A Multi-Terrain Spherical Amphibious Robot for On-land, In-water, and Underwater Operation

P. Nilas, and T. Ngo

Abstract—**This paper presents an innovative multi-terrain amphibious robot that imitates the amphibian animals' locomotion ability for both onshore and offshore performances. The robot can roll on-land, swim in-water, submerge underwater, and crawl on the sea floor. The robot consists of a spherical body and an outer jacket shell with multiple tiny channels that function similar to the wheel tread while on-land and perform as the paddle when in-water. The proposed robot have superior capability that other conventional robots could not achieve. The robot could travel on multiple terrains such as rolling on soft ground, floating in-water, and maneuvering underwater. This research utilizes the Omni-directional wheel, and the propeller system for locomotion and movement control. The proposed system has been implemented to develop a prototypical multi-terrains amphibious robot, and the initial experimental results also demonstrate the capability of such a robot design.**

Index Terms—**Aquatic robot, amphibious robot, robot design and development, mobile robot**

I. INTRODUCTION

AMPHIBIOUS animal have many unique abilities that can walk on ground, travel in-water, and maneuver underwater. Inspired with the amphibious ability to travel both onshore and offshore, this research implements a spherical amphibious robot that could mimics amphibious performances. Even numbers of animal-liked robots have been researched in the past [1] [2] [3]; very few works involved on developing a robot that can emulate the behavioral locomotion of amphibious animals. This paper focuses on implementing a prototypical robot that has the amphibian capability of traveling on-land, gliding in-water, and crawling underwater. The research aims to develop an amphibious robot that could perform tasks in both onshore and offshore applications. The paper designs an amphibious robot with two spherical compartments to form the robot body. The spherical shape has an intrinsic nature of geometrical symmetry that provides advantages over the structural weaknesses of traditional mobile robots. The spherical body has a lower ground contact pressure, providing the spherical amphibious robot a superior locomotion not only traveling on solid ground but also on soft surface such as sand, mud, or sea floor. Conventional mobile robots usually consisted of wheeled or legged locomotion that could limit the robot's maneuvering and movement, especially when the robot has a continual task for both traveling on-land and in aquatic environment, it needs a unique ability to travel on ground, swim on the water surface and crawl the sea floor. Many previous works cannot achieve this type of continuous operation.

This paper proposes a novel approach of implementing a spherical amphibious robot that has the maneuvering ability in all three different working environment; rolls on-land, swim in-water, and travel on the bottom of the sea. The proposed robot also could maneuver on multiple terrains not only moving on solid landscape but also soft soil as well as water surface and seafloor

This research presents a design and implementation of the spherical amphibious robot that consists of the inner and the outer sphere. The inner sphere holds all the mechanical and electrical parts. The outer sphere features as the robot jacket that has multiple tiny channels. These channels allow the water to flow into the ballast tank and function as the wheel thread and the paddle while robot travels on-land and in-water respectively. The paper employs three Omni-directional wheels, a propeller and thruster, and four ballast tanks. The design allows the robot to achieve many operational tasks that other type of mobile robot could not perform. For example, the robot could move on ground as a conventional sphere robot and continuously travels into water. It can roll, swim, stand till in-water, submerge under water, and crawl the bottom of the seafloor.

The paper is organized as follows. Section II discusses the related works and provides some literature reviews. Section III presents the conceptual design of the proposed amphibious robot. Section IV describes the mathematical model. Section V presents the robot implementation in both hardware and software. The evaluation scenarios and the experimental results were explained in section VI. Finally, Section VII summarizes the research and discusses the future works.

Manuscript received July 22, 2019.

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II. RELATED WORKS

Amphibious robots have a wide range of usability and application. The robot could perform various type on-land and underwater operations. In early 2000s, researchers had proposed a variety of amphibious robots with different architecture and framework. Those works included the animal-liked robot [4], the legged robot [5], or the wheeled robot [6]. In 2005, Crespi [7] and Hirose [4] developed a snake-liked robot that crawled and swam in water. In 2009 Tang presented a wheel-propeller-leg-integrated amphibious robot that abled to crawled on-land, swam in shallow water, and crept on the ocean floor [8]. In 2010, Kaznov [9] presented a navigation algorithm employed in an amphibious robot named “GroundBot” which was developed by Rotundus AB. This robot utilized a pendulum driving mechanism, a sealed body with thread on the outer sphere. In 2011, Lin [10] proposed a legged underwater spherical robot utilized with multiple vectored water-jet-based propulsion system for seafloor exploration and observation. Jun [11], in 2012, presented a multi-legged underwater-walking robot that surveyed the coast of the Korean Peninsula. Shi [12] developed a lobster-inspired robot in 2013 that was able to avoid obstacle in water operation.

Watson [13] studied a micro-autonomous underwater vehicle that equipped with thrusters to control the robot movement. In 2014, Li [14] used simulation to study the characteristic of hydrodynamic forces for controlling a spherical underwater robot. A turtle inspired robots, ASR-I and ASR-II, were implemented by Pan [15] and He [16]. The robots could move on-land and underwater as well as swim and travel on soft ground. In 2017, Kinjo and Aoki [17] described a robot that could walk and jump with its spherical outer shell. This robot equipped with legs and air cylinder to provide the jumping mechanism. Chen [18] developed a spherical tensegrity robot that could perform the shape-shifting by contracting and releasing cables connected in parallel with the elastic lattice. In 2018, Zhu [19] studied feasibility and performance of a flipper leg amphibious robot similar to AQUA [20]. The robot was a terrestrial sex-legged robot that capable to swim and crawl the bottom of the sea.

Even a large numbers of amphibious robots have been researched in the last decade, very little works have involved the study of full possible performance and application of amphibious robot that could maneuver not only on ground but also in-water and under water. This research proposed a novel design of a spherical amphibious robot that could operate in multiple terrains and working environments. The robot can move, float, station, submerge, and roll which provides a highly potential for many onshore and offshore applications.

III. CONCEPTUAL DESIGN

A. Spherical Amphibious Robot

The paper concentrates on design and implementation of an amphibious spherical robot that can perform various operations in real world environments: on-land, in-water, and underwater. The research proposes a robot that has very low-ground pressure and can traverse any type of terrain, including soft soil, mud, sand or snow. The robot also could float in-water, swim, submerge, and crawl underwater.

The robot combines of two spherical bodies. The inner sphere is the compartment that contains three Omni-directional wheels, a submersible mechanism, the water hulls, and the thruster (propeller). The inner sphere is a waterproof robot body that holds all the mechanical and electrical parts; the locomotion system, the submersible mechanism, the subaquatic propulsion system, the motor, and the electronics circuit. The outer sphere is the jacket that quipped with threads and tiny channels for on-land and in-water locomotion. The thread functions similar to the wheel tread when travels on-land and works as paddle while in-water operation. These tiny channels also allow the water to flow into the thruster and the propeller during the subaquatic movement. Fig. 1 presents the robot main structure: the inner and outer shell, the locomotion and steering system, the four ballast tanks, and the propulsion system. Fig. 2 provides the side view and top view of the robot inner body, the water hull and ballast tank, and the propeller (thruster) system.

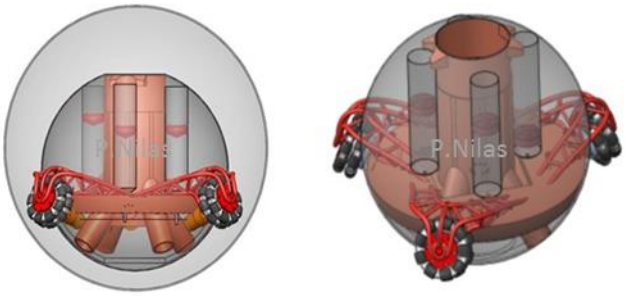

Figure 1. The design concept of an amphibious spherical robot

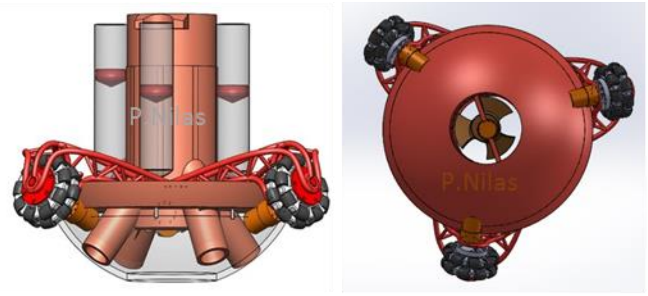

Figure 2. Side view and the top of the robot inner body

According to the robot weight, the inner sphere’s Omni-directional wheels will always touches at the bottom of the outer sphere creating the driving force to roll the other shell.

B. Thruster and Submersible Mechanism

The amphibious sphere robot employs an underwater thruster (propeller) which installed at the center of the robot inner body. This thruster propels the robot in both vertical and horizontal direction. The water is taken into the robot via the water tunnel and exhaust out at the outlet beneath the robot body. The thruster helps to stabilize the robot as well as provide lifting force while robot in the water. Fig. 3 shows the bottom view of the robot thruster and the water hulls (ballast tanks) with the water outlet channel.

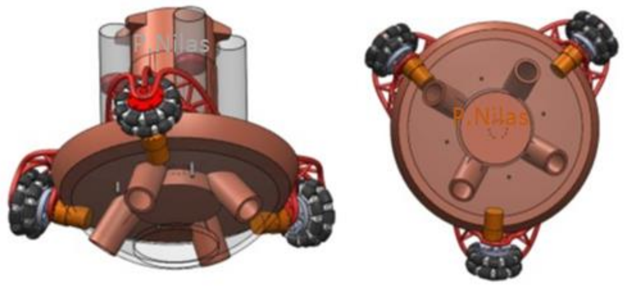

Figure 3. The robot inner body and watar outlet channel

The robot uses the two-way water plump that takes in/out water of the ballast tanks. The robot will submerge or float according to the volume of the water inside its ballast tanks. The robot could adjust the air and liquid volume inside the tank that controls the robot buoyancy. This mechanism provides stability and orientation of the robot during the aquatic operation.

C. *Steering Mechanism*

The robot steering mechanism could be divided into three basic operation: on-land locomotion, floating movement, and submerged maneuvering. However, all the steering behaviors are results of the motor drive control through the Omni-directional wheels. In addition, the robot thruster and propeller as well as the ballast tank will provide in-water robot stability and orientation. The user commands the robot via a remote controller to activate the high level locomotion control. The robot has a control function that provides basic behaviors to roll, dive, float or submerge the robot.

For on-land locomotion, this spherical amphibious robot utilizes three Omni-directional wheels installing under the robot inner body with sixty degree apart from each other. All wheels are perpendicular to the outer shell surface at the fifteen degree pit angle from the ground-contact point. The amphibious robot could maneuver to any direction: forward, backward, turn or spin in its place. The implementation of this steering mechanism will be described in Section V.

For in-water and underwater movement, the sphere robot utilizes its outer shell as well as the vertical propeller for both traversing and stabilizing the robot. The robot outer shell has multiple tiny channel (holes) along with the threads which function as the robot horizontal propeller similar to the boat paddle. While the robot floats or submerges, the robot rotates its Omni-directional wheels and causes the robot outer shell to spin and paddle the robot to the move accordingly. The robot vertical propeller (thruster) intakes water and exhaust it out through the outlet beneath the robot body. This provides the lifting force to counterbalance the robot weight and stabilize the robot while in-water or underwater operation.

IV. MATHEMATICAL MODEL

Using the Omni-directional wheels provide the ability to the spherical robot to move in all directions regardless of its current heading. It provides flexibility for robot driving and steering with low resistance and fiction. Fig. 4 describes the locomotion analysis and parameter assumption.

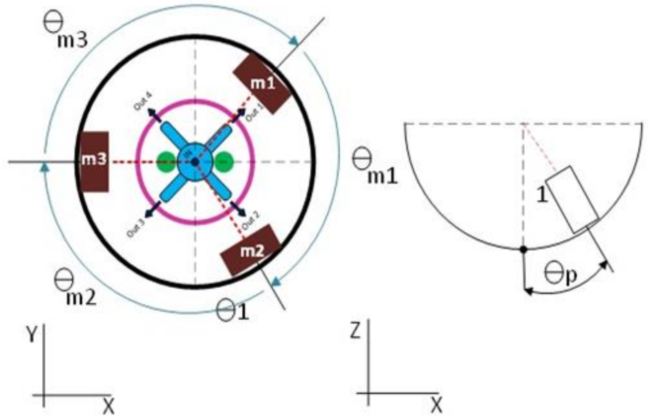

Figure 4. Steering and locomtion analysis

The paper assumes X, Y, Z are the principle axes of the world frame. It demotes M1, M2, M3 as the wheels rotational and assumes (Xb, Yb, Zb) are the axes of the robot body frame. When viewing from the robot, the arbitrary rotation in three dimensional space can be described as a vector space ($\mathcal{R}$b) of the angular velocity (θx, θy, θz) of the robot body. The angular speed of the motors along with their directions ($\mathcal{R}$m) also can be denoted as (θm1, θm2, θm3). Using the Euler's rotational theorem, the angular velocity can be described mathematically.

$$
\begin{aligned}
\theta x &= \left[\; rw/(rr*\sqrt{1-\cos^2(\phi p)\cos^2(\phi 1)}\;) \right]*(\theta m1/\cos(\phi 1)) \\
&= \left[\; rw/(rr*\sqrt{1-\cos^2(\phi p)\cos^2(\phi 2)}\;) \right]*(\theta m2/\cos(\phi 2)) \\
&= \left[\; rw/(rr*\sin(\phi p)) \;\right]+(\theta m3/\cos(\phi 3)) \\
\theta y &= \left[\; rw/(rr*\sqrt{1-\cos^2(\phi p)\sin^2(\phi 1)}\;) \right]*(\theta m1/\sin(\phi 1)) \\
&= \left[\; rw/(rr*\sqrt{1-\cos^2(\phi p)\sin^2(\phi 2)}\;) \right]*(\theta m2/\sin(\phi 2))
\end{aligned}
$$

$$
If \quad \theta m3 = 0 \quad then
$$

$$
\begin{aligned}
\theta z &= \left[\; rw/(rr*\cos(\phi p) \;\right]*(\theta m1) \\
&= \left[\; rw/(rr*\cos(\phi p) \;\right]*(\theta m2) \\
&= \left[\; rw/(rr*\cos(\phi p) \;\right]*(\theta m3)
\end{aligned}
$$

The robot's angular velocity (θx, θy, θz) are the results of the operational parameters and provide the robot moving direction. The angular velocity (θx, θy, θz) equations also can be derived to matrix form with notation term of $\mathcal{R}$b = (rw/rr)*(A)*$\mathcal{R}$m where $\mathcal{R}$b = (θz, θz, θz), $\mathcal{R}$m = (θm1, θm2, θm3) and A is the relational matrix of $\mathcal{R}$b and $\mathcal{R}$m.

The paper assumes the driving mechanism of the spherical robot remain horizontal during its locomotion. Thus, the velocity of the robot in the viewed of the world frame in the axis of Vx, Vy, θm3 can be described in the matrix form of $\mathcal{R}$b. If V = (v_x, v_y, θm3) and R is a relational matrix. Thus, the robot related to the world frame can be derived in terms of robot velocity in x-axis (v_x) and y-axis (v_y) and the orientation of the robot (θm3). The robot velocity could be written in term of $\mathcal{R}$b as follow:

$$\begin{aligned} V &= R*\Re b = R*(rw/rr)*(A)*\Re m \\ \text{or} \quad \Re m &= (rr/rw)*(A^{-1})*R^{-1}*V \end{aligned}$$

$$\text{or} \quad \begin{bmatrix} \upsilon_x \\ \upsilon_y \\ \theta m3 \end{bmatrix} = \begin{bmatrix} 0 & -rr & 0 \\ rr & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \theta x \\ \theta y \\ \theta z \end{bmatrix}$$

This matrix describes the relationship of (Vx, Vy, θm3) and (θx, θy, θz) in term of robot (rw) and wheel (rr) diameter.

V. SYSTEM IMPLEMENTATION

A. Hardware Implementation

The hardware implementation consists of the robot body, the system controller, and the driving mechanism. The robot has two spherical bodies, an inner sphere and outer sphere. The inner sphere contains all mechanical components and circuits, as shown in Fig. 5.

Figure 5. Robot main components

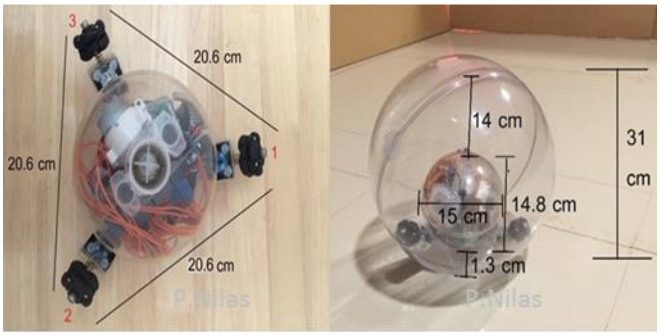

Figure 6. Robot structure and dimension

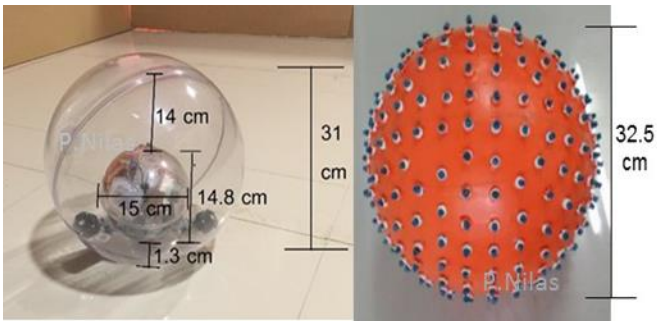

Figure 7. The spherical amphibious robot

The Omni-directional wheels are 60 degrees and 20.6 cm apart. The inner spherical body is around 50 percent smaller than the outer sphere; however, the inner sphere is consisted of three Omni-directional wheels extended out of the body. The robot dimension is presented in Fig. 6. Figure 7 demonstrates the spherical amphibious robot with (right) and without (left) the outer rubber thread and tiny channels. When on-land, all three Omni-directional wheels rotate simultaneously to produce the robot output steering direction. When the robot performs operation in water or underwater, the thruster will provide lifting force and stabilizing the robot body while the system control the Omni-directional wheels to spin and rotate the outer shell to paddle the robot body to move.

B. Software Implementation

An embedded software is implemented for control and communication. The amphibious robot has pre-programmed basic steering behaviors, such as moving forward, backward, turn, dive, and submerge. A remote controller is developed to support the user interface and to input the steering command. The user could wirelessly control the robot to perform basic locomotion, set the robot movement, define turning angle, and speed. The robot is performances were recorded in a database for further study and analysis.

VI. EXPERIMENTAL RESULTS

The measuring scenarios were constructed to evaluation the robot performances. The proposed robot has been tested and the experimental results are encouraging.

A. Evaluation Scenarios

Two experimental scenarios have been setup to evaluate the implemented robot: the basic locomotion testing, and the continual amphibian maneuvering. The basic locomotion testing is designed to illustrate the robot ability to move straight, move in circle, and climb slop. Thus, the testing consists of basic locomotion, circular locomotion, and incline climbing. The continual amphibian maneuvering is designed to demonstrate the amphibious robot capability to function in all different terrains and environments. The spherical amphibious robot will travel on a solid landscape, roll on a shallow water, glide along the water surface, submerge underwater, and crawl the bottom of the water pool. The experimental testbed has been setup as shown in Fig. 8.

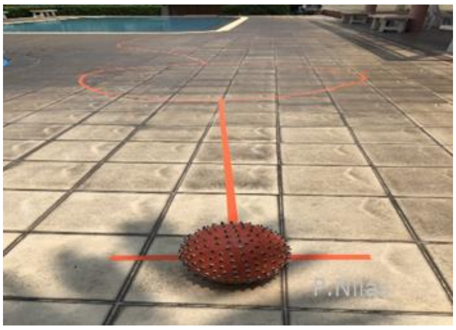

Figure 8. The experimental testbed

B. *Basic Locomotion*

The basic locomotion can be classified into two type of operations; move straightly (forward, backward, left, right), and move circularly (station CW, station CCW, turn CW, turn CCW). The spherical robot can instantly move or turn to any direction without front or rear assignment. Fig. 9 provides the Omni-directional wheel moving direction and the robot's locomotion and direction.

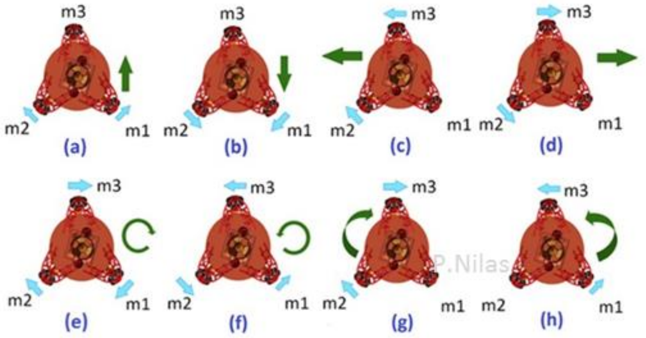

Figure 9. The Omni-directional control

For moving straight experiment, the robot travels for 60 seconds on 5 different terrains; solid floor, soil, sand, mud, and grass. The robot has 20 experiments for each command and the results are measured in term of the average distance of the robot position to the original location. In this testing, the robot is able to travel on all surface with different performance, as provided in Table I.

TABLE I
THE AVERAGE TRAVEL DISTANCE OF THE ROBOT (METERS)

	Forward	Backward	Left	Right	Average
Solid Floor	7.01	7.3	6.95	6.84	7.03
Soil	5.59	5.34	5.44	5.62	5.50
Sand	3.32	3.26	3.45	3.36	3.35
Mud	2.68	2.74	2.57	2.49	2.62
Grass	2.59	2.43	2.55	2.63	2.55

C. *Circular Locomotion*

The circular locomotion demonstrates the robot capability of moving circularly. The robot performs 5 experiments with different speed for 150 cm and 100 cm circle. The results have indicated that higher rolling speed provides higher error and the bigger radian create more error than small circle. Fig. 10 illustrates travel paths of both experiments

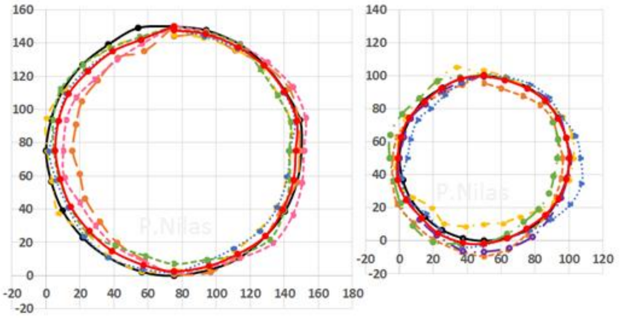

Figure 10. The circular locomotion of 150 cm and 100 cm circle

D. *Incline Climbing*

This experiment studies the incline ability of the robot that can climb up to 12 degree for a solid surface. Fig. 11 demonstrates the robot traveling on a sloped cardboard.

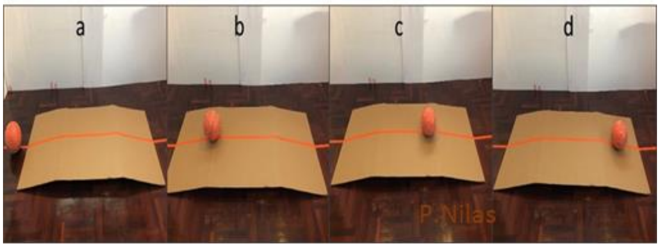

Figure 11. The incline climbing

E. *Continual Amphibian Locomotion*

The continual amphibian locomotion demonstrates the robot ability to perform tasks on-land and in-water environment. The robot travels along the pre-defined path from starting position, circles with 60 cm radian, and moves into the water. The robot is able to float, glide in water, submerge under water, and crawl the bottom of the pool. When in water, robot is able to move according to Omni-directional wheels inside the robot's inner body that drives the external sphere to roll and propel the robot.

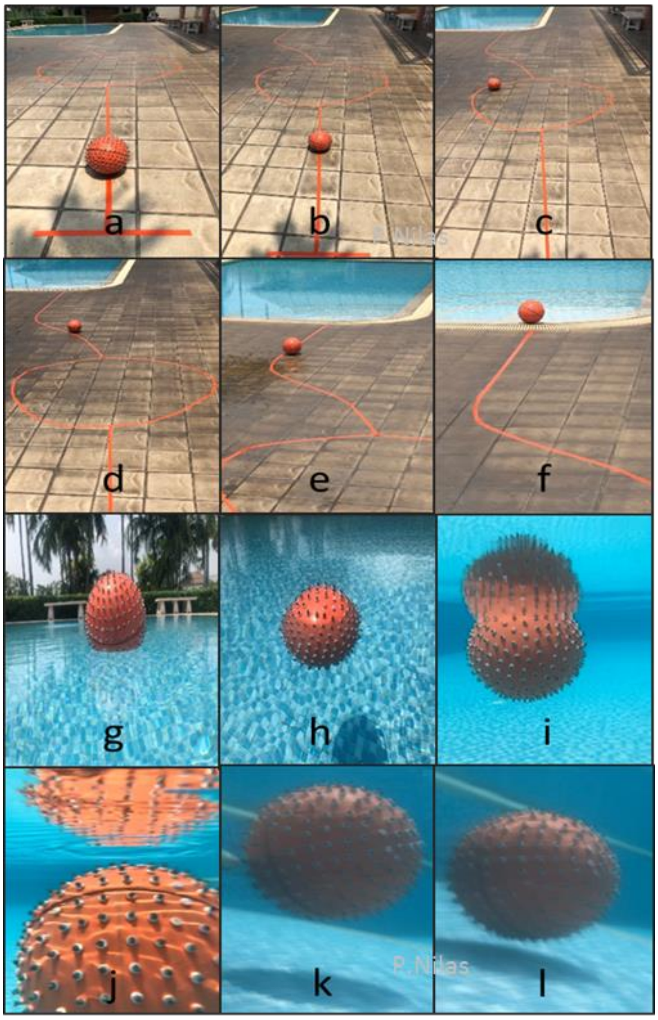

Figure 12. The robot continual locomotion

VII. CONCLUSION

This paper presents the design and implementation of a prototypical amphibious robot that consists of an inner spherical robot body placing inside an outer spherical shell. The inner robot body has the wheeled driving mechanism that propels the outer sphere to roll on land and glide in water. The outer shell equipped with rubber thread and tiny channel that allow the robot to intake water when it submerges. Thus, the robot can float or submerge depending on tasks. This design separates and protects the robot's inner essential parts from the outside hazardous environment. The proposed robot is able to perform amphibian locomotion such as rolling on ground, gliding in water, submerging under water, and crawling the seafloor. The experimental results have indicated that the robot has high capabilities and could be suited to many onshore and offshore applications. More future studies and experiments are needed to enhance the robot abilities and performances. Finally, this spherical amphibious robot requires intelligent system to increase its operational proficiency and usability.

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