv5tcZyM.

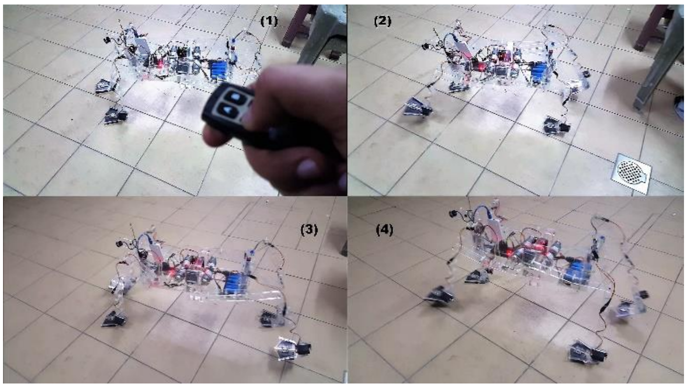

Figure 17. Walking test of the Prototype.

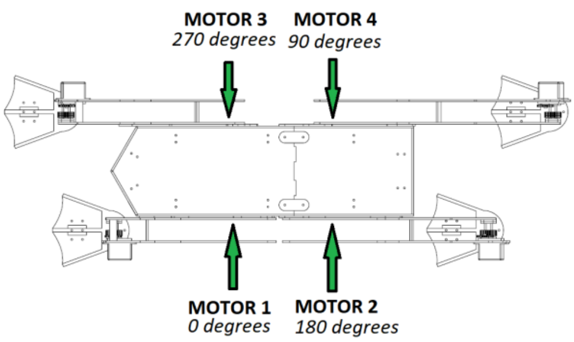

Figure 18. Motor coordination in the robot.

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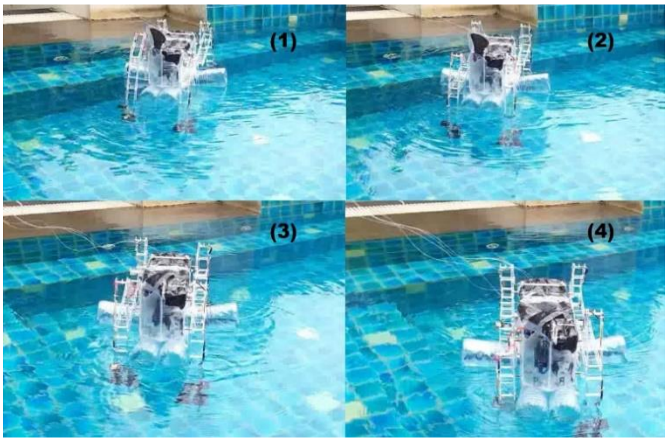

Figure 19. Swimming test of Prototype.

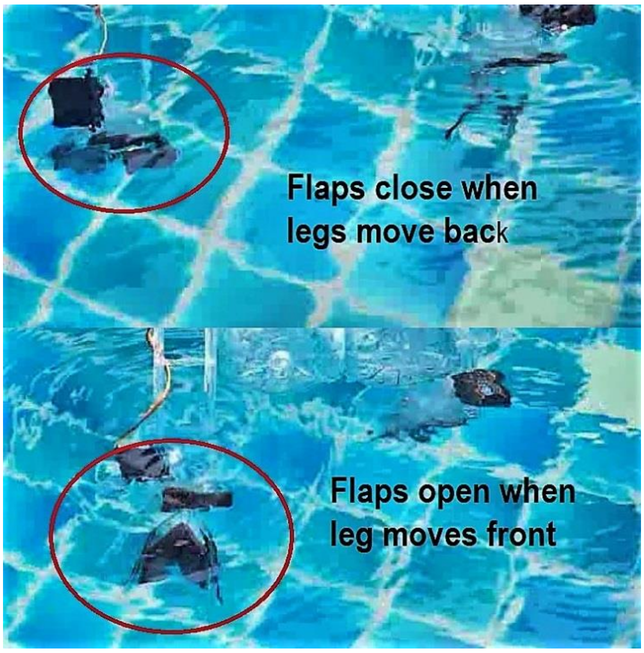

Figure 20. Flap opening and closing while swimming.

5. Conclusion and Future work

In this paper, modeling and designing of an amphibious robot are presented. The proposed design mimics the operational principle of duck feet to move on the land and underwater. The movement of the duck feet is critically analyzed and replication of duck feet is implemented using improved Klann linkage. The body of the robot is made proportionately so that it can be carried by four duck feet and able to carry all control circuitry. Finally, the designed prototype is tested on land and water where the robot successfully walked and swam respectively. It should be noted that the performance of this robot is not up to the efficiency of wheeled robots on smooth terrains or propulsion-based robot in water. Rather, it is expected that this work will be recognized as a unique idea which combines walking and swimming under the unified mechanism. Nevertheless, the proposed idea can be improved further by choosing lighter material instead of acrylic. Moreover, an additional sensor can be used to detect an obstacle on both sides of the robot rather only front obstacle detection. Besides, reconfigurable Klann linkage in place of static one will definitely improve the mobility of the robot significantly.

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