# Design and Evaluation of the Terrestrial Gait of the Bionic Robotic Duck

Zhengyu Li, Liwei Shi(✉), and Shuxiang Guo

Key Laboratory of Convergence Medical Engineering System and Healthcare Technology, The Ministry of Industry and Information Technology, School of Life Science, Beijing Institute of Technology, No. 5, Zhongguancun South Street, Haidian District, Beijing 100081, China
{lizhengyu,shiliwei}@bit.edu.cn

**Abstract.** With the exploration of the ocean, amphibious robots can integrate the advantages of underwater and land robots, and can achieve detection on land, underwater, and seabed. This topic proposed the idea of bionic waterfowl, designed a set of amphibious bionic waterfowl robot prototype, and built the machinery platform and control system platform. The robot's dynamic leg and head and neck are moved by modeling; two kinds of land gait designs and simulation analysis of the robot are carried out by ADAMS software. In the simulation process, by adjusting the leg bending angle and joint rotation frequency of the two basic gaits designed, the robot can have a certain ability to overcome obstacles, and can run smoothly on horizontal ground and slopes with different angles. progress. Finally, according to the experimental results, the relationship curves between the leg bending angle and the anterior distance and the joint rotation frequency and the anterior distance were fitted. The bionic duck robot can choose the most suitable gait through the expression of fitting curve under different land environment conditions.

**Keywords:** Bionic duck robot · Gait design · Adams simulation

## 1 Introduction

Since the 21st century, land resources have become increasingly scarce, and the ocean accounts for 70% of the earth surface area, so human beings have set their sights on the vast sea. At present, more and more scientific researchers have devoted themselves to the exploration and exploitation of marine resources. But it's not enough just to have people involved, we need to rely on the right tools to explore the vast ocean. Now humans have developed a variety of underwater robots. At present, most of the platforms on the sea use unmanned boats, submersibles, underwater robots and other equipment to assist humans in exploring the resources of the ocean, and achieve the goal of underwater research. However, these underwater operating equipment have poor adaptability to complex terrains such as sand spits, sand dams, barrier islands, tidal flats, etc. Therefore, amphibious robots are required to cooperate in related work.

Different underwater vehicles have different propulsion methods. The traditional propulsion method usually takes propeller propulsion as the main propulsion mode [1].


H. Liu et al. (Eds.): ICIRA 2022, LNAI 13455, pp. 317–327, 2022.
https://doi.org/10.1007/978-3-031-13844-7_31

Propeller propulsion has many advantages, such as large thrust, fast real-time response, relatively simple structure, and so on. But it also has some disadvantages, such as low propulsion efficiency, high power consumption, high noise, large volume and weight [2]. But fish which can live in the water, the process that fishes swing their bodies and tail fins is a way of propulsion based on lift force [3].

And amphibians often use resistance-based propulsion methods. For example, turtles and crabs move forward by flapping [4]. Squid and jellyfish move forward by jetting water [5]. Research on bionic underwater vehicles was being carried out gradually in recent years [6].

Xing *et al.* designed a miniature bio-inspired Amphibious Spherical Robot (ASRobot) with a Legged, Multi-vectored Water-jet Composite Driving Mechanism (LMWCDM). They studied locomotory performance of the robot in amphibious field environments. And the results demonstrate that the robot prototype possesses the high locomotory performance [7].

Guo *et al.* proposed a decentralized method of spherical amphibious multi-robot control system based on blockchain technology. They set up the point-to-point information network based on long range radio technology of low power wide area network, and designed the blockchain system for embedded application environment and the decentralized hardware and software architecture of multi-robot control system. On this basis, the consensus plugin, smart contract and decentralized multi-robot control algorithm were designed to achieve decentralization. The experimental results of consensus of spherical amphibious multi-robot showed the effectiveness of the decentralization [8].

Zheng *et al.* design an artificial multi-robot cooperative mode and explore an electronic communication and collaborate devices, the control method is based in particular on underwater environment and also conduct a detailed analysis of control motion module [9].

Shi *et al.* used a fuzzy Proportional-Integral-Derivative (PID) control algorithm to design an underwater motion control system for a novel robot. Moreover, they compared PID with fuzzy PID control methods by carrying out experiments on heading and turning bow motions to verify that the fuzzy PID is more robust and exhibits good dynamic performance. They also carried out experiments on the three-dimensional (3D) motion control to validate the design of the underwater motion control system [10].

Yin *et al.* used the adaptive ability of reinforcement learning to propose a two-layer network framework based on reinforcement learning to realize the control of amphibious spherical robots. Through the cooperation of the planning layer and the control layer, the adaptive motion control of the amphibious spherical robot can finally be realized. Finally, the proposed scheme was verified on a simulated amphibious spherical robot [11].

Zhou *et al.* proposed a two-dimensional trajectory tracking control framework for biomimetic spherical robots (BSR) in a constrained workspace. Meanwhile, the research presents the general dynamics models of the robot and the thrusters allocator scheme to ensure the force generated by the propellers within the feasible range. Finally, they assess the performance and feasibility of the proposed control framework through the simulations [12].

Shi *et al.* developed a small-sized quadruped robotic rat (SQuRo), which includes four limbs and one flexible spine, They proposed a control framework for multimodal motion planning, and the appropriate control parameters were tuned through optimization with consideration to the stability and actuation limits. The results obtained through a series of experimental tests reveal that SQuRo achieves a superior motion performance compared with existing state-of-the-art small-sized quadruped robots [13].

Shi *et al.* proposed key movement joints (KMJs) to capture a decent representation of the rat with a reduced-order model. By extracting the primary KMJs, they determined the number and distribution of robotic joints for the design of a bioinspired spine mechanism. To meet the demand of high biomimicry degree, they generated an optimal compensation term to minimize the trajectory error introduced by simplifying the model. And they calculated the optimal minimum motion cycle based on the constraints of equilibrium under extreme conditions to ensure high flexibility without compromising the stability. The proposed method was successfully verified through simulation and experimental tests with a robotic rat endowed with the bioinspired spine mechanism [14].

In this paper, a bionic amphibious robot is proposed, and its mechanical system is designed, which is divided into head, body, and legs. The land motion gait is designed and optimized based on the bionic duck robot model, and a virtual simulation platform is established by Adams software to simulate and evaluate the designed gait.

The rest of this paper is organized as follows. Section 2 introduces the mechanical structure of the robot. In Sect. 3, the terrestrial gait analysis, included walking gait and running and jumping gait are designed. And in Sect. 4, the designed land gaits are kinematically simulated. Finally, the conclusion is summarized in Sect. 5.

## 2 Mechanical Structure of the Bionic Robotic Duck

### 2.1 Head Structure

The head is a structure with 3 degrees of freedom, which is shown in Fig. 1, including two vertical DOF structures and one horizontal DOF structure. The design of the head, as an auxiliary structure of the whole bionic duck robot structure, plays the role of controlling the direction, maintaining the balance and assisting the movement.

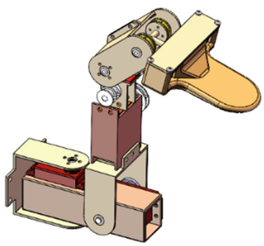


**Fig. 1.** Head structure

### 2.2 Legs Structure

The legs of the bionic Robotic Duck are mainly divided into dynamic legs and soles and auxiliary legs three parts, as shown in Fig. 2.

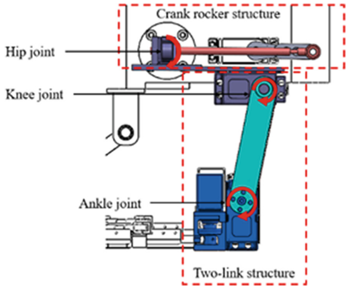



**Fig. 2.** Legs structure

### 2.3 Webbed Structure

As shown in Fig. 3, the structure of the webbed is composed of a telescopic rod, which is controlled by a servo motor. There are three branches of the telescopic rod, and they are all fixed in the barrel.

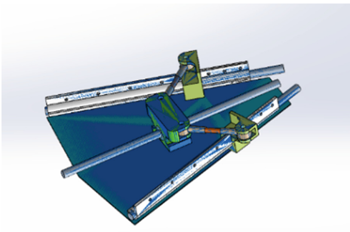


**Fig. 3.** Webbed structure

## 3 Overland Gait Design

The gait design of the bionic robotic duck is mainly based on the movement of bipeds, and is improved according to the mechanical structure of the robot. When walking on the road, the robot will choose different gait and pace according to different task requirements and land environment, so that it can complete it most efficiently. In this paper, there are two kinds of forward gaits of robots on land, namely slow walking gait and running and jumping gait. The most suitable gait can be selected according to different terrain environments.

### 3.1 Walking Gait Design

The walking gait is the most stable gait when the bionic duck robot moves forward on land, as shown in Fig. 4. When the robot moves forward, it always maintains three or more contact points with the land to ensure its stability. When the hip joint is in a horizontal position, and the thigh is kept in a vertical state, it is set to a standing posture.

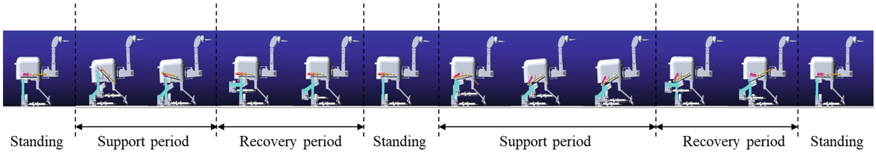



**Fig. 4.** Walking gait cycle

### 3.2 Running and Jumping Gait Design

As shown in Fig. 5, the running and jumping gait is adjusted accordingly on the basis of the slow walking gait. By changing the frequency of hip rotation, it turns faster than in a walking gait.

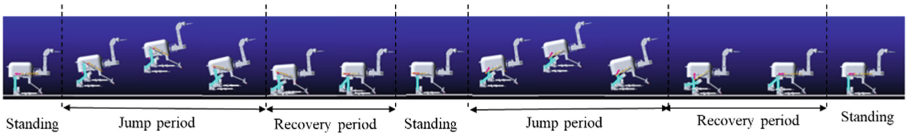



**Fig. 5.** Running and jumping gait cycle

## 4 Simulation and Evaluation of the Gait

### 4.1 Simulation Experiment of the Gait

There are two main gaits in the land gait, including the walking gait and the running and jumping gait. The step function is used in the simulation, which is shown in formula (1).

$$Step(x, x_0, h_0, x_1, h_1) \tag{1}$$

Among them, $x$ is represented as an independent variable, which can be time or any time function; $x_0$ and $x_1$ are the start and end values of the independent variable $x$, which can be constants, function expressions or design variables; $h_0$ and $h_1$ are the start value and end value of the step function respectively, which can be constants, function expressions or design variables.

### 4.2 Analysis of the Gait

This simulation design is designed with 4s as a cycle. In Adams, the kinematics and dynamics of the robot are collected through its detection module; in the post-processing module, the collected simulation data is graphically processed, including the front and near Distance, speed, torque of the robot, angular velocity of rotation, etc. After that, Matlab was used to fit the relevant data and find the relevant laws.

**Gait Analysis on Level Ground**

Under the condition of level ground, the influence on the forward distance was explored by changing the bending angle of the robot's back legs, in which the robot's front legs kept a 60° rotation with a frequency of 2.5 Hz. For the collected forward displacements corresponding to different angles of bending of the hind legs, use Matlab to perform curve fitting on the data points in different functional ways, as shown in Fig. 6(a). The fitted linear function expression is as follows:

$$f(x) = 0.8305x - 2.943 \tag{2}$$

According to different needs, the desired bending angle of the back leg can be found. Among them, when the robot adopts a walking gait on the level ground, the maximum distance that the robot can move in one step is about 105 mm.

Also, under the condition of level ground, the influence on the forward distance was explored by changing the bending angle of the robot's front legs, in which the robot's back legs kept a 120° rotation with a frequency of 2.5 Hz. The curve fitting results are shown in Fig. 6(b). The fitted Gaussian function expression is as follows:

$$f(x) = 101.4 * e^{(-((x-69.57)/53.86)^2)} \tag{3}$$

According to different needs, you can find the desired front leg bending angle.

Under the condition of level ground, the influence on the forward distance is explored by changing the rotation angle of the robot's hip joint, and other parameters remain unchanged. The curve fitting results are shown in Fig. 6(c). The fitted Gaussian function expression is as follows:

$$f(x) = 65.33 * e^{(-((x+20.36)/170.1)^2)} \tag{4}$$

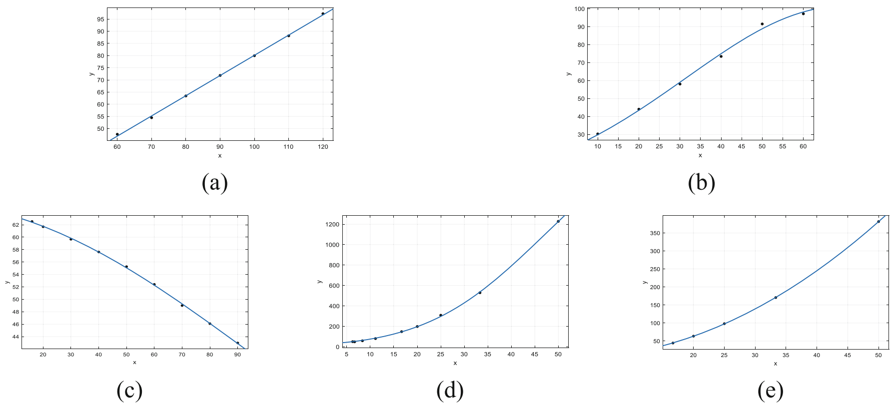
Still under the condition of level ground, the influence of the rotation frequency of the robot's hip joint on the forward distance is explored by changing the frequency of the robot's hip joint, in which the robot's front legs maintain a 40° rotation and the back legs maintain an 80° rotation. The curve fitting results are shown in Fig. 6(d). The fitted Gaussian function expression is as follows:

$$f(x) = 1774 * e^{(-((x-70.81)/34.28)^2)} \tag{5}$$

In addition, the jump height of the hip joint rotating robot at different frequencies is also measured, the curve fitting results are shown in Fig. 6(e). The fitted Gaussian function expression is as follows:

$$f(x) = 0.1529 * x^{1.998} + 2.768 \tag{6}$$

The corresponding rotation frequency can be selected according to the height of different obstacles so that the robot can complete the goal of traveling.




(a)The relationship between the bending angle of the back leg and the forward distance

(b)The relationship between the bending angle of the front leg and the forward distance

(c) The relationship between the hip rotation angle and the forward distance

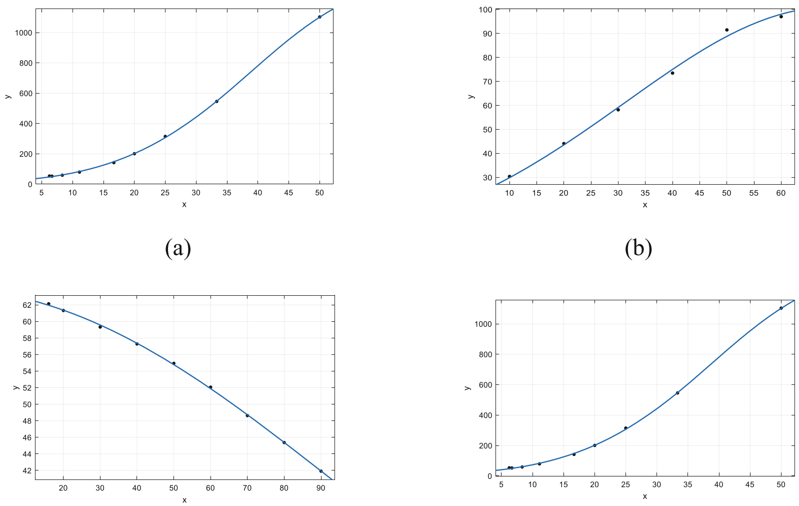
(d) The relationship between joint rotation frequency and the forward distance

(e) The relationship between joint rotation frequency and the jump height

**Fig. 6.** The relationship under level ground condition

**Gait Analysis on Slopes**

The gait simulation experiments of the bionic robotic duck were carried out on the inclined planes of 5°, 15° and 25°, respectively. Similar to the situation in the plane, the bending angle of the robot's back legs, the bending angle of the front legs, and the rotation frequencies of the hip and knee joints are adjusted respectively. And according to the data points obtained from the experiment, the corresponding fitting curve can be obtained (Fig. 7).




(a) (b)

(c) (d)

(a)The relationship between the bending angle of the back leg and the forward distance

(b)The relationship between the bending angle of the front leg and the forward distance

(c) The relationship between the hip rotation angle and the forward distance

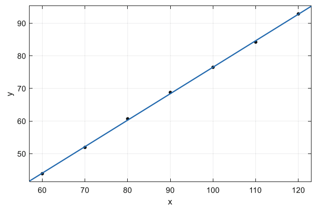
(d) The relationship between joint rotation frequency and the forward distance

**Fig. 7.** The relationship under 5° slope condition

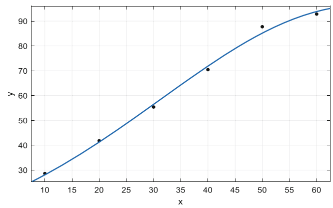
Under the condition of a 5° slope, the bionic duck robot can still walk as smoothly as on a level ground (Fig. 8).

The 15° slope has little effect on the robot's walking gait, but the running-jumping gait is not as stable as it is on a level ground (Fig. 9).

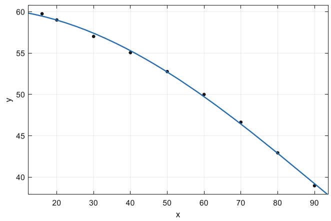
Under the condition of a 25° slope and the robot can walk smoothly, the bending angle of the robot's back legs is more severely limited, and the maximum bending angle is only 87°, but the bending angle of the front legs is still not affected. The angle does not cause the robot's center of gravity to change. In the running and jumping gait, the front distance is further reduced, and more energy is used to work against gravity.



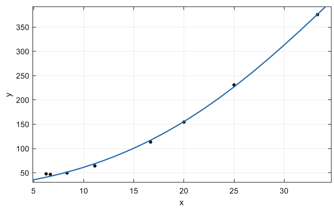

(a)




(b)




(c)




(d)

(a)The relationship between the bending angle of the back leg and the forward distance

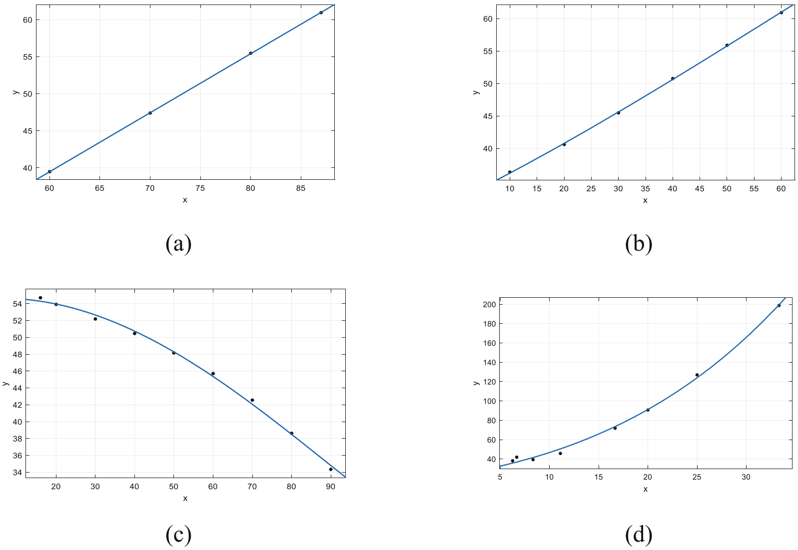
(b)The relationship between the bending angle of the front leg and the forward distance

(c) The relationship between the hip rotation angle and the forward distance

(d) The relationship between joint rotation frequency and the forward distance

**Fig. 8.** The relationship under 15° slope condition

It can be seen from the simulation results that the robot can complete the gait of walking, running and jumping on flat ground and slopes of different angles. When the robot encounters an obstacle, it can jump from the top of the obstacle by running and jumping to achieve the purpose of crossing the obstacle, and the appropriate rotation frequency can be selected according to the fitted functional relationship and the height of the obstacle. However, since the running and jumping gait is completely suspended in the air for a period of time after jumping, it will generate a large force on the joints when landing, so the mechanical structure of the bionic duck robot requires high strength. In addition, the running and jumping gait is to increase the frequency of joint rotation, so this requires the motor to provide a larger frequency. To sum up, the walking gait will be used as the common gait of the bionic duck robot. When the robot needs to overcome obstacles or walk quickly, it can choose the running and jumping gait.




(a)The relationship between the bending angle of the back leg and the forward distance

(b)The relationship between the bending angle of the front leg and the forward distance

(c) The relationship between the hip rotation angle and the forward distance

(d) The relationship between joint rotation frequency and the forward distance

**Fig. 9.** The relationship under 25° slope condition

## 5 Result

Based on the previously completed bionic duck robot model, this study designs two novel gaits, which enable the robot to walk in various complex terrain conditions. The designed gait was then simulated and evaluated using Adams software. According to the needs of different environments, robots can carry out a combination of various gaits to complete tasks such as land survey, exploration, search and rescue, and have broad research prospects. However, limited by the time limit of the research, the gait of the bionic duck robot designed in this research still needs to be improved and improved. In the follow-up research, other software needs to be used for simulation verification. Besides, only the land gait simulation has been achieved. In the future, the actual control experiments will be carried out.

## References

1. Wang, X., Song, W., You, M., et al.: Bionic single-electrode electronic skin unit based on piezoelectric nanogenerator. ACS Nano **2**(8), 8588–8596 (2018)
2. Zhong, J., Luo, M., Liu, X., et al.: Frog-inspire jumping robot actuated by pneumatic muscle actuators. Adv. Mech. Eng. **10**(6), 2–5 (2018)
3. Li, R., et al.: Computational investigation on a self-propelled pufferfish driven by multiple fins. Ocean Eng. **197**, 106908 (2020)

4. Roper, D.T., et al.: A review of developments towards biologically inspired propulsion systems for autonomous underwater vehicles. Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ. **225**(2), 77–96 (2011)
5. Richards, C.T., Clemente, C.J.: Built for rowing: frog muscle is tuned to limb morphology to power swimming. J. R. Soc. Interface **10**, 20130236 (2013)
6. Wang, Y., Zhu, J., Wang, X., et al.: Hydrodynamics study and simulation of a bionic fish tail driving system based on linear hypocycloid. Int. J. Adv. Robot. Syst. **15**(2) (2018)
7. Xing, H., et al.: Design, modeling and control of a miniature bio-inspired amphibious spherical robot. Mechatronics **77**(1), 102574 (2021)
8. Guo, S., Cao, S., Guo, J.: Study on decentralization of spherical amphibious multi-robot control system based on smart contract and blockchain. J. Bionic Eng. **18**(6), 1317–1330 (2021). https://doi.org/10.1007/s42235-021-00073-0
9. Zheng, L., Guo, S., Piao, Y., Gu, S., An, R.: Collaboration and task planning of turtle-inspired multiple amphibious spherical robots. Micromachines **11**, 71 (2020)
10. Shi, L., et al.: A fuzzy PID algorithm for a novel miniature spherical robots with three-dimensional underwater motion control. J. Bionic Eng. **17**(5), 959–969 (2020). https://doi.org/10.1007/s42235-020-0087-3
11. Yin, H., et al.: The vector control scheme for amphibious spherical robots based on reinforcement learning. In: 2021 IEEE International Conference on Mechatronics and Automation (ICMA), pp. 594–599 (2021)
12. Zhou, M., et al.: Trajectory tracking control for a biomimetic spherical robot based on ADRC. In: 2021 IEEE International Conference on Mechatronics and Automation (ICMA), pp. 319–324 (2021)
13. Shi, Q., et al.: Development of a small-sized quadruped robotic rat capable of multimodal motions. IEEE Trans. Robot. (2022). https://doi.org/10.1109/TRO.2022.3159188
14. Shi, Q., et al.: Implementing rat-like motion for a small-sized biomimetic robot based on extraction of key movement joints. IEEE Trans. Robot. **37**(3), 747–762 (2021)