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Dynamic Gait Analysis of a Multi-functional Robot with Bionic Springy Legs

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***Abstract* - Developing efficient movement gaits for quadruped robots has intrigued investigators for years. Trot gait, pace gait, as fast and stable dynamic locomotion gaits, have been widely used in robot control. Therefore, the purpose of this paper is to control an amphibious spherical quadruped robot to achieve these two gaits. Firstly, this paper references the trot gait and pace gait pattern of quadruped creature and identifies the order and the law of quadruped bionic robot. Secondly, based on the virtual leg techniques and the Spring-Loaded Inverted Pendulum (SLIP) model, a simplified dynamic analysis model is established, and the relationship between force and motion is obtained by using Lagrange dynamics equation. Thirdly, by adjusting the force and moment of the joint of robot, continuous and stable trot gait and pace gait motion are simulated in ADAMS platform. Finally, a comparison of theoretical calculations and simulation results demonstrated the robot's potential and its feasibility of trot gait and pace gait.**

***Index Terms* - Amphibious Spherical Quadruped Robot; SLIP Model; Dynamic Gait; Gait Control.**

I. INTRODUCTION

Modeling and control of legged robots has long been a challenging issue in the control community. One of the advantages of legged locomotion is that legged robots usually tolerate much larger discontinuities in the terrain than that of wheeled robots. Among legged robots, a widely investigated class is the quadruped robot, which is expected as an attractive machine of transportation in a complex environment. Early quadruped robots were usually walking in static gait with controlling the center of mass from the support polygon formed by the legs in contact with the ground. However, when the robot walks or runs faster, the inertial force on robot could not be neglected, and the traditional control approach could not be used in this case. An extensive literature is currently available on the issues of quadruped robots such as modeling, adaptive gait pattern control, gait transition, and learning locomotion.

The quadruped presents a rich set of running gaits such as trot, pace, gallop and bound. To date, numerous studies have shown that trot gait and pace gait are the preferred gait of quadruped robots with respect to the viewpoint of high speed, energy efficiency and ground adaptability. With reference to the concept introduced by Raibert et al [1], grouped legs can be represented by one virtual leg to simplify its walking design. Consequently, the trot gait design to the quadrupeds usually can be equivalent to the one for bipeds. Therefore, SLIP or other simplified models developed from SLIP were widely used in legged robot research [2]. Orin and Palmer in the Ohio State University realize a quadruped robot KOLT running in the sagittal plane and presents a fuzzy control strategy based on the SLIP model. They have regulated the pitch motion by redistributing the forces exerted on the forelimb and hindlimb and the roll motion by controlling the driving torques on the joints, and developed a banked turning control algorithm to successfully execute high-speed turns over a range of velocity and turning rates [3]-[4]. The research of National Technical University of Athens focused on pronking gait of two-legged robot model which could be easily applied to the trotting gait. It showed that setting the difference of the angles with which the back and front legs strike the ground is sufficient for controlling the pitching motion in the pronking gait [5].

Researchers have also studied gait transition algorithms based on common positions. Ma et al. studied a gait transition method to realize omnidirectional static walking [6]. Their method achieved gait transition within the number of steps as least as possible by designing the feet to have common positions before and after gait transition. Similarly, Masakado et al. proposed a gait transition method similar to the common foot position [7]. They improved Ma's method and it could start from any leg arrangement in a standard gait such as crawling gait. The currently domestic research on quadruped robot gait is almost limited to the walking gait which is enable body in a statically stable and trot gait which is a kind of dynamical gait, and hardly research exists there on other dynamical gaits.

In our previous study, in an attempt to address some of the limitations of previous amphibious robot designs, we created a three-dimensional (3D) printing technology-based amphibious spherical robot with transformable composite propulsion mechanisms [8]-[18]. Although our previous researches have demonstrated its stable static walking gait, and the results showed good performance of adaptability and stability, its walking speed is too small while the robot is walking on the ground with good road conditions. Consequently, the purpose of this paper is to control our robot

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achieve two dynamic gaits with higher speed, including trot gait and pace gait.

This paper is organized as follows. Section II describes the basic theory and gait generation of our amphibious spherical robot. Section III is dedicated to detail the mathematical dynamic analysis of robot based on SLIP model, and the relationship between force and motion is obtained from Lagrange dynamics equation. Section IV simulated continuous trotting and pacing in ADAMS also with some theoretical calculations comparison. Finally, Section V presents some conclusions and future work.

II. Dynamic Gait Plan of Robot

Quadruped animals have different gaits to fit for different terrains and speeds, like walking gait, trot gait, pace gait, bound gait and gallop gait. Walking gait is a common static gait in robot control, in which one leg lifts while others support the body, and our previous researches have demonstrated its adaptability and stability. Here we mainly focus on two dynamic gaits analysis --- trot gait and pace gait.

A. Trot Gait

Trot is a common gait in robot motion control, in which the diagonal legs lift simultaneously while the other two legs are supporting the body. Details of the trotting are shown in Fig.1, from the initial state (a four-footed support state) to the final state (corresponding to sixth state-motion left front leg and right back leg lift and swing while the other two legs are in a support state). Fig.2 shows the standard trotting diagram of amphibious spherical robot, in which the shadow portion indicates that the leg is in the stance state at the moment. As shown in Fig.2, in the process of robot's movement with trot gait, the LF leg and the RH leg have the same movement state, as the RF leg and the LH leg have the same movement state.

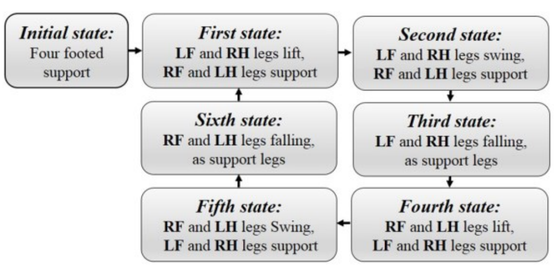


Fig.1 Trot gait of amphibious spherical robot within one cycle

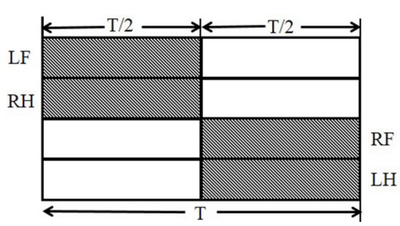


Fig.2 The phase relationship in trot gait

B. Pace Gait

Pace gait is another dynamic common gait in robot motion control, in which two legs in the same side always maintain consistent movement. Details of the pacing are shown in Fig.3, from the initial state (a four-footed support state) to the final state (corresponding to sixth state-motion left front leg and left back leg lift and swing while the other two legs in the right side are in a support state). Fig.4 shows the standard pacing diagram of amphibious spherical robot. As shown in Fig.2, when the robot moves with pace gait, the LF leg and LH leg have the same movement state, as the RF leg and the RH leg always have the same movement state.

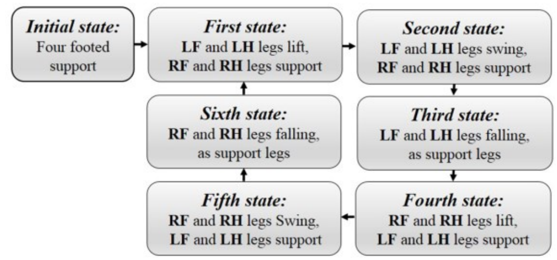


Fig.3 Pace gait of amphibious spherical robot within one cycle

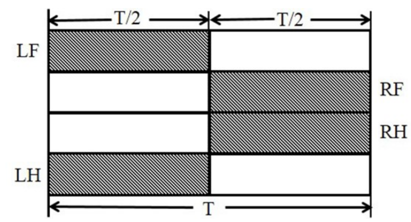


Fig.4 The phase relationship in pace gait

In Fig.1-Fig.4, T refers to the period of motion, LF is the left fore leg, LH is the left hind leg, RF is the right fore leg and LH is the right hind leg.

III. Dynamic Analysis of Amphibious Spherical Robot

A. Virtual leg technique

The technique of virtual leg is a kind of structure simplification of the gait with respect to a pairs of legs of quadruped robot, and the function of simplified virtual legs are fully consistent with the previous legs. It is the virtual legs that have the same force of the physical legs on the ground, and have the same force and torque of the body also with a concerted action. Consequently, some parameters of the virtual leg, like mass, moment of inertia, elastic link, elastic stiffness, damping coefficient, etc. is twice as much as a single physical leg [19]. Since the trot gait and pace gait use the legs in pairs, based on the concept of virtual leg, our quadruped robot can be treated as an equivalent biped robot.

SLIP model is a commonly used analytical model for the study of legged robots [20]. A variety of experiments and researches have proved that the dynamics of the SLIP model could fit well with the experimental results of biological motion, by setting the reasonable parameters of SLIP model and initial conditions, which can be used to represent some motion data like human walking, dog jumping and some other diagonal movement approximately. Fig.5 shows the equivalent diagram of SLIP model. From the Fig.5, the quadruped robot can be treated as an equivalent SLIP model, and the biped robot also has its equivalent SLIP model, so the quadruped robot can be finally equivalent to a biped robot.

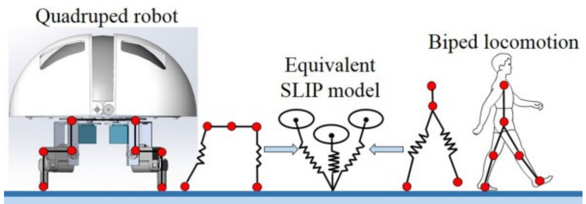


Fig.5 Equivalent diagram of SLIP model

B. *Mathematical analysis of trot gait*

Throughout the trotting cycle, the legs contact the ground under gravity and retract passively with the spring compressed from initial length. When the springs of the legs are in recovery state, the desired thrust is exerted on the legs to make the robot bounce. After one pair of diagonal legs lift off the ground, it would retract instantly while the other pair would protract for landing. Based on the concept of virtual leg, our amphibious spherical robot can be treated as an equivalent biped robot [21]-[22], some equivalent details as Fig.6 shows.

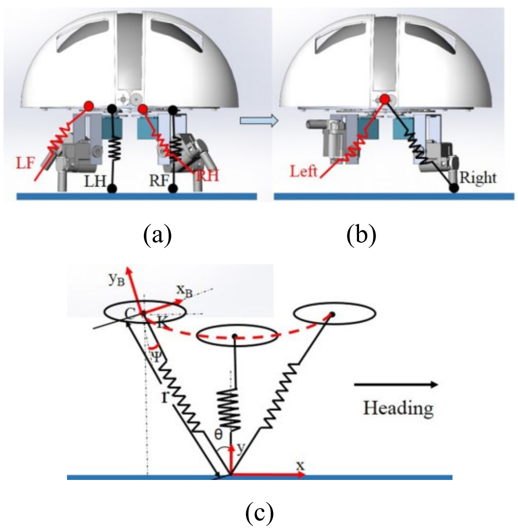


Fig.6 Simplified SLIP model for the trot gait

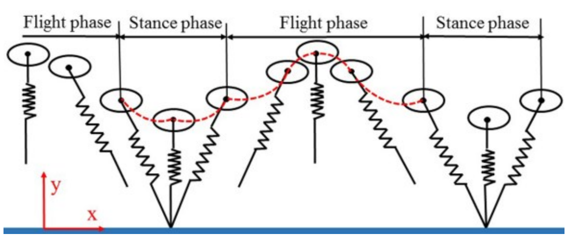


Fig.7 Schematic diagram of SLIP movement

Where m is the mass of body, J is the inertia, C is the centroid of body, K is the elastic coefficient of spring, r is the length of leg, r_0 is the initial length of leg, c is the damping. {x, y} is the Global Coordinate System, the positive direction of x is the forward direction, and the negative direction of y is the direction of gravity, in which the proper body fixed coordinate system (x_B, y_B) has its origin C located in the geometric center of robot, α is the pitching angle, τ is driving torque, and θ is the angle with respect to the vertical plane.

The process of the basic motion of SLIP system as shown in Fig.7 consists of periodic flight phase and stance phase intersection. The flight phase is defined as a system of which equivalent spring leg does not touch the ground. The stance phase is defined as a system of which equivalent spring leg touch the ground, and then the contact force of the equivalent spring leg is larger than zero. In the control of our amphibious spherical robot, we only consider and analysis the dynamic model of robot in its stance phase.

Based on the SLIP model as shown in Fig. 7, the body is connected with a springy leg. Assuming that the mass of the leg is negligible, the dynamics of the SLIP model is given by [23]-[24]. In the stance phase, the contact between the leg and the ground is considered to have no relative slip. The polar coordinate system is established along the length of the equivalent spring leg and the vertical leg. By using the Lagrange dynamic function, the dynamic equation in the stance phase is established, and the kinetic energy of robot can be expressed as:

$$E_k = E_k^{\ T} + E_k^{\ R} \tag{1}$$

E_k^T is the average kinetic energy of the robot, E_k^R is the rotational kinetic energy of the robot , considering the pitching motion of the body.

$$E_k^{\ T} = \frac{1}{2} m\dot{r}^2 + \frac{1}{2} m(r\dot{\theta})^2 \tag{2}$$

$$E_k^{\ R} = \frac{1}{2} J\dot{\alpha}^2 \tag{3}$$

The potential energy of the robot in the stance phase, including gravity potential energy and elastic potential energy of the spring, can be expressed as:

$$E_P = mgr\cos\theta + \frac{1}{2}k(r_0 - r)^2 \tag{4}$$

The Lagrange dynamics equation can be expressed as:

$$L = E_k - E_P \tag{5}$$

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} = Q \tag{6}$$

To define the generalized coordinate system is $q = [r, \theta, \alpha]$, where Q is the generalized force acting on the robot. For the SLIP system, in the stance phase, we only consider the spring damping force $-c\dot{r}$ and the joint driving torque τ, so the value of the Q is determined by:

$$Q_i = \tau \frac{\partial(\theta - \alpha)}{\partial q_i} - c\dot{r}\frac{\partial r}{\partial q_i} \qquad (k = 1,2) \tag{7}$$

Then the dynamic equation of the system can be further expressed as:

$$\begin{cases} \dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{r}} - \dfrac{\partial L}{\partial r} = -c\dot{r} \\ \dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{\theta}} - \dfrac{\partial L}{\partial \theta} = \tau \\ \dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{\alpha}} - \dfrac{\partial L}{\partial \alpha} = -\tau \end{cases} \tag{8}$$

Correspondingly, the dynamic equations are given by the following:

$$\begin{cases} m\ddot{r} - m\dot{\theta}^2 r + mg\cos\theta - k(r_0 - r) = -c\dot{r} \\ 2mr\dot{r}\dot{\theta} + mr^2\ddot{\theta} - mgr\sin\theta = \tau \\ J\ddot{\alpha} = -\tau \end{cases} \tag{9}$$

For our robot, each leg is composed of a hip joint and a knee joint. Consequently, the driving torque of these two joints can be calculated to give some references for the selection of servo motor. In addition, the dynamic analysis and control strategy of pace gait is similar to the trot gait. Some dynamic analysis of pace gait are presented in other studies, therefore, we will not repeat them not.

IV. Dynamic Simulation and Discussion

In order to achieve stable and coordinated movement of robot, it is necessary to implement body control algorithm based on the SLIP model. The forward and lateral running velocity of robot with straight legs could be regulated by setting the forward and lateral angle on hip joints and knee joints. After determining the control strategy of robot, firstly, a 3D model of the robot was established and simplified in Solid-Works. Second, the simplified 3D model of the robot was imported into ADAMS. Given that the simplified 3D model of the robot will lose some parameters, it was necessary to redefine these parameters. Moreover, some related constraints, motion function, control variables and sensor information and forces must be applied to the virtual prototype model. Then the simulation results could be viewed in the post-processing module of ADAMS.

A. Simulation results of trotting

In Adams post-processing module, the animation graph of trotting could be obtained during the simulation process. Fig.8 shows some snapshots that the amphibious spherical robot completes a cycle of trotting. The positive direction of x is the forward direction, and the negative direction of z is the direction of gravity.

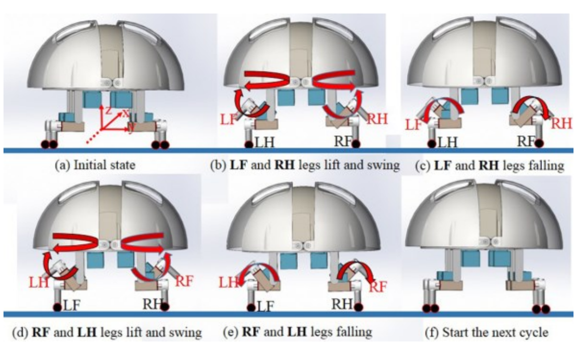
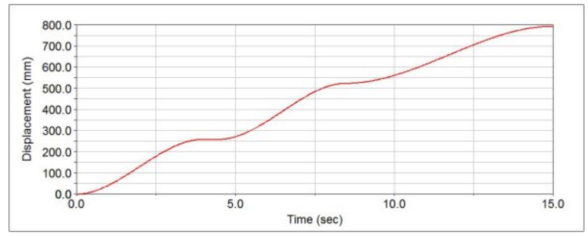
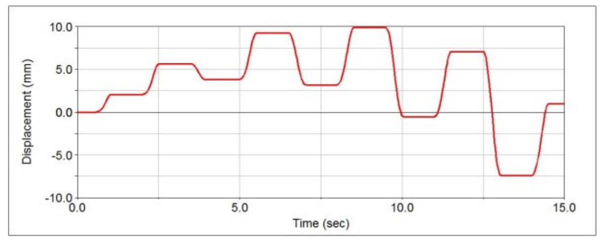


Fig.8 The process of trotting in one cycle

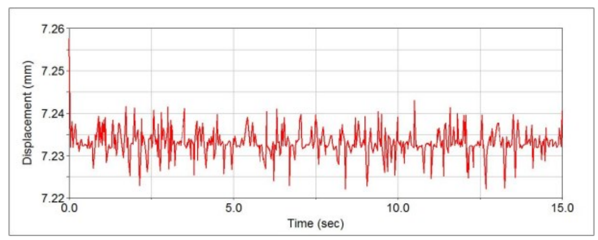
Through the post-processing function of ADAMS/View, and after determining the angle of hip joints and knee joints, the moving trajectory of the centroid of the robot in three different directions were obtained. These movement trajectories also demonstrate the velocity and stability of the robot (Figs 9-11).



(a) X axis direction.



(b) Y axis direction.



(c) Z axis direction.

Fig 9. Displacement curve of the centroid in different directions.

In Fig.9 (a), we see that the change of the centroid displacement in the X direction is stable, and the gradient remained close to 0.053. In this curve, the gradient represents the velocity of the robot. Thus, this result showed that the velocity of the robot remained stable in the process of trotting and was basically maintained at around 0.053 m/s. Fig.9 (b) shows the centroid displacement curve in the Y direction; this displacement curve indicates the deviation of the robot in its horizontal direction. Left and right deviation can occur during robot trotting; the maximum deviation of the robot was approximately 0.01 m. Consequently, despite some deviations during trotting, the final trajectory was still basically along the initial setting. The displacement curve of the centroid in the Z direction represents the phenomenon of the bumping up and down of the robot; the results showed that the maximum translocation is 0.007 m; because the height of the amphibious spherical robot is approximately 0.27 m, 0.007 m is about 2.5% (Fig.9 (c)). Consequently, jumping and sudden changes should not appear, and the robot can implement stable trotting.

In order to verify the dynamic characteristics of the robot with trot gait, we selected some sampling points of rotation angle of hip joint and knee joint, angular velocity and angular acceleration, and then from equations (7-9), the driving torque of hip joint and knee joint can be obtained. Simultaneously, through the post-processing function of ADAMS, simulation results of the average driving torque of joints are shown in

Fig.10 with respect to the hip joint and knee joint, respectively.

By comparing the driving torque, the error curve can be obtained shown in Fig.11. The results showed that the error between the calculated driving torque and the ADAMS simulation is less than 0.178N.mm, which is kept in a reasonable range. Fig.12 shows the energy curve of amphibious spherical robot in the stance phase. It can be seen that the energy of the robot first increases and then decreases, and the whole energy remains unchanged.

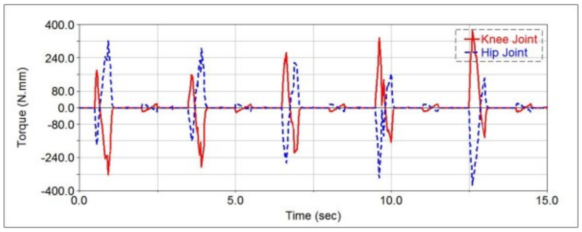


Fig 10. Average driving torque of knee joint and hip joint

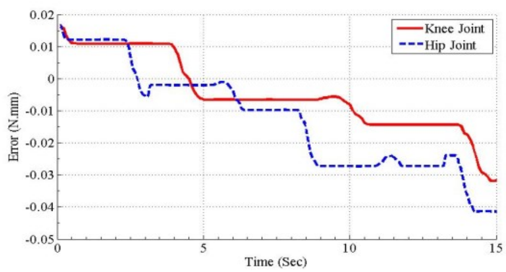


Fig 11. The error curve of the average driving torque

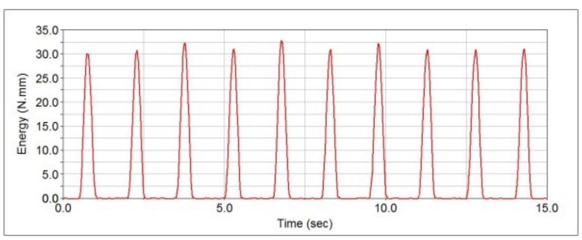


Fig 12. The energy curve of amphibious spherical robot

B. *Simulation results of pacing*

Similarly, the animation graph of pacing could be obtained during the simulation process, and Fig.13 shows some snapshots that the amphibious spherical robot completes a cycle of pacing. Simultaneously, the moving trajectory of the centroid of the robot was shown in Fig.14.

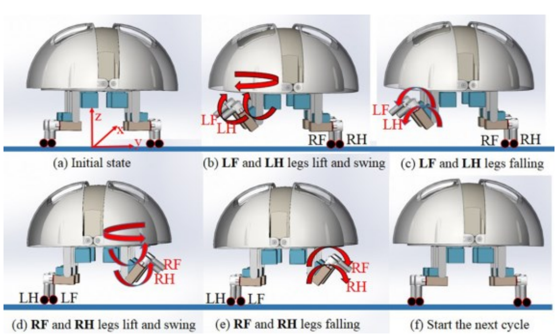


Fig.13 The process of pacing movement

In Fig.14, the solid red line indicates the centroid displacement in the X direction, and the velocity of the robot remained stable in the process of pacing and was basically maintained at around 0.043 m/s. The dashed blue line indicates the centroid displacement curve in the Y direction; as we can see, left and right deviation can occur with robot pacing and the maximum deviation of the robot was approximately 0.1 m. The dotted purple line indicates the centroid displacement curve in the Z direction, and the results showed that the translocation basically remained at 0.007 m. Consequently, jumping and sudden changes should not appear, and the robot can implement stable pacing basically.

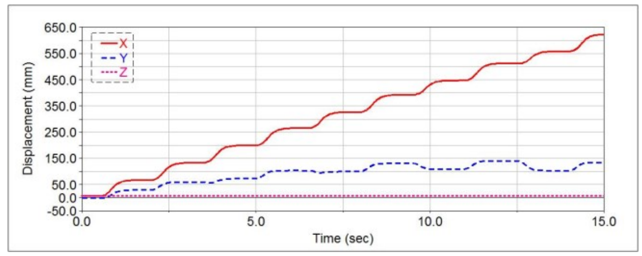


Fig.14 Displacement of robot in different directions

Similarly, in order to verify the dynamic characteristics of the pace gait, the driving torque of hip joint and knee joint can be obtained from theoretical calculation. Simulation results of the average driving torque of the joints are shown in Fig.15 with respect to the hip joint and knee joint, respectively. By comparing the driving torque, the error curve can be obtained shown in Fig.16. The results showed that the maximum error is 0.106N.mm. Fig.17 shows the energy curve of amphibious spherical robot in the stance phase. In general, it can be proved that the accuracy of the Lagrange dynamics equation, and the dynamic model can provide a theoretical basis for the design and control of the robot's structure.

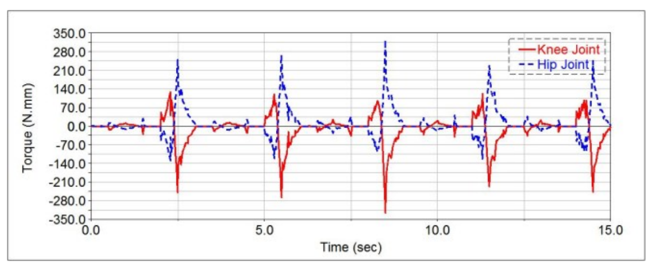


Fig 15. Average driving torque of knee joint and hip joint

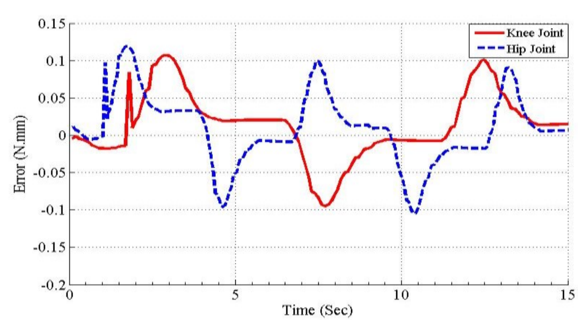


Fig 16. The error curve of the average driving torque

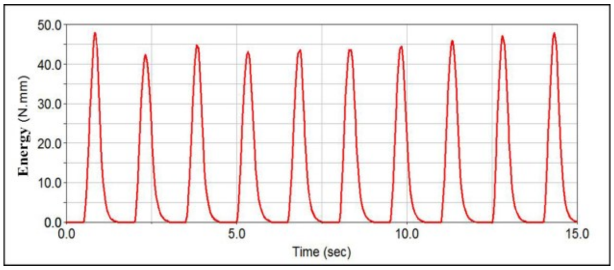


Fig 17. The energy curve of amphibious spherical robot

V. Conclusions and Future Work

To summarize, this paper have mainly designed and demonstrated two dynamic gaits for a 3D-printed amphibious spherical robot, trot gait and pace gait. From our initial modeling and experimental work, we have further increased the design efficiency and reliability. Simulation examples were presented to demonstrate the trot gait and pace gait of the amphibious spherical robot. Through ADAMS simulation software, several dynamic characteristic parameters for each joint, as well as for the robot as a whole, were determined. Conclusions from this paper are summarized below.

Firstly, gait analysis and implementation of our amphibious spherical robot have been presented. Secondly, this paper has built the connection between the trotting quadruped robot and the SLIP model by the control algorithm of the joint of leg. Simultaneously, the relationship between force and motion has been obtained by using Lagrange dynamics equation. Thirdly, referring to the actual geometric parameters and the physical characteristics of the robot, some kinematic simulations were conducted in ADAMS using the planned gait. Simultaneously, a comparison of theoretical calculations and simulation results demonstrated the robot's potential and its feasibility of trot gait and pace gait. Moreover, various data were collected that would provide valuable information for gait control of our amphibious spherical robot.

The future work will focus on actual experimental to evaluate the validity of these two dynamic gaits, and optimizing the robot's performance on challenging terrain and the mechanical design of robot.

Acknowledgements

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