Structural Design of a Biomimetic Amphibious Quadruped Robot

Jie Zhao*

Associate Prof., School of Naval Architecture and Ocean Engineering, Wuhan Technical College of Communications, Wuhan, China

*E-mail: zhaojieyujun@163.com

Abstract

The biomimetic amphibious quadruped robot is a multi-environment adaptive robot capable of performing well both on land and in water. Based on biomimetic principles and the physiological and motion characteristics of animals, this paper analyzes the motion mechanism of the robot and designs a biomimetic robot that can adapt to both terrestrial and aquatic environments. An innovative integrated design combining serial legs and propeller thrusters is proposed. On land, a four-legged, 3-degree-of-freedom serial leg structure is adopted to ensure terrain adaptability; underwater, six propellers arranged on the body and legs enable omnidirectional propulsion, thereby meeting the diverse application requirements of land locomotion and underwater paddling. This study provides a reference for the structural design of biomimetic amphibious robots.

Keywords

Amphibious Quadruped Robot; Propeller Integration; Gait Control; Locomotion Mechanism.

1. Introduction

Amphibious robots capable of operating in terrestrial, underwater, and transitional water-land environments can perform numerous tasks including ecological environment monitoring, underwater resource exploration, and post-disaster search and rescue. They enhance human ability to understand and respond to complex water-land transitional environments and have broad application prospects.

Inspired by the morphological structure, physiological characteristics, and motion patterns of amphibians, many researchers have proposed a series of biomimetic robot prototypes. Professor Wang Liquan's team at Harbin Engineering University developed a foot-propeller hybrid-driven amphibious robot inspired by the crab. Its propulsion device completely imitates the crab's motion physiology and requires two different actuator systems for underwater propulsion and terrestrial crawling [1-2]. Professor Zhang Shiwu's team at the University of Science and Technology of China developed the AmphiHex amphibious robot, which combines curved legs and paddle structures. By employing a deformable mechanism, it effectively changes the shape of the moving legs, thereby enhancing the robot's amphibious performance [3]. The Institute of Automation, Chinese Academy of Sciences, combining fish-inspired propulsion and dolphin-inspired swimming, proposed a wheel-propeller-fin multimodal biomimetic amphibious robot [4-5]. Given that amphibious robots need to cope with complex water-land environments, legged robots with walking legs offer better terrain adaptability. Professor Guo Shuxiang's team at Kagawa University in Japan developed a four-spherical amphibious robot featuring an integrated design of legged locomotor limbs and composite water-jet motors [6-7]. Although this robot adopts a quadruped design, each leg has only two degrees of freedom, which limits the diversity of its motion posture control.

Most existing quadruped robots adopt serial leg mechanisms, such as the MIT Cheetah developed by the Massachusetts Institute of Technology [8], BigDog and LittleDog developed by Boston Dynamics [9], HyQ developed by the Italian Institute of Technology [10], Hyperion 4 developed by Chiba Institute of Technology in Japan, and the hydraulically driven quadruped biomimetic robot developed by Shandong University [11], among others. In quadruped robots with serial legs, the actuators and corresponding sensors are installed on the legs, increasing the mass at the bottom of the legs, which in turn increases the moment of inertia and reduces maneuverability. Parallel leg mechanisms, on the other hand, are mainly used in single-legged or bipedal robots, with relatively few applications in quadruped robots. Although parallel legs offer high stiffness, their complex mechanisms reduce high-speed motion and high load-bearing capacity, making them unfavorable for the integrated design of biomimetic paddling functions.

To achieve diversity in motion posture control for amphibious quadruped robots, this project proposes a water-land amphibious quadruped robot based on the MIT Cheetah. It adopts a quadruped serial leg mechanism, combining the motion physiological characteristics of canines to establish a three-joint serial structure model for the leg, consisting of "abduction/adduction - hip - knee". To meet the six-degree-of-freedom requirements of underwater motion, a "body - leg-propeller thrust vector" model is established to achieve six-degree-of-freedom (X, Y, Z, α, β, γ) motion in water. Underwater motion tests are conducted to verify the feasibility of the biomimetic amphibious quadruped robot's motion mechanism and control logic.

2. Research on the Motion Mechanism Analysis of the Biomimetic Amphibious Quadruped Robot

To achieve amphibious locomotion of the biomimetic quadruped robot, inspired by animal motion and physiological characteristics, dynamic models for its terrestrial motion posture and underwater paddling posture are established based on these principles.

2.1 Terrestrial Kinematics

The following approach is adopted in this project. During three-dimensional spatial motion of the biomimetic amphibious quadruped robot, the base torso of the robot has six degrees of freedom, namely translation along the three coordinate axes of the global coordinate system and rotation about the three coordinate axes. Each leg of the robot has three degrees of freedom, located at the abduction/adduction joint, the hip joint, and the knee joint, respectively. The global coordinate system {O}, the robot coordinate system {B}, the hip joint coordinate system {H}, and the robot's center of mass (CoM) are defined, as shown in Figure 1.

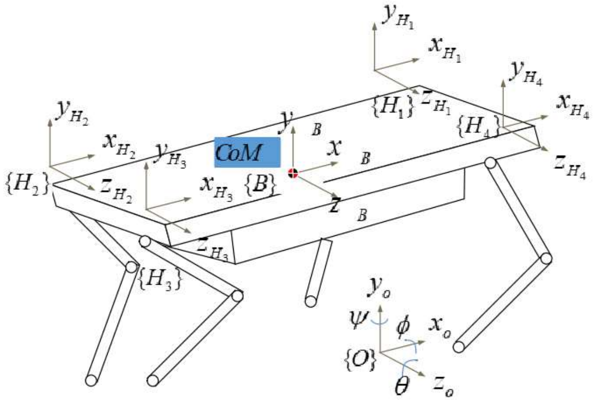

Figure 1. Definition of the coordinate system for the biomimetic amphibious quadruped robot

The robot has 12 active rotational joints and produces motion under the action of joint driving forces, making it a complex nonlinear dynamic system, as shown in Figure 2. In order to make subsequent control problems more precise and reduce the burden on the control system, the dynamic model of the robot is derived and necessary simplifications are made.

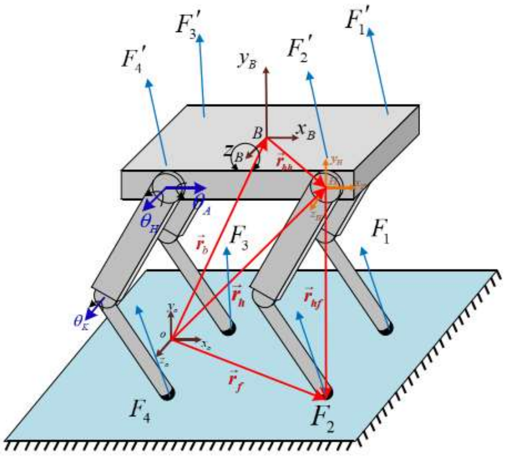

Figure 2. Forces on the robot (terrestrial state)

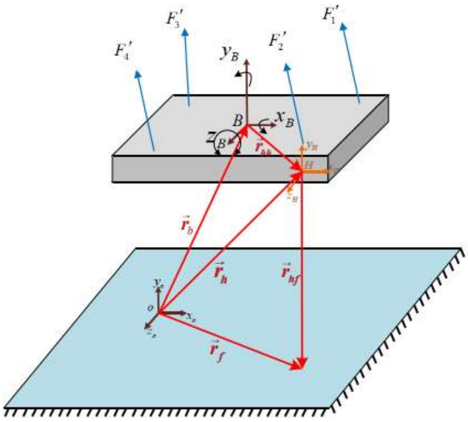

Figure 3. Description of base dynamics

The dynamic decoupling of the robot's base torso and the leg actuation mechanisms is performed.

$$\mathbf{M}_u(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{h}_u(\mathbf{q},\dot{\mathbf{q}})=\mathbf{J}_u(\mathbf{q})^T\mathbf{f}$$
$$\mathbf{M}_a(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{h}_a(\mathbf{q},\dot{\mathbf{q}})=\boldsymbol{\tau}+\mathbf{J}_a(\mathbf{q})^T\mathbf{f}$$

According to the description of base dynamics in Figure 3, the following vector relationships hold:

$$\boldsymbol{r}_h{}^i=\boldsymbol{r}_b{}^i+A^i\boldsymbol{r}_{bh}{}^i$$

Differentiation yields: $\dot{\boldsymbol{r}}_h{}^i=\dot{\boldsymbol{r}}_b{}^i+\dot{A}^i\overline{\boldsymbol{r}}_{bh}{}^i$

Since $\dot{A}^i=\tilde{\omega}^iA^i$ then: $\dot{\boldsymbol{r}}_h{}^i=\dot{\boldsymbol{r}}_b{}^i+\tilde{\omega}^iA^i\overline{\boldsymbol{r}}_{bh}{}^i=\dot{\boldsymbol{r}}_b{}^i+\tilde{\omega}^i\boldsymbol{r}_{bh}{}^i$

where, $\omega^i=2E^i\dot{\theta}^i$ then:

$$\theta=[\theta_1,\theta_2,\theta_3,\theta_4]^T$$
$$\dot{\theta}^i=[\dot{\theta}_1{}^i,\dot{\theta}_2{}^i,\dot{\theta}_3{}^i,\dot{\theta}_4{}^i]^T$$
$$E=\begin{bmatrix}-\theta_1^i & \theta_0^i & -\theta_3^i & \theta_2^i\\ -\theta_2^i & \theta_3^i & \theta_0^i & -\theta_1^i\\ -\theta_3^i & -\theta_2^i & \theta_1^i & \theta_0^i\end{bmatrix}$$

2.2 Underwater Kinematics

Figure 4. Changes in motion posture upon water entry

In underwater motion scenarios, to improve propulsion efficiency, the biomimetic paddle rowing function of the legs is abandoned in favor of more practical and efficient propeller propulsion. Based on six sets of propeller propulsion systems, precise six-degree-of-freedom (6-DOF) motion control of the robot underwater is achieved.

When the robot enters the water from land, its motion posture changes to bring the propeller thrusters to their designated positions, the quadruped legs enter a fixed state, and the propeller thrusters are activated. The robot's motion in water is regarded as that of an underwater vehicle. The legs are usually fixed and serve as auxiliary control surfaces, while propulsion mainly relies on the six propellers. The simplified model assumes that the added mass and damping are diagonal matrices, and neglects the nonlinear parts of the Coriolis terms. Based on this simplified model, it is assumed that the body coordinate system is consistent with that for terrestrial motion (i.e., the body coordinate system {B} is attached to the robot's center of mass, with the x-axis pointing forward, the y-axis pointing rightward, and the z-axis pointing downward), and higher-order terms in the hydrodynamic forces are ignored. Kinematics describes the relationship among the robot's position, attitude, and velocity.

The generalized pose vector of the rigid body is defined as:

$$\boldsymbol{\eta} = [x, y, z, \phi, \theta, \psi]^T$$

where x, y, z are the positions in the inertial coordinate system, and φ, θ, ψ are the roll, pitch, and yaw angles, respectively.

The generalized velocity vector expressed in the body coordinate system is:

$$\boldsymbol{\nu} = [u, v, w, p, q, r]^T$$

where u, v, w are the linear velocity components, and p, q, r are the angular velocity components.

The kinematic equation is: $\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{\nu}$

where J(η) is the transformation matrix, given in detailed form as:

$$\mathbf{J}(\boldsymbol{\eta}) = \begin{bmatrix} \mathbf{R}(\phi, \theta, \psi) & \mathbf{O}_{3\times3} \\ \mathbf{O}_{3\times3} & \mathbf{J}_{\Theta(\phi,\theta)} \end{bmatrix}$$

$\mathbf{R}(\phi, \theta, \psi)$ is the rotation matrix from the body coordinate system to the inertial coordinate system:

$$\mathbf{R} = \begin{bmatrix} cos\psi\, cos\theta & cos\psi\, sin\theta\, sin\phi - sin\psi\, cos\phi & cos\psi\, sin\theta\, cos\phi + sin\psi\, sin\phi \\ sin\psi\, cos\theta & sin\psi\, sin\theta\, sin\phi + cos\psi\, cos\phi & sin\psi\, sin\theta\, cos\phi - cos\psi\, sin\phi \\ -sin\theta & cos\theta\, sin\phi & cos\theta\, cos\phi \end{bmatrix}$$

The relationship between the attitude change rate and the angular velocity is given by $\mathbf{J}_{\Theta(\phi,\theta)}$:

$$\mathbf{J}_{\Theta(\phi,\theta)} = \begin{bmatrix} 1 & sin\phi\, tan\theta & cos\phi\, tan\theta \\ 0 & cos\phi & -sin\phi \\ 0 & \dfrac{sin\phi}{cos\theta} & \dfrac{cos\phi}{cos\theta} \end{bmatrix}$$

When $\theta = \pm 90^{\circ}$, $\mathbf{J}_{\Theta}$becomes singular, so large pitch angles must be avoided.

The dynamic equation of an underwater vehicle is typically an extension of the Newton-Euler equation in a fluid medium, taking into account hydrodynamic effects. The dynamic equation is:

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}$$

When conducting dynamic analysis, attention must be paid to issues such as water-land dynamic coupling, structural sealing and weight distribution, mutual interference among the six propellers, and optimization of energy efficiency across different media and motion modes.

This project proposes a dynamic model of the biomimetic amphibious quadruped robot to reveal its motion characteristics and patterns under amphibious working conditions.

3. Overall Design of the Biomimetic Amphibious Quadruped Robot

In this study, a biomimetic amphibious quadruped robot is designed. Its structural design is based on the mature torso architecture of MIT Cheetah, with amphibious adaptability optimizations.

The overall architecture adopts a modular design concept. The electronic control cabin serves as the main watertight compartment (IP68 rating, design depth of 30 meters), centrally housing all core electronic equipment, including the main controller, sensor processing unit, communication system, and power management module. The interior of the fuselage is a non-watertight area, housing eight joint motors with IP68 protection rating and an independently sealed battery compartment, which are connected to the electronic cabin via waterproof connectors. External equipment includes two waterproof cameras and various environmental sensors, directly exposed to the working environment.

For terrestrial locomotion, a serial leg configuration is adopted. Eight joint motors are symmetrically arranged on the torso, driving the legs through precision linkage mechanisms. This centralizes the motor weight, significantly reduces leg inertia, and supports fast dynamic running.

For underwater propulsion, six propeller thrusters are configured (two vertical thrusters on both sides of the torso, and four azimuth thrusters at the thighs). In underwater mode, the legs are fixed and folded, relying on the propellers to achieve precise six-degree-of-freedom underwater control.

Figure 5. Design drawing of the biomimetic amphibious quadruped robot

Based on multi-sensor fusion for environmental perception, autonomous recognition and smooth switching between terrestrial and underwater modes are achieved. Two efficient motion modes are integrated on the same platform, and a hybrid power system combining centralized motors and multiple thrusters ensures excellent adaptability in amphibious environments.

According to the performance requirements for terrestrial locomotion and underwater attitude of the biomimetic amphibious quadruped robot [12], the basic dimensions and performance parameters of the robot are determined.

3.1 Leg-Propeller Integrated Structure Design

Since the development of quadruped robots mainly originated from the inspiration of canine locomotion, quadruped robots with serial legs, represented by MIT Cheetah, have actuators and corresponding sensors installed on the legs. This increases the mass at the bottom of the legs, leading to an increase in moment of inertia and reduced maneuverability [13]. Parallel leg mechanisms, represented by Stanford Doggo, offer high leg stiffness, but their complex mechanisms reduce high-speed motion and high load-bearing capacity, making them unfavorable for the integrated design of biomimetic paddling functions. Consequently, research on quadruped robots for underwater motion remains limited [14].

To enable the quadruped robot to operate effectively in complex integrated environments such as gravel land, grassland, and deep-water lakes, and considering the requirements for underwater maneuverability and load capacity of an amphibious robot, the biomimetic robot in this study adopts a quadruped serial leg structure. Combined with the motion physiological characteristics of canines, its terrestrial motion posture is established. On this basis, thrusters and a buoyancy adjustment system required for underwater motion are added. Through the leg-propeller integrated design, the biomimetic paddle rowing function of the legs is abandoned in favor of propeller propulsion. The propellers reach their designated positions, the quadruped legs enter a fixed state, and the propellers are activated simultaneously. Thus, the robot can perform tasks in environments such as land, water surface, underwater, and the seabed. Each leg is equipped with one hip joint motor, one knee joint motor, and one propeller thruster, as shown in Figure 6.

Figure 6. Design model and physical diagram of the leg-propeller integrated structure

Based on MIT Cheetah, this paper replicates a quadruped robot with a serial leg mechanism. The specific parameters of a single leg are shown in Table 1, and its single-leg structure is shown in Figure 6

Table 1. Parameters of the serial leg mechanism quadruped robot leg

Parameter	Value
Upper leg length	0.25m
Lower leg length	0.18 mm
Leg rotation angle	±180°
Mass	1.0kg

Under the requirements of structural strength and stiffness, this serial leg achieves minimal mass and inertia as well as maximum range of motion and workspace. It can perform operations such as moving forward, backward, and laterally with equal ease. The capability of the knee joint motor enables the robot to climb up or down stairs, while the lower leg link does not collide with the stair edges. Since the hip joint motor can rotate ±270° horizontally, both legs can be lifted above the quadruped robot's body, allowing it to climb over high obstacles. The abduction/adduction joint motor, with a range of motion exceeding ±90°, enables the robot to roll its body by 90° during movement.

3.2 Terrestrial Motion Posture

When the amphibious robot moves on land, the leg-propeller integrated modules provide forward propulsion, meeting the requirements for terrestrial locomotion. By simulating the walking patterns of a canine, the gait requirements are determined: three feet must be in contact with the ground during walking; during slow walking and trotting, the feet on opposite sides cross-contact the ground alternately; during ambling, the feet on the same side cross-contact the ground. During motion, the thigh is raised first, followed by bending of the lower leg, with the center of gravity shifting forward. The timing diagram of the gait, showing the stance phase and swing phase, is illustrated in Figure 7.

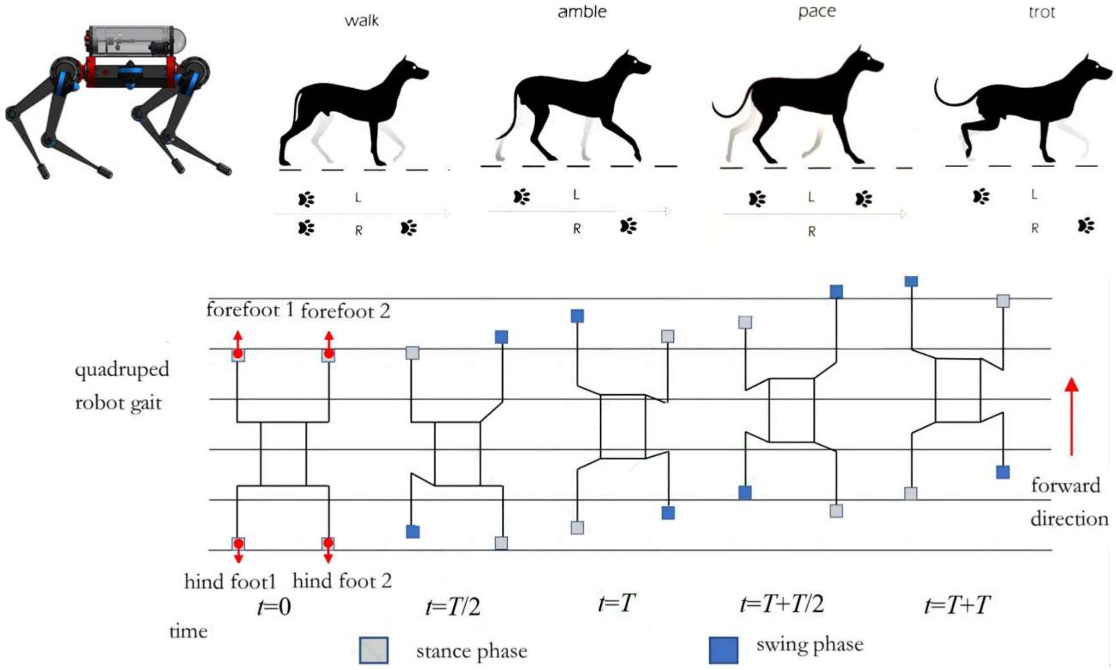

Figure 7. Timing diagram of the biomimetic amphibious quadruped robot simulating a canine walking gait

3.3 Underwater Paddling Posture

When the biomimetic amphibious quadruped robot is in water, it is in an unconstrained state. Considering the effects of buoyancy, water currents, and waves on the quadruped robot, each leg is integrated with a propeller. To improve propulsion efficiency in water, the biomimetic paddle rowing function of the legs is abandoned in favor of more practical and efficient propeller propulsion. The overall biomimetic amphibious quadruped robot integrates six propeller thrusters, enabling six-degree-of-freedom (6-DOF) motion in water, including translational movements (longitudinal, lateral, and vertical) and rotational movements (roll, pitch, and yaw) [15]. The layout is shown in Figure 8: two thrusters are arranged on the robot's torso, and four are arranged on the four thighs.

Each propeller is an independent, self-watertight unit. It consists of a brushless motor, a propeller, a duct, and a watertight housing. During installation, high-strength 3D-printed streamlined mounting brackets are designed on the robot's body (on the outer sides of the thighs and the rear sides of the torso). The propellers are directly fixed to the mounting brackets with circumferentially distributed screws, and the mounting brackets are then securely connected to the robot's aluminum alloy frame with screws.

Figure 8. Layout of propeller thrusters

3.4 Sensing and Control

In order for the robot to perceive and adapt to its environment, sensors are configured in various parts of the robot's body to provide environmental perception and feedback information on the robot's own state, which are used for control and decision-making. Cameras are used to acquire image information of the surrounding environment for functions such as navigation, obstacle detection, and path planning. Ultrasonic sensors are used to measure the distance between the robot and obstacles for obstacle avoidance. Gyroscopes and accelerometers are used to perceive the robot's attitude and motion state, providing feedback signals for walking and maintaining balance.

The quadruped locomotion of the robot is achieved through motors and drivers, with PID control algorithms used for precise gait control and movement. Neural network methods are employed to achieve cooperative motion control of the robot's four legs, enabling the robot to move stably and efficiently. Combined with sensor data, machine learning algorithms are used to perceive and understand the environment, select appropriate paths, avoid obstacles, and make corresponding decisions.

4. Conclusion

The biomimetic amphibious quadruped robot, by imitating the biological characteristics and locomotion modes of animals, typically adopts multiple gaits to achieve flexible movement and adaptability both on land and in water. This structural design enables the robot to possess functions such as environmental perception, obstacle avoidance, and gait control, thereby better accomplishing various tasks. Future development will further enhance the intelligence and autonomy of the robot, bringing more convenience and innovation to people's lives and work.

Acknowledgments

The author acknowledges the financial supported by Hubei Provincial Natural Science Foundation of China (Grant No.2022CFB331).

References

[1] WANG L, WANG H, WANG G, et al. Investigation of the hydrodynamic performance of crablike robot swimming leg [J]. Journal of Hydrodynamics, 2018, 30(4): 605-617.

[2] WANG G, CHEN X, YANG S, et al. Subsea crab bounding gait of leg-paddle hybrid driven shoal crablike robot [J]. Mechatronics, 2017, 48: 1-11.

[3] ZHONG B, ZHANG S W, XU M, et al.On a CPG-based hexapod robot:AmphiHex II with variable stiffness legs[J].IEEE/ASME Transactions on Mechatronics, 2018, 23(2):542-551.

[4] YU J, DING R, YANG Q, et al. Amphibious Pattern Design of a Robotic Fish with Wheel-propeller-fin Mechanisms [J]. Journal of Field Robotics, 2013, 30(5):702-716.

[5] DING R, YU J, YANG Q, et al. Dynamic modeling of a CPG-controlled amphibious biomimetic swimming robot [J]. International Journal of Advanced Robotic Systems, 2013, 10(4):199.

[6] HE Y L, DONG M L, SUN G K, et al. Research on underwater motion control of a composite-driven small amphibious robot [J]. Chinese Journal of Scientific Instrument, 2019, 40(1): 219-226.

[7] RAIBERT M, BLANKESPOOR K, NELSON G, et al. BigDog, the rough-terrain quadruped robot [C]//Proceedings of the 17th World Congress of the International Federation of Automatic Control. Seoul, Korea, 2008:10822-10825.

[8] KALAKRISHNAN M, BUCHLI J, PASTOR P, et al. Learning, planning, and control for quadruped locomotion over challenging terrain [J]. The International Journal of Robotics Research, 2011, 30(2): 236-258.

[9] SEMINI C, TSAFARAKIS N G, GUGLIELMINO E, et al. Design of HyQ: A hydraulically and electrically actuated quadruped robot [J]. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 2011, 225(6): 831-849.

[10] LI Y B, LI B, RONG X W, et al. Structural design and gait planning of a hydraulically driven quadruped bionic robot [J]. Journal of Shandong University (Engineering Science), 2011, 41(5): 32-36.

[11] TAN M, WANG S. Research progress on robotics [J]. Acta Automatica Sinica, 2013, 39(7): 964-972.

[12] WANG Y, ZHOU S, LI Y X. Design and performance evaluation of an amphibious hexapod robot [J]. China Mechanical Engineering, 2022, 33(17): 2079-2086.

[13] RAIBERT M, BLANKESPOOR K, NELSON G, et al. BigDog, the rough-terrain quadruped robot [C]//Proceedings of the 17th world congress of the international federation of automatic control. Seoul, 2008: 10822-10825.

[14] KALAKRISHNAN M, BUCHLI J, PASTOR P, et al. Learning, planning, and control for quadruped locomotion over challenging terrain [J]. The International Journal of Robotics Research, 2011, 30(2): 236-258.

[15] LIU H T, ZHANG M, ZENG Q J, et al. Research on dynamic positioning of underwater robot against wave disturbance [J]. Computer Measurement & Control, 2016, 24(1): 199-203.