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Modeling and experimental evaluation of an improved amphibious robot with compact structure

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A R T I C L E I N F O

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A B S T R A C T

This paper describes an improved three-dimensional (3D)-printed, low-cost, multi-functional, high-maneuverability, high-concealment, turtle-inspired mobile amphibious spherical robot for environmental monitoring and data collection. The major challenge in developing such a robot lies in its limited physical size and compact structure that allows for only one type of propulsion system to be used both on land and in water. This paper focuses on the optimization of the kinematic and hydrodynamic model of the amphibious spherical robot, so as to improve the control accuracy and stability of the robot. In order to optimize some kinematic and dynamic modeling parameters of the robot, such as the drag coefficient of robot, the angular velocity and swing angle of each joint, a solid model of the 3D-printed robot was built by SolidWorks. Our simulation results and theoretical calculations confirmed the validity of the virtual model and facilitated identification of key parameters in the design. The correctness of the modeling was demonstrated by the stability of consecutive crawling and underwater movements, providing a basis for driving and controlling methods for this amphibious robot, as well as guidance for the robot's gait trajectory. Combining the robot's crawling mechanism with related simulation results, an optimized prototype of the 3D-printed amphibious spherical robot was constructed. A series of crawling experiments on a common floor were performed with the improved robot prototype, which was also done using the previous robot. The results were evaluated by a novel optical positioning system, NDI Polaris. Moreover, several experiments were carried on land crawling and underwater swimming to verify the performance of the improved amphibious spherical robot. Comparison of experimental and simulation results demonstrated the improved robot had better amphibious motion performance, as well as more potentiality and applicability to the real structures.

1. Introduction

In an effort to build robots that can carry out sophisticated tasks or collect data from unstructured environments, researchers have continued to emulate living creatures and their materials, morphology, and movements. Over the last several years, mobile robots have provided more detailed and complex data, allowing scientists to develop new perceptions and deeper insights into the functioning of the numerous ecosystems on the planet. The use of mobile robots yields unprecedented precise measurements of environmental processes and pushes forward the frontiers of robotics and other sciences.

Amphibious robots have generated significant interest due to their wide range of potential applications; this is due to their ability to operate in various surroundings, with multiple functions and high maneuverability. As a typical example, high-durability, waterproof, snake-inspired robots propel themselves by undulation movements of their bodies on land and underwater [1]. Unlike snake robots, many amphibious robots use different propulsion methods to adapt to different environments. For example, the actuator of the "Whegs" amphibious robot is a combination of propellers and legs that allows the robot to move on rough terrain and in underwater environments [2]. AmphiRobot-II is an amphibious biomimetic fish-like robot with a wheel–propeller–fin mechanism and a specialized swivel mechanism [3]; specifically, the wheel–propeller–fin mechanism functions as a drive wheel for crawling on land and as a common screw propeller or pectoral fin in water. A salamander-like amphibious robot named Sala-mander Robot

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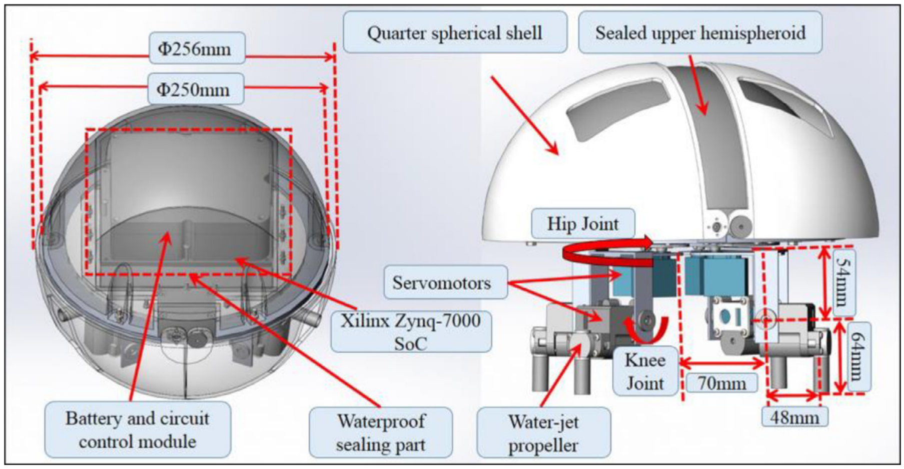

Fig. 1. Diagram of the improved three-dimensional (3D)-printed amphibious spherical robot.

mimics the terrestrial to aquatic locomotion transition via a combination of body undulation and limb crawling [4]. As mentioned above, there is also an amphibious mobile robot with a spherical rotary paddle mechanism, as shown in [5]. Each of these amphibious robots has its own characteristics and advantages. Wheeled robots have good performance on even ground, whereas tracked and legged robots have better mobility on rough terrain. Compared with screw propellers, undulatory and oscillatory propulsion with lower environmental disturbance can also achieve high efficiency and maneuverability. Some robots use two sets of propulsion mechanisms for terrestrial and aquatic motions, which lead to a heavier machine body. To simplify the structure, robots such as ACM-R5 and AQUA2 use composite propulsion mechanisms to move in amphibious environments.

However, it is still problematic for these amphibious robots to move in confined spaces. There are no manipulators on existing amphibious robots to improve mobility and flexibility for complex terrains on land or with underwater operations. Moreover, it is difficult for these amphibious robots to achieve accurate position control underwater via a swimming motion. For example, currents in the water prevent the amphibious robots without legs from retaining their position for precise manipulation. In our previous study, in an attempt to address some of the limitations of previous amphibious robot designs, we created a novel three-dimensional (3D) printing technology-based amphibious spherical robot with transformable composite propulsion mechanisms [6–8], to control and carry micro-robots. A spherical body provides maximum internal space and the advantages of flexibility, due to its symmetry both underwater and on land [9–15].

Traditional methods to design quadruped robots rely on mechanical prototype experimentation for design validation, which can be costly and time-consuming due to the numerous calculations involved and usually provides poor visualization outcomes. However, given the complex structure of the 3D-printed amphibious spherical robot, kinematic and hydrodynamic characterization is important for optimal performance. The kinematic model describes the relationship between the movement of each leg motion rod and the position and orientation of the end-actuator; a precise model is required for motion control and trajectory planning and is, thus, important basic work [16]. To date, numerous kinematic simulation studies have been performed [17–19]; some have focused on gait planning and control algorithms for an amphibious spherical robot [20]. For underwater robots, hydrodynamic characteristics are significant factors that directly affect the efficiency of the motion control algorithm; many researchers have studied the hydrodynamic characteristics of underwater robots and illustrated interaction effects [*e.g.*, 21–24]. These studies used many different methods for kinematic and hydrodynamic analyses to improve the robot's design efficiency and reliability.

In this paper, the kinematic and dynamic model of the amphibious spherical robot is optimized to provide some references for the controlling method and prototype production of the robot. Firstly, some on-land kinematic and dynamic modeling parameters are evaluated in ADAMS simulation. Then, in order to simplify the hydrodynamic model and improve the control accuracy and stability of the robot, some simulation analysis are carried out in ANSYS-FLUENT. Finally, several experiments are carried on land crawling and underwater swimming to verify the performance of the improved amphibious spherical robot. For the remaining sections of this paper in Section II the mechanical design and kinematic analysis of the improved 3D-printed amphibious spherical robot is described. Section III is dedicated to the kinematic simulation in ADAMS. Section IV discusses the hydrodynamic characteristics of the robot. The experimental validation is shown in Section V. Finally, Section VI presents the conclusions of this paper and future research directions.

2. Modeling and kinematic analysis of the robot

2.1. 3D-Printed amphibious spherical robot

As introduced in references [6,7], 3D printing technology was used to fabricate an amphibious spherical robot. We attempted to integrate the design and ensure seamless connections between every part to increase stability during the crawling process. To this end, and to avoid manual errors during fabrication, we sought to maximize the use of the upper hemispherical space and resources, to make the overall profile of the robot more compact and aesthetically pleasing. The diameter of the upper and lower hemisphere of this improved 3D-printed amphibious spherical robot is 250 mm and 256 mm respectively, the height of the actuating unit in standing state is 118 mm, the weight of the robot is approximately 2.26 kg, and the thickness of the spherical shell is 4 mm. Some more specifications of robot are shown in Fig. 1. The hip and knee joints of the robot have two active degrees of freedom (DOFs), referred to as the hip flexion and the knee flexion. The movement mechanisms of this improved 3D-printed amphibious spherical robot are the same as those presented in previous reports [10–12]. With adjustable complex actuation methods, the robot can change its movement mode between quadruped crawling and water-jet propulsion without manual manipulation. The robot walks on land by changing the gait of its four water-jet propellers as legs, with adjustment for the desired velocity. Simultaneously, by changing the directions and propulsive forces of its four water-jet propellers, the robot can not only move forward or backward but can also rotate clockwise or counterclockwise, with the ability to ascend, dive, or float in the underwater environment.