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Design and Evaluation of Quadruped Gaits for Amphibious Spherical Robots*

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***Abstract*—Aiming at exploration tasks in complex amphibious environments, quadruped gaits were designed, implemented and evaluated for our amphibious spherical robot to enhance its adaptabilities to various terrains. A simplified locomotion model of the robot was established to analyze the walking process. Then three types of walk gait were implemented on the robotic platform using FPGA, which provided different stability and adjustable motion speeds to adapt various terrains. Furthermore, the attitude of the robot was estimated online using an inertial measurement unit. And the adopted gait was adaptively adjusted with the acquired compensation value, which ensured that the robot was able to walk on a slope no larger than 20 degrees. Experimental results indicated that the amphibious spherical robot was capable of walking stably with the designed gaits at different speeds in multiple environments, which enhanced its mobility and viability.**

I. INTRODUCTION

With the deepening of ocean exploitation activities, autonomous underwater vehicles have become an important tool for scientific research and marine exploitation [1]. As a special kind of autonomous mobile robot, spherical robots have advantages in environmental adaptability and robustness to disturbance, which made it suitable for investigation missions in complex ocean environments. And they have been successfully used in practical applications like security surveillance and disaster zone search [2]. In 2010, a spherical amphibious robot named Rotundus Groundbot was developed by Rotundus AB in Sweden [3]. Driven by a pendulum, it was able to roll in water, mud or snow at a speed of up to 10 km/h. In 2013, Chen *et al*. presented an omnidirectional spherical robot with no singularity [4]. Instead of using wheels or flywheels, it was driven by a driven ball and two orthogonally-mounted rollers which were installed inside the shell. In 2014, Halvorsen proposed a transformable spherical robot named MorpHex which was inspired by desert spiders [5]. It could roll on land at any direction or walk like a spider after transformation.

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Aiming at exploration applications in littoral regions, a novel amphibious spherical robot inspired by turtles was proposed by our team in 2012 [6]. Unlike most spherical robots which moved by rolling, it walked on land with four legs and swam in water with four vectored water jets. With good kinematic dexterity, it was capable of carrying micro-robots to complete delicate tasks in narrow spaces like pipes and rock crevices. In 2014, an improved version of the robot was proposed using sensors including a set of inertial sensors, an industrial camera, a ToF (Time of Flight) camera, etc. [7] However, all the studies mentioned above did not involve the gait design. And only a primitive walk gait was deployed on the robotic platform, which greatly limited the adaptability of the robot to amphibious environments.

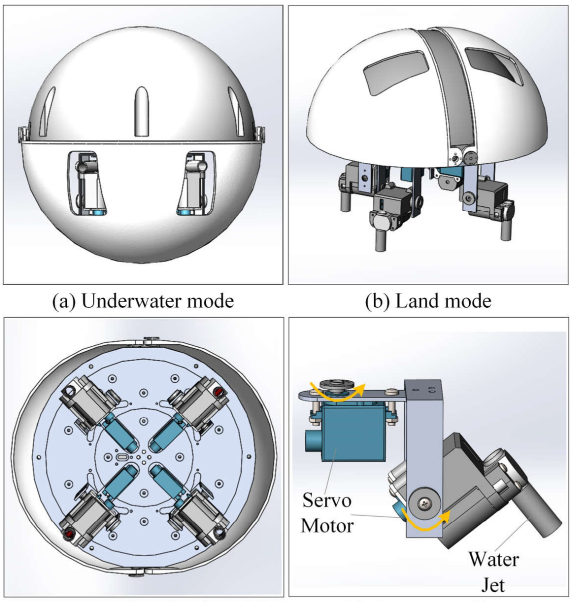
To make our amphibious spherical robot be capable of walking on various terrains like mud and slopes, a set of quadruped gaits were designed, implemented and evaluated for it in this paper. First, the locomotion model of the robot in walking mode was established and analyzed, which provide a theoretical reference for designing proper gaits. Second, three types of walk gait were realized on the robotic platform using FPGA (Field Programmable Gate Array). And the adopted gait and the walking speed of the robot were designed to be online adjustable for a better mobility and stability. Finally, the attitude of the robot was estimated online using the quaternion algorithm and MEMS inertial sensors including a gyroscope, an accelerometer and an electronical compass. Then the robotic gait was adaptively adjusted with the derived compensation value, which ensured a stable motion on a slope no larger than 20 degrees. Experimental results indicated that the amphibious spherical robot could walk stably at different speeds in multiple environments, which enhanced its mobility and viability.

The rest of this paper is organized as follows. The mechanical structure and the locomotion model of the amphibious spherical robot will be introduced in Section II. Design and implementation details of the gaits for the robot will be elaborated in Section III. The gait adjustment mechanism for stable motion on slopes will be described in Section IV. Experimental results will be provided in Section V. Section V will be conclusion and follow-up relevant research work.

II. LOCOMOTION MODEL OF AMPHIBIOUS SPHERICAL ROBOT

A. Mechanical Structure of Amphibious Spherical Robot

As shown in Figure 1, the amphibious spherical robot consisted of an enclosed hemisphere hull (250 mm in diameter) and two openable quarter-sphere shells (266 mm in diameter). Four legs, each of which was equipped with two servo motors and a water jet motor, were symmetrically installed in the lower hemisphere of the robot. Electronic devices and batteries were installed insider the hemisphere hull which was waterproof and protected them from collision. In land mode, the openable shells opened and the robot walked with four legs driven by servo motors. In underwater mode, the openable shells closed. Due to the counterweight design, the robot would suspend in water. And it was able to realize omnidirectional motions with four vectored water jets.



(a) Underwater mode (b) Land mode

(c) Bottom view (land mode) (d) Structure of legs

Figure 1. Mechanical structure of amphibious spherical robot

The motion principle of the robot's legs was as shown in Figure 1 (d) and Figure 2. Driven by the two servo motors, the upper joint and lower joint of a leg was able to rotate around the vertical axis and the horizontal axis respectively. The water jet motor was fixed in the lower joint and could generate a vectored thrust towards a specialized direction in water. In land mode, the walking motion of a leg consisted of four steps. First, the vertical servo motor rotated anticlockwise to lift the leg. Second, the horizontal motor rotated anticlockwise to stretch the leg. Third, the vertical servo motor rotated clockwise and the leg turned into stance phrase. Fourth, the horizontal motor rotated clockwise and then the body of the robot was pushed forward because of the ground friction force.

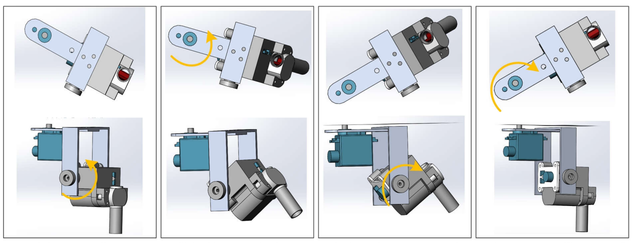

(a) Lift leg (b) Stretch leg (c) Hit ground (d) Push Ground

Figure 2. Walking principle of a leg

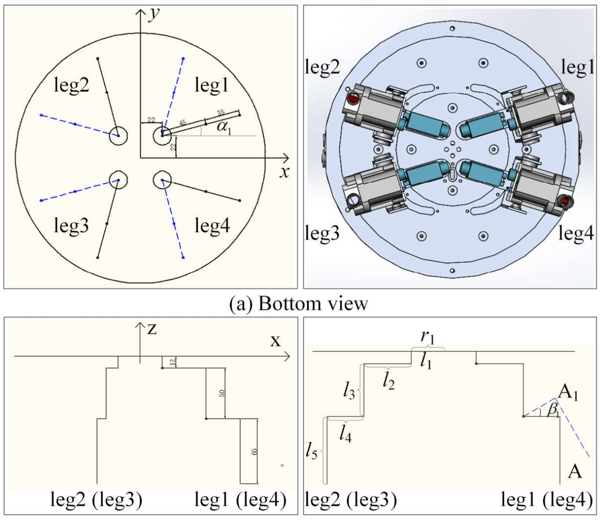
B. *Motion Analysis of Amphibious Spherical Robot*

Using the integrated amphibious actuating units, the robot was capable of realizing 6 DoF (Degree of Freedom) motions in water and walking on land flexibly. The robot adopted the spherical shape for a stable hydrodynamic model in water [8]. Given the unique mechanical structure and the potential application scenarios of the robot, a coarse gait system was designed and implemented on an AVR microcontroller (ATmega2560) for the prototype of the robot in 2013 [9]. A standard walk gait was adopted for stability of the robot, which had a duty factor of 0.75 and ensured that there were at least three legs in the stance phrase.

To make a quantitative analysis on the walking motion of the robot, a simplified mechanical model was established as shown in Figure 3. A three-dimension coordinate was built with the origin at the center of the robot. The black solid lines and the blue dash lines indicated the motion range of legs on the horizontal and vertical plane. $r_1=22\sqrt{2}$ mm, $l_1=12$ mm, $l_2=45$ mm, $l_3=50$ mm, $l_4=35$ mm and $l_5=65$ mm were determined by mounting dimensions or part dimensions of a leg. α_i and β_i respectively represented the horizontal and vertical rotation angle of the i-th leg. The position of leg1 could be gotten with A_1 and A, the coordinates of which were:

$$\begin{cases} x_A = r_1\cos(\frac{\pi}{4}) + (l_2 + l_4\cos\beta_1 + l_5\sin\beta_1)\cos\alpha_1 \\ y_A = r_1\sin(\frac{\pi}{4}) + (l_2 + l_4\cos\beta_1 + l_5\sin\beta_1)\sin\alpha_1 \\ z_A = -(l_1 + l_3 - l_4\sin\beta_1 + l_5\cos\beta_1) \end{cases} \quad (1)$$

$$\begin{cases} x_{A1} = r_1\cos(\frac{\pi}{4}) + (l_2 + l_4\cos\beta_1)\cos\alpha_1 \\ y_{A1} = r_1\sin(\frac{\pi}{4}) + (l_2 + l_4\cos\beta_1)\sin\alpha_1 \\ z_{A1} = -(l_1 + l_3 - l_4\sin\beta_1) \end{cases} \quad (2)$$

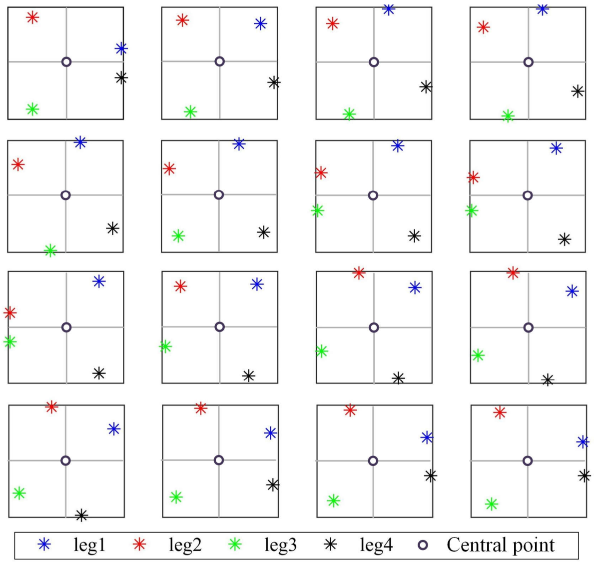


(a) Bottom view

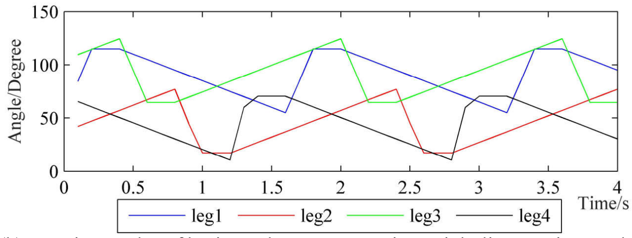
(b) Left view

Figure 3. Simplified mechanical model of robotic legs

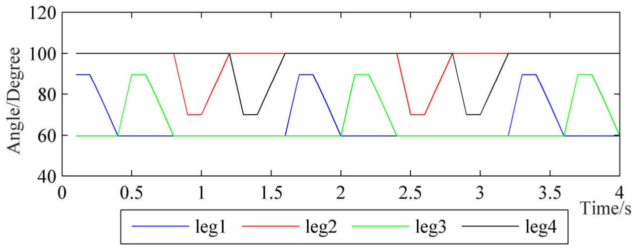
When the robot walked in a straight line, the four legs would move in the sequence of "leg1–leg3–leg2–leg4". And each leg would follow the operation sequence shown in Figure 2 (a). So a robotic walking cycle could be divided into 16 steps. The footholds of each step were as shown in Figure 4 (a). In any step, three legs were in the stance phrase and only a leg was in the swing phrase. And the gravity center of the robot, which was gradually pushed forward to realize the robot movement, remained inside the triangle formed by footholds of the three legs in the stance phrase. Referring to equation (1) and (2), the rotation angles of the servo motors were as shown in Figure 4 (b) and (c). The walk gait could be realized by properly configuring timers of a microcontroller which would output PWM (Pulse-Width Modulation) signals in order.



(a) Foothold sequence of the robot in straight line moving mode



(b) Rotation angles of horizontal servo motors in straight line moving mode



(c) Rotation angles of vertical servo motors in straight line moving mode

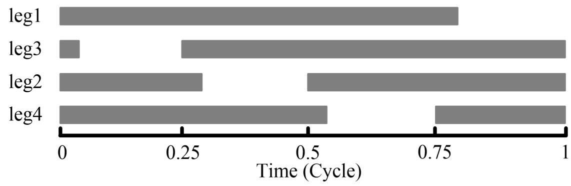
Figure 4. Control parameters of the robot in straight line moving mode

The porotype gait system has basically meet motion requirements of our amphibious spherical robot. However, it has two drawbacks. On the one side, there was only a simple and static gait type. Consequently, the robot could only walk on flat ground at a median speed, which limited the adaptability of the robot to rough terrains. On the other side, the hardware platform was centered with an AVR microcontroller, which made it not easy to implement diversified gaits. To enhance the mobility of the robot, it is necessary to design and implement an improved gait system on the basis of the locomotion model.

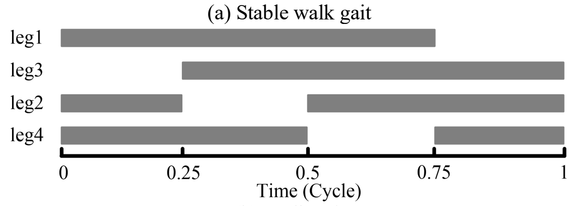
III. Design and Implementation of Gait System

A. Gait Design

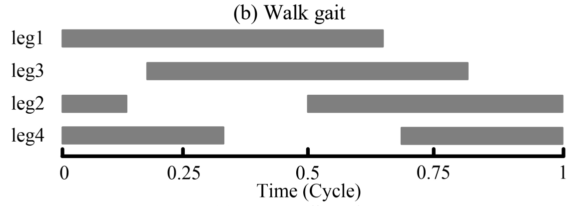
Generally, there are five types of gait that commonly used in quadruped robots: walk, trot, pace, bound and gallop [10]. The gallop gait and the bound gait need a strong driving force. So they are not feasible for our spherical robot which has limited power resources. The pace gait will lead to an obvious rolling motion of the robot body [11]. Because our robot has a symmetrical structure, that will greatly influent the stability. The walk gait and the trot gait are suitable for our robot. Considering that the potential working environment of the robot may be adverse, the walk gait was adopted in the design to ensure stability. And parameters of the walk gait, including the duty factor and the gait cycle, were adjusted to design various types of gaits for different scenarios.



(a) Stable walk gait



(b) Walk gait



(c) Fast Walk Gait

Figure 5. Sequence chart of the designed gaits

TABLE I. Overview of the Designed Gaits

Parameters	***Stable Walk Gait***	***Walk Gait***	***Fast Walk Gait***
Frequency of PWM	100 Hz	100 Hz	100 Hz
Time of a Stride	0.4 s	0.4 s	0.4 s
Time of a Step	0.1 s	0.1 s	0.1 s
Steps of a Cycle	20	16	12
Time of a Cycle	2 s	1.6 s	1.2 s
Maximum Legs Landing on Ground	4	3	3
Minimum Legs Landing on Ground	3	3	2
Unstable Time	0 s	0 s	0.204 s
Very Stable Time	0.1 s	0 s	0 s
Stability	High	Normal	Low

The sequence charts of the designed walk gaits were as shown in Figure 5. The duty factors of the three gaits were respectively set to 80%, 75% and 66.6%. The four legs also moved in the sequence of "leg1–leg3–leg2–leg4" and followed the operation order in Figure 2. As shown in Table I, there were three or four legs in the stance phrase when adopting the stable walk gait. And there were two or three legs in the stance phrase when adopting the fast walk gait, which may result in instabilities. Because there were four more steps in a cycle of the stable walk gait, the robot would walk 25% slower. Correspondingly, the robot would walk 25% faster when adopting the fast walk gait. It is necessary to adopt the stable walk gait when the robot walked on rocky or mud ground. The standard walk gait was suitable for movement on brick floor or on grass field. And the robot was capable of moving at a fast speed using the fast walk gait in emergency or on ideal ground.

B. Gait Implementation

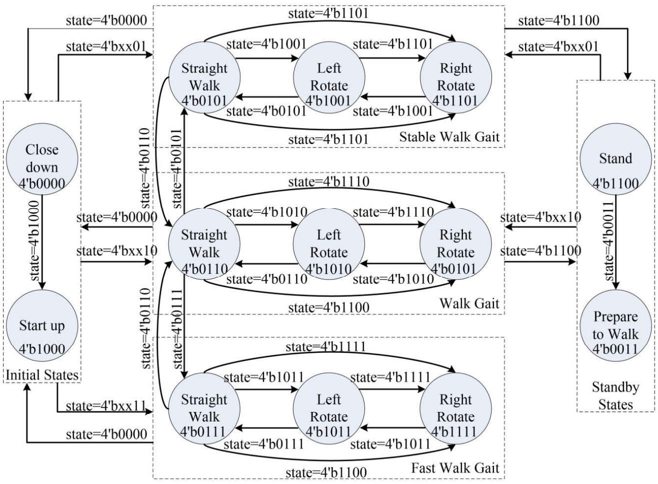


Figure 6. State transition diagramof the FPGA-based gait system

The improved version of the robot was fabricated around a Xilinx Zynq-7000 SoC, and the designed gaits were implemented on the FPGA section of the SoC with hardware description languages. The designed digital logics were packed as an IP core connecting to the ARM section of the SoC through an AXI (Advanced eXtension Interface) bus. And the robot control program running on the ARM-Linux system configured the work status of the system by accessing the 4-bit state register. The state transition diagram of the gait system was as shown in Figure 6. After starting up, it could choose a type of gait (stable walk gait, walk gait or fast walk gait) and select the motion direction (walking straight, turning left or turning right). When encountering interested things or scenarios, the robot could stop movement and then stand in the current position. Given that the robot could not stand steady with two legs in the stance phrase, the fast walk gait was only used for racing and could not switch into standby states directly.

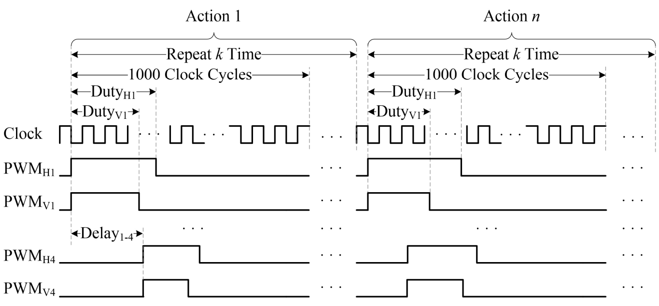


Figure 7. Sequence chart of PWM waves for servo motor control

The output signals of the gait system were as shown in Figure 7. Eight PWM waves were generated with timers and frequency dividers to control of servo motors driving robot legs. In the standard scenario, the frequency of the clock signal and the PWM waves were 100MHz and 100Hz respectively. Different types of gait were realized by adjusting the delay time between PWM signals for different legs (i.e. $\mathrm{Delay}_{1\text{-}4}$). And k, which was the number of output pulses in a leg operation, could also be modified by the control program to adjust the rotation speed of motors and the walking speed of the robot. Because the robot has a symmetrical body and a slow motion speed, it is more stable to realize speed regulation using the same gait with different parameters than designing many gaits.

IV. Adaptive Adjustment Mechanism of Gait

A. Motion Analysis of Slope Climbing

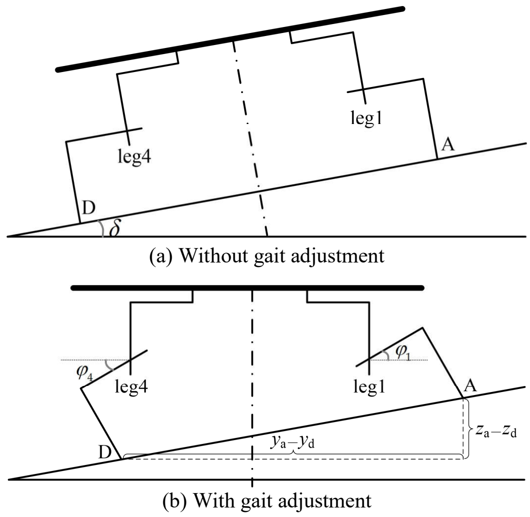


Figure 8. Motion analysis of slope climbing

The robot was able to walk on uneven ground with the gait system designed in Section III. However, it could not yet climb a slope steadily. As shown in Figure 8 (a), the gravity center of the robot would rise and fall periodically if it tried to climb a slope without adjusting the gait. That would impact the normal work of devices install inside the robot body. More than that, the robot may fail to move with continues slips.

As shown in Figure 8 (b), the gravity center of the robot was lowered by adjusting the original gait with adjustment angles, which would increase the stability of the robot platform. Suppose that leg1 and leg4 were in the initial position, then coordinates of A and D could be represented as:

$$\begin{cases} x_A = r_1\cos(\frac{\pi}{4}) + \left[l_2 + l_4\cos(\beta_1+\varphi_1) + l_5\sin(\beta_1+\varphi_1)\right]\cos\alpha_1 \\ y_A = r_1\sin(\frac{\pi}{4}) + \left[l_2 + l_4\cos(\beta_1+\varphi_1) + l_5\sin(\beta_1+\varphi_1)\right]\sin\alpha_1 \\ z_A = -\left[l_1 + l_3 - l_4\sin(\beta_1+\varphi_1) + l_5\cos(\beta_1+\varphi_1)\right] \end{cases} \quad (3)$$

$$\begin{cases} x_D = r_1\cos(-\frac{\pi}{4}) + \left[l_2 + l_4\cos(\beta_4+\varphi_4) + l_5\sin(\beta_4+\varphi_4)\right]\cos\alpha_4 \\ y_D = r_1\sin(-\frac{\pi}{4}) + \left[l_2 + l_4\cos(\beta_4+\varphi_4) + l_5\sin(\beta_4+\varphi_4)\right]\sin\alpha_4 \\ z_D = -\left[l_1 + l_3 - l_4\sin(\beta_4+\varphi_4) + l_5\cos(\beta_4+\varphi_4)\right] \end{cases} \quad (4)$$

where $\beta_1=\beta_4=0$, $\alpha_1 = \pi/4$ and $\alpha_4 = -\pi/4$. Because $\overrightarrow{AD}$ was vertical with the axis x, coordinates of A and D should satisfy the condition:

$$z_A - z_D = (y_A - y_D)\tan\delta \quad (5)$$

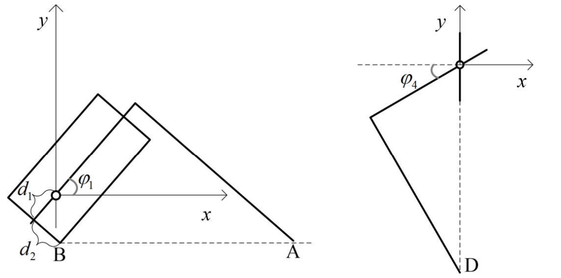
By solving equation (3), (4) and (5), the adjustment angle could be acquired. Limited by the mechanical structure of the legs and the load of the robot, the robot could only climb gentle slopes. The critical case was as shown in Figure 9. The coordinates of A, B and D could be represented as:

$$\begin{cases} x_A = l_4\cos\varphi_1 + l_5\sin\varphi_1 \\ y_A = l_4\sin\varphi_1 - l_5\cos\varphi_1 \end{cases} \quad (6)$$

$$\begin{cases} x_B = \sqrt{d_1^2 + d_2^2} \cdot l_4\cos\left(\varphi_1 - \arctan\frac{d_2}{d_1}\right) \\ y_B = \sqrt{d_1^2 + d_2^2} \cdot l_4\sin\left(\varphi_1 - \arctan\frac{d_2}{d_1}\right) \end{cases} \quad (7)$$

$$\begin{cases} x_D = l_4\cos(\pi + \varphi_4) - l_5\sin(\pi + \varphi_4) \\ y_D = l_4\sin(\pi + \varphi_4) + l_5\cos(\pi + \varphi_4) \end{cases} \quad (8)$$

where d_1=7.5mm, d_2=30mm and x_A=x_B. The acquired maximum adjustment angles of leg1 and leg4 were φ_1=45° and φ_4=24°. Consequently, the robot was capable of climbing slopes no larger than 20°.



(a) Critical state of leg1 (b) Critical state of leg4

Figure 9. Critical case of slope climbing

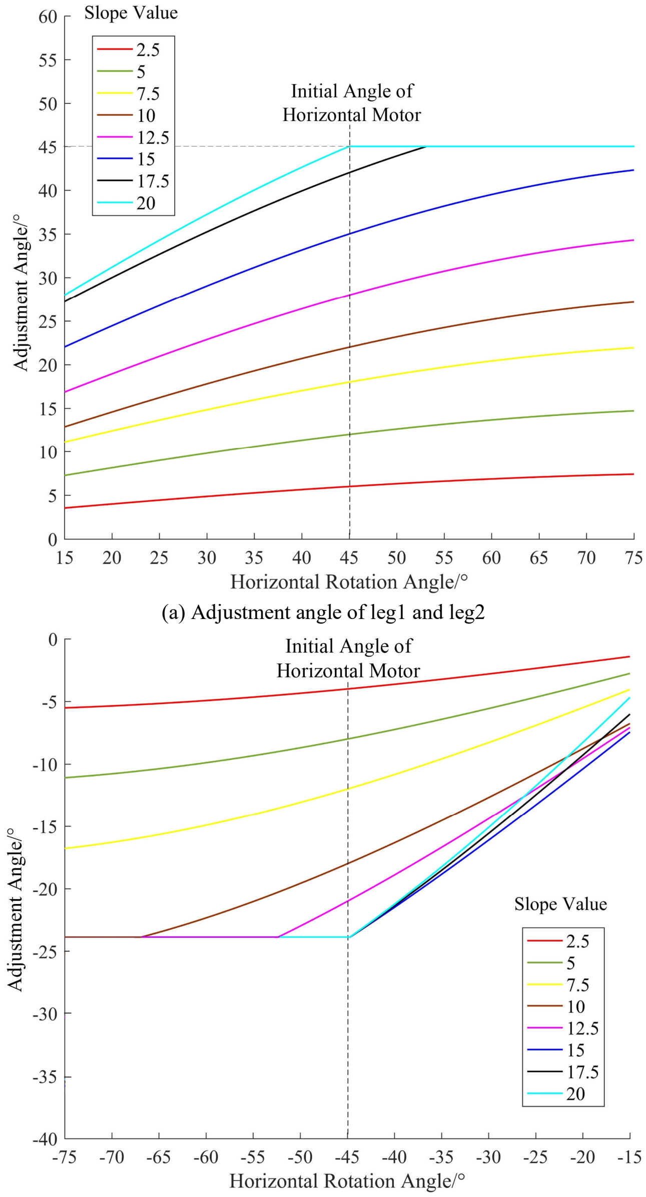
B. Gait Adjustment Mechanism

In the reference [12], an attitude estimation system was designed for the robot using the quaternion algorithm and a set of MEMS inertial sensors. A gyroscope (ITG-3200) was adopted to monitor the motion status of the robot; and an accelerometer (ADXL345) and an electronical compass (HMC5883L) were adopted to correct the measurement results. To measure the slope value δ, the attitude estimation system would estimate the pitch angle of the robot periodically and then try to solve the adjustment angles online with equation (3), (4) and (5).

TABLE II. PRACTICAL ADJUSTMENT ANGLES IN THE INITIAL STATE

Slope Value	Leg1	Leg2	Leg3	Leg4
0°	0°	0°	0°	0°
2.5°	6°	-4°	-4°	6°
5°	12°	-8°	-8°	12°
7.5°	18°	-12°	-12°	18°
10°	22°	-18°	-18°	22°
12.5°	28°	-21°	-21°	28°
15°	35°	-24°	-24°	35°
17.5°	42°	-24°	-24°	42°
20°	45°	-24°	-24°	45°

The motion model established in Section III B assumed that the slope value was constant. But in practice, the slope surface is often fluctuant. To avoid the robot flipping over on the slope, a slight disturbance was added to the slope value δ. As shown in Table II, the adjustment values were selected to make the error value of equation (5) minimum. Using the adjustment angles in the initial state of horizontal servo motors, the adjustment angles of legs on different slopes could be acquired as shown in Figure 10. A look-up table was created in accord with the curves. And it was deployed on the FPGA-based gait system to adjust the motion of legs on-line, so that the robot could climb slopes successfully.



(a) Adjustment angle of leg1 and leg2

(b) Adjustment angle of leg3 and leg4

Figure 10. Adjustment angles of legs on different slopes

V. EXPERIMENTS AND EVALUATION

To evaluate the performance of the designed gait system, experiments were conducted on flat ground and slight slopes. NDI Polaris Vicra, which was a real-time three-dimensional measurement system with the precision of 0.5 mm, was used to monitor the displacement of the robot.

In the ground test phrase, the robot was configured to move in straight line with different types of gaits and speed grades. The speed of the robot was as shown in Figure 11. The robot was able to walk at a speed up to 8.5 cm/s (0.34 body length per second). The fast walk gait provided an average speed 12.1% faster than the normal walk gait. And the motion speed of the stable walk gait was 14.3% slower on average than that of the normal walk gait.

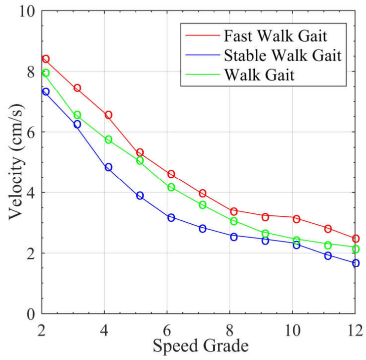
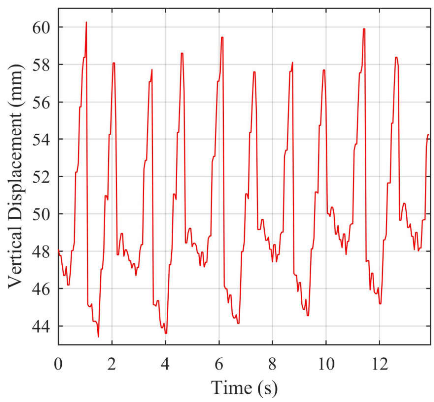
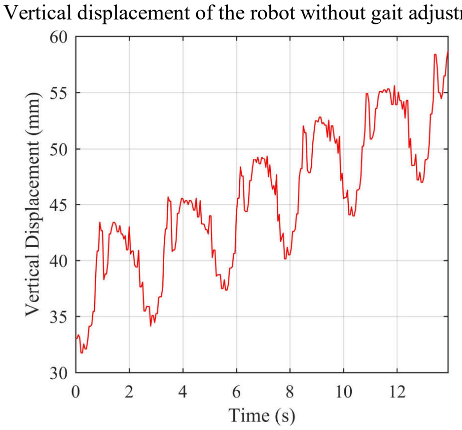


Figure 11. Speed evaluation on flat ground

In the slope test phrase, the robot was configured to climb a slope of five degrees. And the vertical displacement of the robot was as shown in Figure 12. Without gait adjustment, the amplitude of fluctuation of the robot body was nearly 20mm; and the robot kept slipping on the slope. After adding gait adjustment, the amplitude of fluctuation of the robot body was reduced to less than 10mm. And the robot climbed up the slope steadily. So it was proved that the gait adjustment mechanism could meet demands in both stability and mobility.



(a) Vertical displacement of the robot without gait adjustment



(b) Vertical displacement of the robot with gait adjustment

Figure 12. Speed evaluation on a slope of five degrees

VI. CONCLUSION

Focus on robotic applications on various terrains, quadruped gaits were designed, implemented and evaluated for our amphibious spherical robots in this paper. Firstly, a simplified locomotion model of the robot in walking mode was established and analyzed. On this basis, three types of walk gait were designed to provide steady movement methods for the robot. And a FPGA-based gait system was designed and implemented, which was capable of providing various motion speeds in different scenarios. Furthermore, an online adjustment mechanism was designed on the basis of attitude estimation, so that the robot could climb up slopes successfully. Experimental results indicated that the amphibious spherical robot could walk stably at different speeds in multiple environments. Benefited from the gaits designed in this paper, the mobility and viability of the robot was enhanced.

The study may provide valuable reference for the design of small-scale quadruped robots and amphibious robots. But it also has some drawbacks. For example, the power consumption of robot in different motion modes was not considered yet. Our future work will focus on the energy saving design of the gait system.

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