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VIRTUAL PROTOTYPE-BASED KINEMATIC MODELING AND SIMULATION OF A MULTI-MODE AMPHIBIOUS ROBOT

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ABSTRACT: The amphibious robot, which has the capability of multi-mode motion, can maneuver diverse environments with high mobility and adaptability. These are employed in the area of reconnaissance, search and rescue operations, and monitoring. The existing amphibious robots have lower maneuverability over the crawling period on uneven and slope surfaces on the land. In this paper, a kinematic model of the amphibious robot based on virtual prototyping is designed for multi-mode locomotion. ADAMS (Automated dynamic analysis of mechanical systems) is a multi-body dynamic solver adopted to build the simulation model for the robot. The novel amphibious robot employs a Rockerbogie mechanism equipped with wheel paddles. The locomotion analysis on land involves straight-going and obstacle negotiation, which is simulated using ADAMS. The simulation analysis result demonstrates increased maneuverability, achieving a robot's velocity of 1.6 m/s. Normal forces on the front and rear wheels show equal load distribution, contributing more to the robot's equilibrium over uneven terrain. The simulation result reflects the accurate kinematic characteristics of the amphibious robot and provides a theoretical basis for developing an algorithm for robot motion control and optimization. Further, this research will concentrate on the kinematic simulation maneuvering in water mode with the wheel paddle.

ABSTRAK: Robot amfibia yang memiliki berbilang mod pergerakan, dapat bergerak dalam persekitaran berbeza dengan ketinggian mobiliti dan adaptasi. Kebolehan ini dapat digunakan dalam kawasan pengintipan, operasi pencarian dan menyelamat, dan peninjauan. Robot amfibia sedia ada mempunyai kurang kebolehgerakan sepanjang tempoh merangkak pada permukaan cerun dan permukaan tidak rata pada tanah. Dalam kajian ini, model kinematik robot amfibia berdasarkan prototaip maya dibentuk berdasarkan gerak alih pelbagai mod. Sistem Mekanikal Analisis Dinamik Automatik (ADAMS) adalah penyelesai dinamik berbilang badan telah diadaptasi bagi membina model simulasi robot. Robot amfibia baru dicipta berdasarkan mekanisme Rockerbogie beserta padel tayar. Analisis gerak alih atas tanah ini termasuk gerakan-lurus dan rundingan halangan, disimulasi menggunakan ADAMS. Dapatan simulasi kajian menunjukkan peningkatan kebolehgerakan, mencapai halaju robot sehingga 1.6 m/s. Daya tujahan normal pada depan dan belakang tayar menunjukkan keseimbangan agihan beban, menyumbang lebih kepada keseimbangan robot ke atas permukaan yang tidak rata. Dapatan kajian dari simulasi menunjukkan ciri-ciri kinematik yang tepat pada robot amfibia dan menyediakan teori asas bagi membangunkan algoritma kawalan pergerakan dan pengoptimuman. Seterusnya, kajian ini mengfokuskan simulasi gerakan kinematik dalam mod air beserta padel tayar.

KEYWORDS: *amphibious robot; kinematic modeling; virtual prototype; ADAMS*

1. INTRODUCTION

Nature inspires to develop locomotion systems that exhibit functionality and performance close to the locomotion of animals [1]. Amphibians encourage developing locomotion strategies since they have excellent locomotion features in the terrestrial and aquatic environments. They smoothly transit between these mediums by simply alternating body mechanisms to adapt to the environment. The terrestrial and aquatic locomotion environment like near-shore, shallow waters demand high mobility and adaptability because of diverse terrain profiles such as sand, wetlands, rocks, uneven surfaces, and varying obstacles to overcome for complete maneuvering. Locomotion metrics like mobility and adaptability in these environments are excellent characteristics of amphibious animals [2].

Amphibious robotics has shown advancement in the past two decades; however, the research focuses on developing the propulsive mechanisms of robots to improve mobility performance in the aquatic medium. The research work in the past focused on bio-mimic swimming characteristics to enhance performance in water. However, these amphibious robots' practical applications demand more capabilities on the land environment, including high terrain adaptability and speed on land, thrust performances, and heading control in the aquatic environment. Consequently, maneuvering ability in these robots needs to focus on driving mechanisms and control performance on both land and water.

Amphibious locomotion of snakes utilizes the undulation of their bodies for propulsion and motion on water and land [3]. The locomotion strategies developed to achieve amphibious locomotion are inspired by legged amphibians like water runners and basilisk lizards [4]. The hybrid mechanism combining leg and wheel is adopted in the whegs robot for terrestrial and underwater locomotion. Whegs series use propellers for underwater locomotion and wheel-leg for locomotion on irregular terrain. The amphibious spherical robot by Guo. et al. mimics turtles' legged locomotion on ground and uses waterjet thrusters for generating thrust in underwater environments [5]. The locomotion performance of amphibious robots reported in the literature is suitable for a smooth land environment with lower speed performance in the water. The hybrid mechanisms achieve improved mobility but at the cost of complex control design. An amphibious robot with a single design is proposed with compact control design. The present amphibious robot is suitable for smooth land surfaces, and legged amphibious robots have lower propulsive speed. There is a need for an amphibious robot with higher mobility capable of traversing uneven land.

Traditionally, researchers utilize experimental methods to validate the mechanical design structure. The experimental work is close to the real environment; however, it involves cost and time. The virtual prototyping validates the kinematic characterization of the model to achieve optimal performance before developing the actual prototype [6]. Lin et al. [7] utilizes a virtual prototyping robot to obtain kinematic parameters and validate the model using ADAMS for dynamic analysis of an amphibious spherical robot. Zong et al. [8] study the locomotion performance of amphibious robots using a virtual prototype created in ADAMS. The kinematic simulations validate transformable flipper leg performance on complex terrain and underwater environment. Zhuang et al. [9] propose a hydraulic-driven quadruped amphibious robot leg movement analysis using ADAMS that facilitates gait selection of quadruped amphibious robots to crawl on uneven terrain. Virtual prototyping of the model aims to achieve optimal performance before developing the actual prototype and facilitates the iterative process to verify the complete model at early stages, reducing the time and cost of development.

Dynamic and kinematic analysis of the rocker-bogie based mechanism in ADAMS is performed to study the working principle of an amphibious robot. Cao et al. [10] illustrate the modeling process of simple linkage mechanisms like gear and a cam performed in an ADAMS environment. Virtual prototyping has become a common tool to analyze the performance of models before they are physically developed. The virtual prototype provides a vital steppingstone for the design optimization of the model. The virtual prototype tool gives the kinematical analysis capability of an amphibious robot, dynamic characteristics, structural parametric study, and static analysis. The robot's complete motion performance analysis is possible by virtual prototyping simulations before physical prototype development. The simulation analysis is also the basis for motor selection and other electronics [11].

To achieve amphibious locomotion in complex environmental conditions, mobility (velocity of robot vehicle on ground and thrust in water) and adaptability in these environments (obstacle negotiating and climbing capability on uneven terrain) are two important performance metrics analyzed in the literature. Mobility of some amphibious robots is discussed. For example, ACM is a snake-inspired amphibious robot that uses a modular design that can propel itself at 0.4m/s. Salamander amphibious robot achieves 0.42 m/s on land 0.28 m/s on water using body undulation and limb design. Turtle robot design uses a spherical body and four legs for motion, achieving a crawling velocity of 22.5 cm/s and surge velocity of 16.5 cm/s. Amphirobot -III uses a modular body design with a wheel propeller fin mechanism giving the speed of 0.59 m/s. Amphihex-I robot uses a flipper leg design that has higher adaptability with a speed performance of 0.2 m/s. The mobility of present amphibious robots is lower and suitable for smooth land surfaces.

Kinematic modeling enables development and verification of the model. The implemented kinematic modeling is divided into two methods- one related to the geometric approach [12,13] and the other concerning the transformation approach. A general approach to kinematic modelling of articulated robots traversing uneven terrain was developed by Tarokh et al. [14]. In this paper, the kinematics modelling of a six-wheel rocker-bogie mobile robot based on the above literature is deduced. The kinematics model will be helpful and fundamental to subsequent studies on the mobile robot's trajectory tracking and motion control [15].

A novel wheel leg hybrid-based amphibious robot with an integrated rocker-bogie wheel paddle mechanism is introduced in this paper to negotiate obstacles on uneven terrain exploiting the legs of the robot and high-speed mobility using wheels attached to legs. The amphibious robot with a rocker-bogie mechanism can maneuver over uneven terrain on land and achieve efficient propulsive maneuvering on the water with a wheel paddle mechanism. The amphibious robot can locomote a single design of multimodal locomotion on multiple terrains of land and water. The unified mechanical design gives the capability of compact control design.

2. KINEMATIC ANALYSIS OF MODEL

Amphibious robots require good propulsive performance on both land and water. In the past literature, amphibious robots were proposed keeping in mind a low demand of terrain complexity on the land environment. However, a real environment is uneven, demanding maneuvering on complex terrain profiles. The amphibious robot employs either legged, tracked, wheeled, spherical or hybrid mechanisms for propulsion. A legged robot is suitable and adaptable on complex terrains but at the cost of control and lower speed [16]. Wheeled robots are best suited to flat ground surfaces, maneuvering at high speed [17]. However, they are less flexible as compared to legged over uneven terrain. Wheeled robots with passive suspension mechanisms increase adaptability on complex terrain and achieve higher obstacle negotiation capability. Rocker-bogie mechanisms with a passive suspension mechanism with a wheel paddle fin represent a hybrid mechanism for amphibious operation. The hybrid mechanism on land is a wheel-driven mobile robot with passive suspension. The wheel-driven mechanism increases the motion speed and passive suspension increases the adaptability on uneven terrain, thus increasing overall propulsive performance on land.

The general view of the virtual prototype of the amphibious robot is shown in Fig. 1. The amphibious robot virtual prototype consists of two major parts, the rocker-bogie mechanism, and the wheel paddle mechanism. The rocker-bogie mechanism has passive suspension [15].

The mechanism has a single rocker attached to the body by a pivot joint. A differential joint appends the rocker and the bogie. The two rockers and bogies are attached on each side of the chassis (main base). The wheel paddle mechanism is a combination wheel design with paddles on the outer surface of the wheel. The wheel's rotation is utilized for locomotion on land, and the same wheel with paddles is used as propulsion in water.

2.1 Kinematic Modeling

The amphibious robot's main body consists of a rocker-bogie mechanism with six wheels driven by individual actuators. The rocker-bogie is a passive suspension mechanism utilized to adapt to uneven terrain and obstacle negotiation. The rocker-bogie mechanism comprises a rocker attached at the front and two bogies attached to a rocker at the rear end.

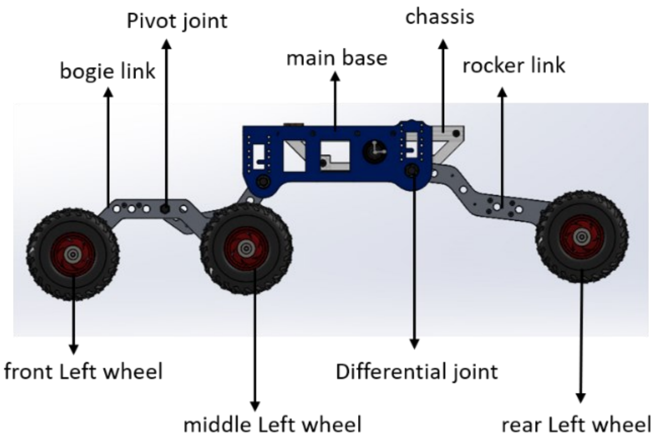
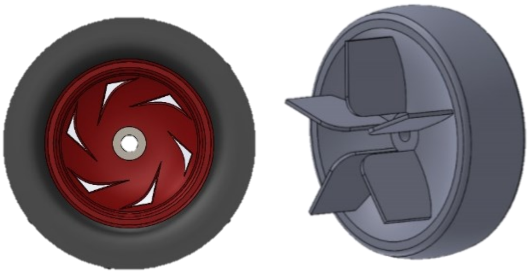


Fig. 1: General view of amphibious robot.

The wheels are attached to the rocker and bogie with joints. The joints are attached with bearings. Solidworks software is utilized to accomplish design indices and carry out the assembly process of the robot body, including the rocker-bogie mechanism and wheels. The ADAMS software accepts geometric position relationships in Parasolid format. Solidworks exports the model in the required format. However, this process loses model features like material, mass information, and mechanisms due to the constrained relationship.



(a) (b)

Fig. 2: (a) Tire, (b) Wheel paddle.

Additionally, the robot assembly has a large set of parts; the model is highly complex. The model in ADAMS adopts Boolean operation that minimizes the independent parts quantity and retains only the main parts (geometry, mass information) and joints appended to main parts [16]. Figure 2 shows the tire used in the kinematic simulation of the amphibious robot. The amphibious locomotion on the water is achieved using a wheel paddle design. Table 1 and Table 2 detail amphibious robot model specifications.

Kinematic analysis of an amphibious robot on land is considered for simplicity. According to the kinematic theorem, the velocity relationship of wheel locomotion may be described as follows. Eq. (1) and Eq. (2) represent the linear velocity of the left and right wheel, respectively. The velocity relationship is related to the radius of the wheel r and angular velocity of the wheel w_L. The angular velocity of each wheel is related by revolutions of each wheel n_L or n_R. Eq. (3)- Eq. (5) represents the wheel velocities while turning the wheel, where w is the identical turning angular velocity of the wheel.

$$V_L = r.w_L = r.\frac{2\pi n_L}{360} \tag{1}$$

$$V_R = r.w_R = r.\frac{2\pi n_R}{360} \tag{2}$$

$$V_L = w.\left(R \pm \frac{d}{2}\right) \tag{3}$$

$$V_R = w.\left(R \mp \frac{d}{2}\right) \tag{4}$$

$$n = \frac{n_L}{n_R} = \frac{R - \frac{d}{2}}{R + \frac{d}{2}} \tag{5}$$

Table 1: Amphibious robot mechanical structure specification

Structural part	**Weight (kg)**	**Dimensions (mm)**
Main base	1.135	240 x 156 x 60
Rocker link	1.410	267 x 96 x 36
Bogie	2.634	256 x 87 x 36
Rocker top	1.022	255 x 105 x 56
Tire/Wheel paddle		120 x 60

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The study of kinematics modeling and simulation of amphibious robots is the basis of robot development and optimization. The kinematic analysis verifies the motion model of the moving robot by overcoming the obstacles without tipping or flipping over the terrain profile for the simulation period with the given constraints of the mechanism. The rationality of the kinematics model of the moving robot is verified by analysis of displacement and velocity curves. Designers adopted the ADAMS software to build the simulation model of the robot [21]. The robot's kinematics curve was obtained through the kinematics simulation of linear driving and pivot steering performance. This robots' mechanism design verifies the correctness of the kinematic model.

2.2 Modeling Environment

The modeling environment adopted for virtual prototyping is a widely used dynamic modeling and simulation software ADAMS; the environment facilitates the analysis of dynamic systems. The amphibious robot locomotion speed and drive forces on the wheel-driven mechanism can be obtained using the simulation approach based on ADAMS. However, ADAMS has limitations in modeling complex design structures in the spatial domain. Therefore, a 3D designing environment like Solidworks is employed with Parasolid as a base to design solid parts and assemblies. The Parasolid design is exported in ADAMS for motion analysis.

Table 2: Robot model specifications

Vehicle load	8 kg (78.4 N)
Wheel specification	
- Width	0.06 m
- Radius	0.06 m
- circumference	0.377 m
Motor Torque, M_T	0.7848 Nm

Therefore, by combining the powerful three-dimensional solid modeling functionality of Solidworks with the accurate movement simulation performance in ADAMS through a common data exchange interface [19], the kinematic simulation environment can be established. Then the relationship between structural parameters and propulsive speed can be analyzed, aiming to offer some reference for the optimization design of the propulsive mechanism and motion control.

This work acts as a reference for the optimal design of motion control and the propulsive mechanism by analyzing the structural parameters of the rocker and bogie link lengths, pivot and differential joint angles, rocker and bogie height to wheel center, angle of inclination with respect to ground, and maneuvering speed of the amphibious robot. The analysis is possible by exploiting the excellent three-dimensional modeling capability in CAD software like Solidworks and motion simulation and a common data exchange interface [20-22].

3. RESULTS AND DISCUSSION OF KINEMATIC SIMULATION BASED ON ADAMS

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3.1 Straight Going Path

To verify the robot model, it is required to validate the motion stability of the robot. The simulation of the model on land aimed at robot locomotion over the surface along the planned trajectory and tested for stability and heading to reach the target. The rocker-bogie integrated wheel paddle mechanism is designed considering the uneven terrain profile and obstacle negotiation capability. The robot's stability is studied by observing the variation of the center of mass of the robot structure along the horizontal X-axis direction. Figure 4 shows the oscillations are smooth on flat terrain profile and encounter sharp changes when the model encounters the obstacle and steady state after the robot passes over the obstacle stabilizing the overall model. Figure 4 shows center-of-mass variation is lower than the robot head height, confirming the stability of the model. The robot vehicle is stable when it is in a quasi-static state in which it does not tilt over, as the asymmetric suspension system of the passively articulated vehicle has a significant influence on the vehicle's effective stability [23]. The computation of the longitudinal stability of the rover makes use of a statical model as it is not symmetric in the longitudinal direction. In a statical model, the mechanical properties of the suspension system are considered. According to [24], the longitudinal stability of the vehicle is given when all wheels have ground contact, and the condition Ni > 0 is satisfied, where Ni is the normal force at the wheel i. It should be noted that even though this condition is compulsory for the statical model to work, a physical robot vehicle does not necessarily tip if a wheel loses contact with the ground.

The velocity of the robot vehicle, as in Fig. 4 in the longitudinal direction, achieves 1.6 m/s, which is higher than similar amphibious robots reported in literature like wheg series [5], RHex and ASGAURD [25,26], wheel leg propeller [27] and aqua robot [16]. However, it is less than the max speed of the seadog amphibious robot [28] of 2.23 m/s, but mobility on the water of the seadog decreases due to the use of the simple non-holonomic wheels as paddle wheels. The peripheral of the wheel is further encased with adhesive material to reduce the fluctuations affecting other parts and system components. The simulation analysis result demonstrates increased maneuverability, achieving a robot's velocity of 1.6 m/s, verifying the theoretical value obtained from Eq. (1) and Eq. (6).

$$V_L = r.w_L = r.\frac{2\pi n_L}{360} = 0.06\,.\frac{2\pi}{60}255rpm\ = 1.6\,m/s \tag{6}$$

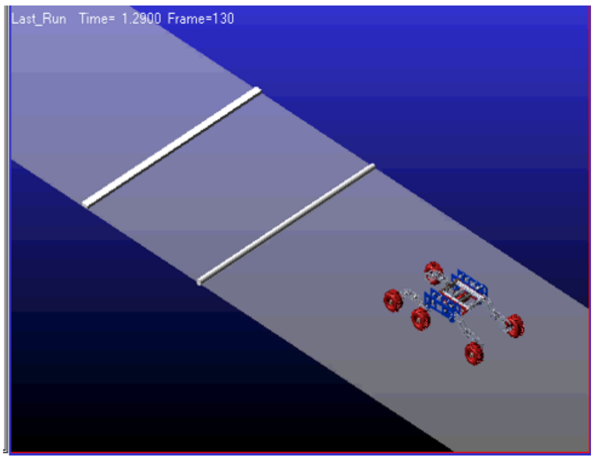

Fig. 3: Terrain profile.

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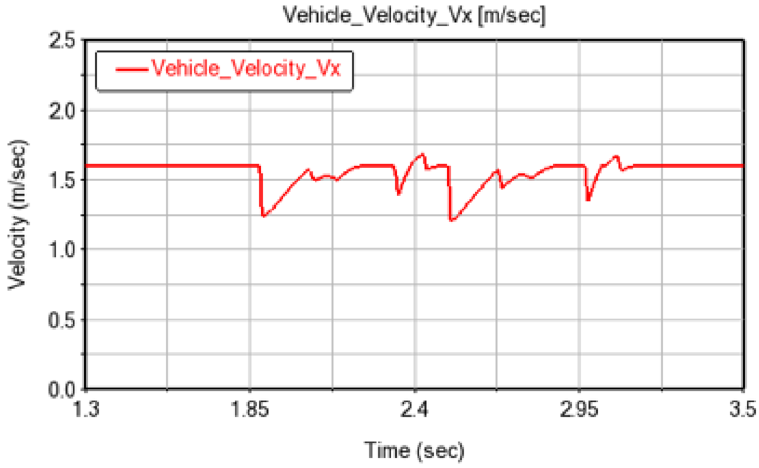

Fig. 4: Velocity of robot in the X direction.

3.2 Obstacle Negotiation of the Amphibious Robot

The terrain profile to test the obstacle negotiation capability of the robot is chosen with different shapes and heights. The obstacle's height should be less than the diameter of the wheel for stability or it will flip over the robot. The obstacle negotiation determines the climbing capacity of the robot. The obstacle shape chosen for simulation is a rigid rectangular block with a height of 20 mm and a width of 50 mm, as shown in Figure 5. The load on each wheel for equilibrium studies using wheel terrain contact forces is discussed in section 3.2.1. The other obstacle chosen is hemispherical with a radial height of 20 mm; these obstacle negotiations exhibit the slip conditions of the robot. Figures 4 and 6 show the velocity and normal forces of all the wheels successfully negotiating at the obstacles of the chosen terrain profile.

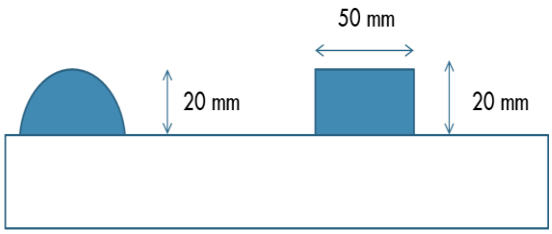

Fig. 5: Obstacle profile.

3.2.1 Wheel Terrain Contact Forces

The mobile robot locomotion on uneven terrain profiles requires a closer look to critically understand the capability of the robot overcoming obstacles completing the trajectory. The wheel ground contact forces analysis facilitates the study of locomotion on uneven terrain profiles. Figure 6 demonstrates the normal forces of the front left tire 1(front wheel), front left tire 2 (middle wheel), and the rear left tire (rear wheel) have equal loading on all wheels up to 1.9 sec because of smooth flat surface. At 1.9 sec, as soon as the left front tire 1(front wheel) touches the hemispherical obstacle, the load is distributed to the middle and rear wheel. The rear wheel is loaded max with a normal force of 29 N at 2.3 sec when both the wheels(bogie) are passed over the hemispherical obstacle. Figure 6 shows the middle wheel peak of normal force at 2.75 sec, indicating the middle wheel is entirely at the top of the 50mm rectangular block. At 2.25 sec, the rear wheel crosses the rectangular block followed by equal forces on all the wheels over the flat smooth surface locomotion at the trajectory completion stage.

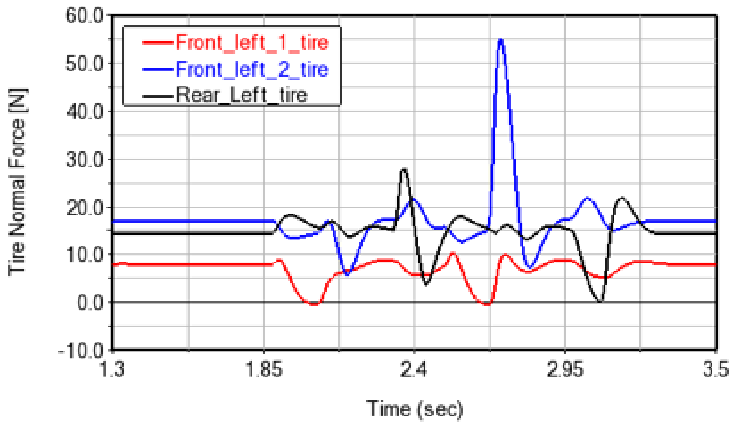

Fig. 6: Normal forces on wheels.

4. CONCLUSION

A novel wheel leg hybrid-based amphibious robot with an integrated rocker-bogie wheel paddle mechanism is introduced in this paper to negotiate obstacles on uneven terrain exploiting the legs of the robot and high-speed mobility using wheels. The existing amphibious robots in the literature [2] have minimal suspension suitable only for flat terrain profiles. However, the suspension is achieved through a legged robot with lower speed and mobility performance on both land and water. The analysis proves that the propulsive principle and feature of the wheel paddle mechanism enable efficient locomotion on land and water. The robot is capable of multimodal locomotion on uneven terrain on terrestrial and aquatic mediums. The simulation in the ADAMS environment provides a basis for the kinematic validation of the model. The kinematic simulation in ADAMS of the virtual prototype amphibious robot measures the speed, angular torque, and velocities of the integrated mechanism.

In this kinematic simulation, the capabilities on a smooth and uneven surface on land are achieved. The capabilities include straight going on a flat surface, and obstacle negotiations over the obstacles of various heights and shapes that are selected for performance evaluation of the model.

In the future, the experiment will be carried out on benchmark terrain profiles considering different height obstacle negotiations for the robot to locomote on land. Furthermore, kinematic simulation using the wheel paddle on the water will be tested. The control capability for the amphibious robot can be carried out using the co-simulation capability of ADAMS and Matlab/Simulink Environment.

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