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

45 feet where toes are attached by folds of skin. The objective of this research is to design and develop a
46 prototype which will mimic the webbed feet of the duck, and, consequently, is capable of roaming in
47 diversified terrains with acceptable efficiency and effectiveness.

2. Literature review

49   There are several commercially available amphibious robots, which use different methods to
50 move around on land and in water. Many robots such as quadruped robots, snake robots, and bi-
51 pedal robots were designed with inspiration from animal morphologies. Tuan Dai [2, 3] observed the
52 duck's movement underwater and found that the feet movement could be divided into stroking
53 forward and backward phases. The backward stroking motion drives the body through the reacting
54 force from the water, as duck feet fully open to maximize the contact area with water. In the forward
55 motion, the feet fully contracts to minimize the contact area with water. Tuan Dai [1] has also
56 designed a structure of an underwater vehicle with a biomimetic propulsion mechanism. It included
57 the body, steering engines, and propulsion mechanisms. The working process of the biomimetic
58 propulsion mechanism was divided into two phases, the stroking back phase, and contracting
59 forward phase. Initially, the fins at the propulsions mechanism would be fully closed, and with the
60 swinging of the shaft, it would gradually open due to force from the water. This will give the fins
61 enough thrust to move forward in the water. In the second phase, the fins contract due to the pressure
62 of water from the opposite side, reducing the contact area with it. With the shaft's swinging
63 movement, the vehicle has enough force to move forward when the shaft swings back, and
64 minimized force when shaft swings forward. This design has a limitation of only moving in water,
65 and not being functional on land as a terrestrial robot. A. J. Ijspeert [2, 3] has conducted an extensive
66 review of locomotion control in animals and robots. Several amphibious robots have been designed
67 and tested in recent years. Amoeba II has been designed by Li, et al. [4] which is a transformable
68 amphibious robot. The actuation system of this robot contains four main elements. Each element
69 comprises of a water-jet propeller, two servo motors, and a stainless-steel stand. Water-jet propellers
70 actuate the robot when underwater. This design has its limitations, as it uses different mechanisms
71 for movement in land and water. FroBot [5] is a novel amphibious robot which consists of dual-
72 swing-legs propulsion mechanism. Yu, et al. [6] developed a Bio-inspired Amphibious Robot named
73 as AmphiRobot which is capable of Multimodal Motion. Hyung-Jung, et al. [7] have designed a turtle-
74 like robot having a soft-morphine turtle flipper using a smart soft composite (SSC) structure. A crab-
75 like robot has been created by Chen, et al. [8]. A squid-like Underwater Robot with Two Undulating
76 Side Fins has been constructed and tested by Rahman, et al. [9]. This robot was designed based on
77 the Median and Paired Fin (MPF) movement, which uses the undulating side fin for propulsion
78 mimicking the squid. Although this robot moves slowly, it is preferred in applications where stealth
79 is required, as in experimentations where it is important to keep the surrounding undisturbed.
80   Salamandra Robotica II, an advanced version of Salamandra Robotica I, is a salamander-inspired
81 robot. This robot, designed by Crespi, et al. [10], can swim in water as well as walk on land. The robot
82 has an actuated spine and four legs which allow it to walk in the ground and anguilliform swimming
83 in water. This robot has disadvantages of going slow and more chances of problems in hinge joints.
84   In the legged system design, numerous biological locomotors are analyzed and adapted. Animal
85 locomotion and their walking patterns are widely researched with high interest in their complexity,
86 flexibility, and energy efficiency. The task of designing and developing a legged robot also requires
87 a thorough optimization and cost analysis. The design must be made by taking performance,
88 function, and maneuverability into consideration.
89   As compared to wheel-based robots, legged robots have some advantages on rough terrains,
90 Silva and Machado [11], In terms of speed and energy consumption, the wheeled robot is far superior
91 to the legged robot. However, many researchers are designing improved legged robots with
92 enhanced performance. Raibert, et al. [12] designed Big Dog which has four legs and quite effective
93 in performing various locomotion and logistical tasks. Lokhande and Emche [13] have designed a
94 walking robot, which follows the locomotion of a spider and utilizes the Klann linkage mechanism.
95 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 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.

After actual observation of duck's movement underwater, it has been found that the leg movement could be divided into two phases: stroking back and contracting forward. When stroking back, the webbed feet fully open to increase the contact area with water thus driving the body forward. When contracting forward the webbed feet closed. By imitating these movements, it is expected to provide better locomotion capabilities for the amphibious robot.

Ribak, et al. [16] explained in their research that the maximum propul... 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.
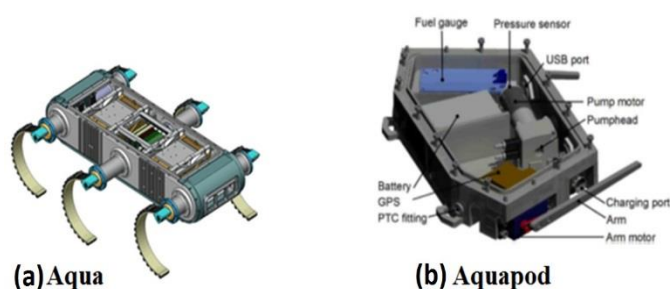
3. Materials and Methods

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

The propulsion generated through the feet system is better and more controlled. The direction of movement can be managed, and the speed can be controlled using a larger contact area with water. The initial design and prototype of designed duck feet robot is reported in [1] and some modification had been done in [21-23]. In this manuscript, we have provided the final design, layout of the electrical circuit, the final prototype with dimensions and testing results.

133 *3.1. Design and Methodology*

134 3.3.1. Mechanical Design

135 The design of the duck [comment: Where the simulations were conducted? On SolidWorks too?] o check
136 the validity of the design, [*The simulation was conducted on SolidWorks. Results*] ly were
137 simultaneously simulated. [*and conclusion have been added in section 3.*] uck feet
138 as shown in Figure 2. The figure shows the design from various viewpoints and annotated for the
139 dimensions.
140 By the aid of two hinges, the two flaps were linked to the bottom of the foot. For walking and
141 swimming purposes, the foot base was made such that it provided a large contact area, to provide
142 stability while standing, and to push forward in the water. The feet were connected to the respected
143 Klan linkage. The angle of the foot can be changed by the high torque servo motor as shown in Figure
144 3.
145 This design of the duck feet has provision for the duck to walk without falling over during the
146 walking mode. To achieve the structure stability, the robot was converted to a quad pod by adding
147 four identical feet to the robot's body. The feet were set in such a way that at any given time two feet
148 always remain in contact with the ground. During swimming in the water, four feet can go forward
149 and backward at the same time to maximize the speed. The flaps of the foot close automatically
150 when pushing back to maximize the contact area with water as shown in Figure 4(a). This helps to
151 push the maximum amount of water in the backward direction which helps the robot move forward.
152 On the other hand, when feet move forward, the flaps open automatically to minimize the force
153 required by the motors since the feet are obstructing less water as presented in Figure 4(b).
154 [comment: There are simulations or experimental results to show that the four feet going forward in swim mode is better?

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.]
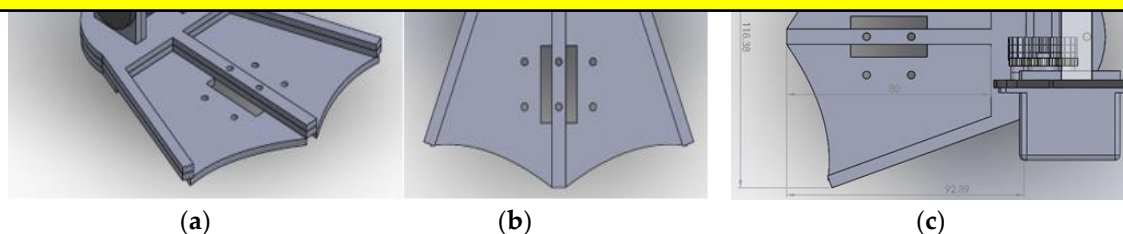

155 **Figure 2.** Feet design. (a) Isometric view (b) Top view (c) Top view with dimensions.

156 Figure 5 shows the interconnected joint movements in the overall foot/leg assembly. This is
157 shown with the help of the trace path of the Klan linkage and shows various joint elements in terms
158 of their displaced positions with respect to the various positions during the walking/swimming
159 movements. The actual design dimensions are also illustrated in the figure. The vertical distance
160 covered by this linkage is approximately 3 cm whereas the horizontal distance is approximately 7.5
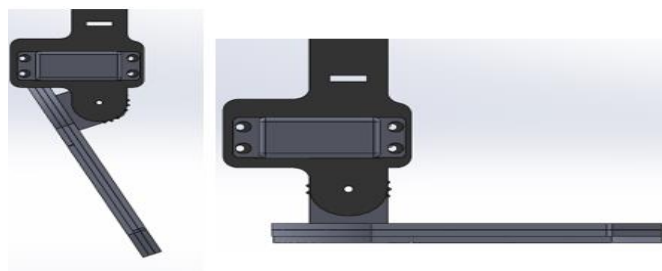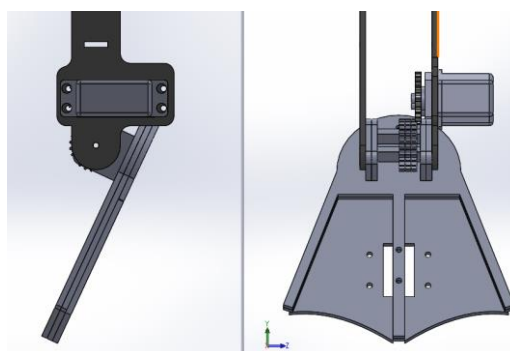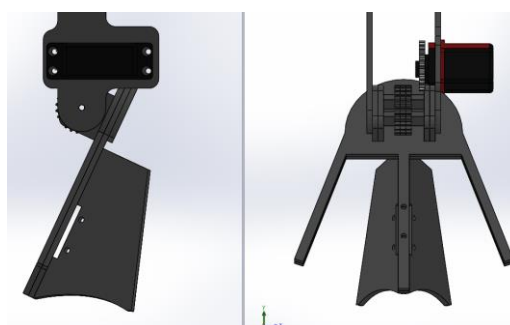161 cm, which has been shown graphically in Figure 6.
162

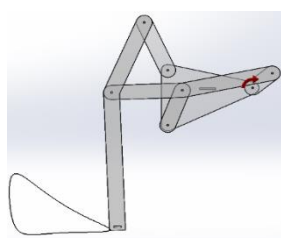**Figure 3.** Foot orientation during swimming and walking mode.
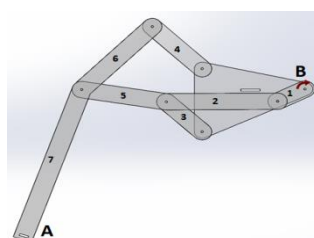

(a)

(b)

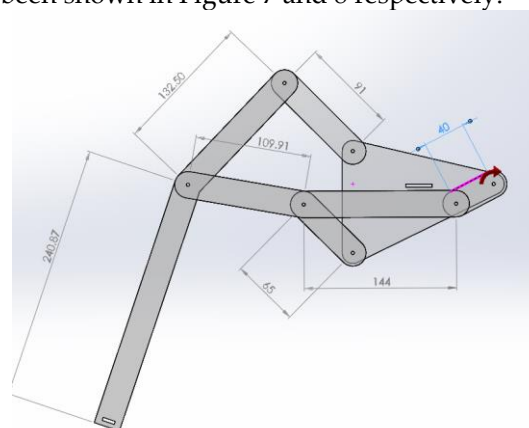**Figure 4.** Duck feet position during (a) Backward motion, (b) Forward motion.

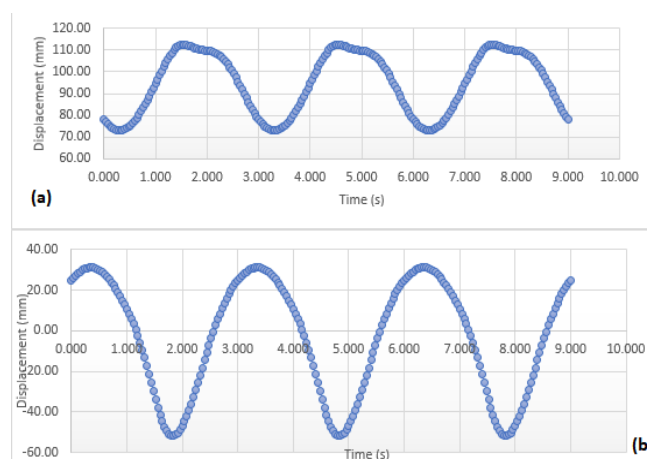163   The full model isometric view and top view have been shown in Figure 7 and 8 respectively.

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

164   **Figure 5.** Trace the path of the Klan linkage foot (a) closed position (b) Extended position (c) Linkage
165   with dimension.

A XY plot with a color interpolation representing the time also should be interesting.

I dont have the data with me right now since I left Swinburne University

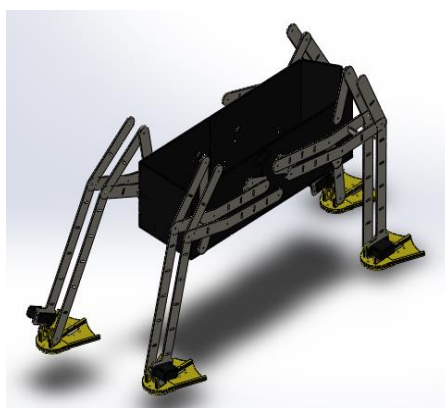**Figure 6.** (a) Vertical displacement; (b) Horizontal displacement.
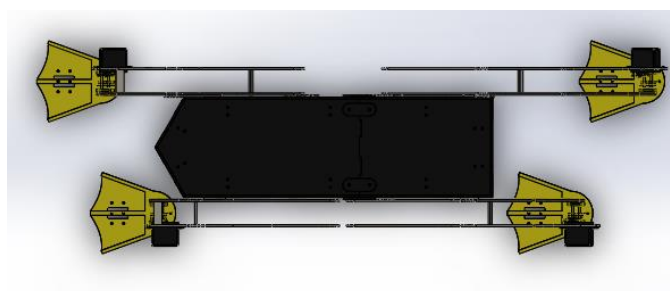

Figure 7. Full model isometric view.

Figure 8. Full model top view.

3.3.2. 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.

178   Apart from servo motors, Mybotic DC gear motor JGB37 was used to control the linkage of the
179   forward movement. It has a speed of 30 rpm and rated load torque of 25 kg.cm. Every foot is fixed
180   with one DC motor which is paired with Hall effect sensor (built-in with motor) for feedback position,
181   to control the leg movement, and to avoid any desynchronizing.
182   JSN-SR04T waterproof ultrasonic sensor (range of up to 4.5 m), and water sensor are used in this
183   project. The ultrasonic sensor is used to detect any obstacle in front so that the robot can avoid it. In
184   addition to that, it measures the water depth to perform switching from walking to swimming.
185   Water sensor is used to detect the presence of water. Whenever the presence of water is detected with
186   sufficient depth for swimming, the robot instantaneously switches from walking to swimming mode.
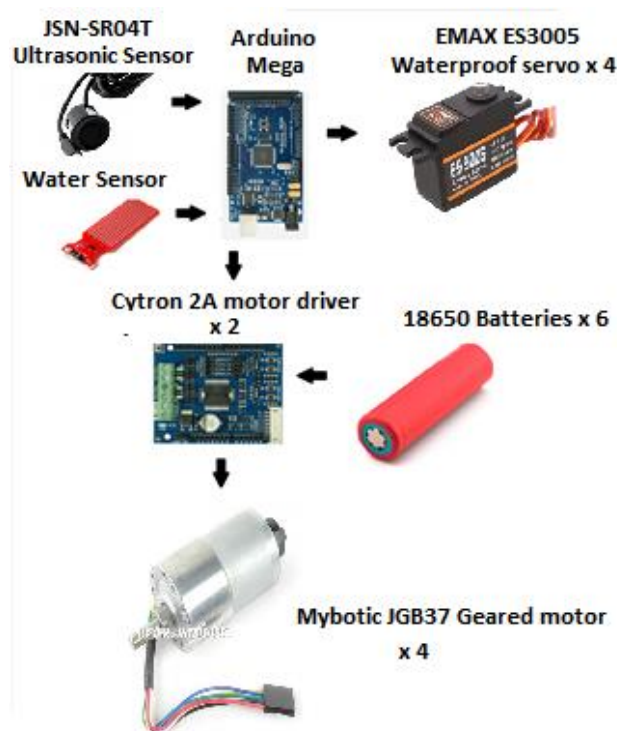187

189   **Figure 9.** Electrical components used in the design.
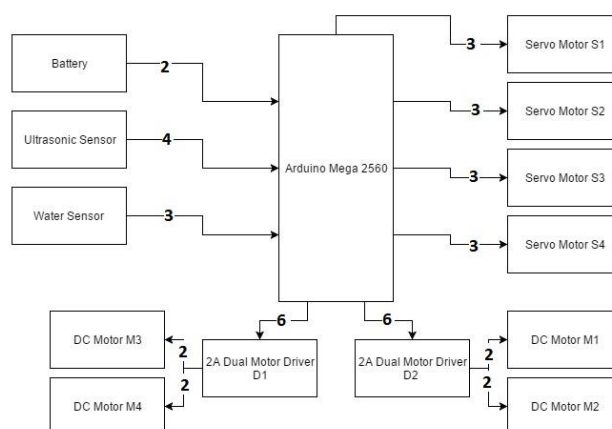

191   **Figure 10.** Block diagram showing the Electrical connection layout.

192   For the power supply, compact and efficient 18,650 Lithium-ion batteries have been used which are high
193   capacity rechargeable batteries. These batteries have a rated capacity of 3800 mAh, and provide 3.7 V. Such

194 batteries were highly suitable for this project due to their compact nature, and hence total 6 batteries were used,
195 two parallel banks of three series connected batteries, in order to get the combined voltage of 11.1 V with the
196 enhanced current. Figure 9 illustrates the internal connections of the electrical components detailed above. The
197 same block diagram is converted into a circuit layout in Figure 10. Finally, Figure 11 depicts the complete design
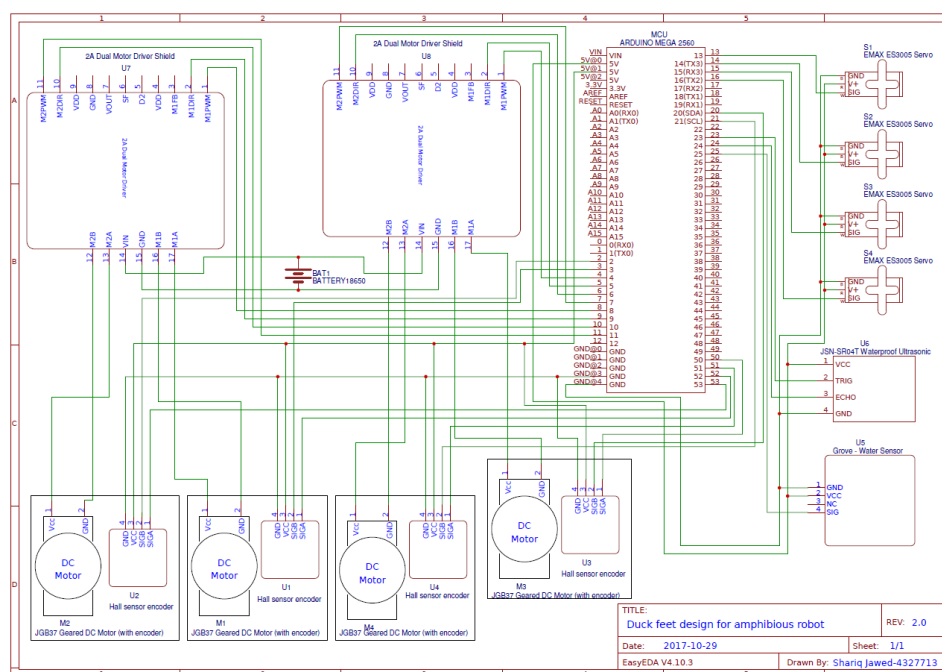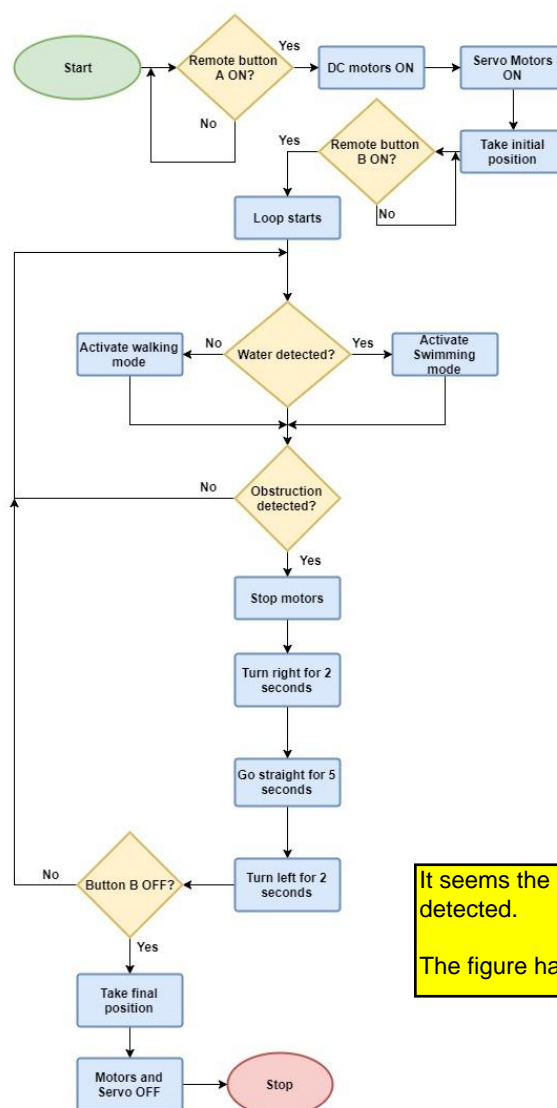198 of the operational circuit board.

199

200 **Figure 11.** Detail circuit diagram of the overall system.

Figure 12. Program Flow.

3.3.3. 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 12. 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.

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 13.

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.
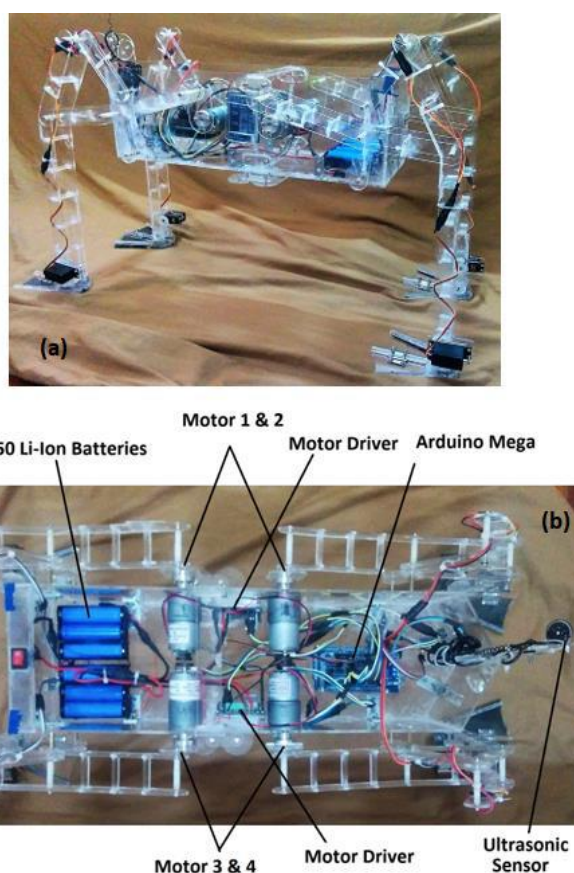

Figure 13. Completed Prototype of the Robot (a) Isometric layout of the prototype (b) top view of the design.

When the water sensor, attached under the body of the robot, detects the presence of water, it provides the necessary signal to the controller that, in turn, sends the activation signal to the actuator attached to the legs in order to rotate and change the legs positions from walking to swimming mode. This also happens by the time the water reaches the body level, and hence, 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 14) using an ultrasonic sensor which is attached to the front of the body. 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.

It seems its is missing a go forward instruction on the program flow of Figure 12.
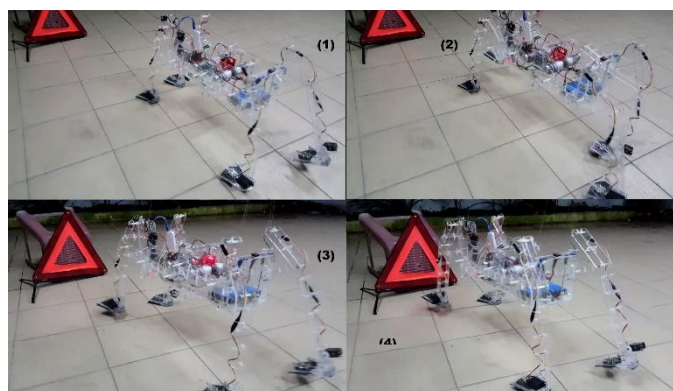
I have replaced the figure.

Figure 14. 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 15 while the motor coordination is shown in Figure 16.

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 17 shows a swimming test and Figure 18 depicts the flap opening and closing while swimming. The video of these tests can be seen at https://youtu.be/du9R-pkJYzc.

The swin test is not in this video.

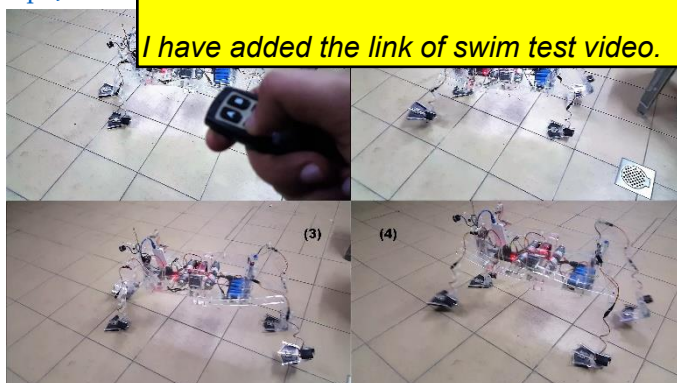*I have added the link of swim test video.*

Figure 15. Walking test of the Prototype.
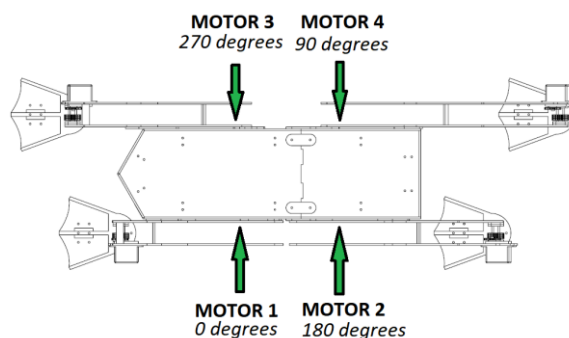

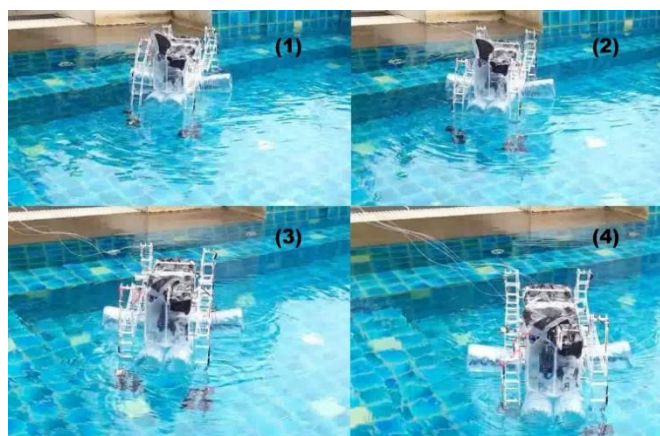**Figure 16.** Motor coordination in the robot.
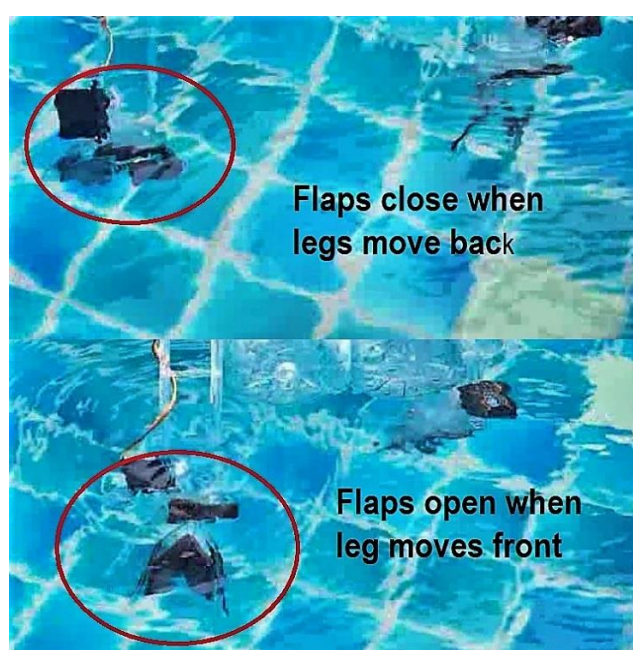
Figure 17. Swimming test of Prototype.

Figure 18. 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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