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Virtual Prototyping Technology-based Dynamics Analysis for an Amphibious Spherical Robot

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Abstract –**The amphibious robot, which has favourable adaptability to the practical environment and good stability to move, is applied to a large number of areas such as rescue realm, mine countermeasures, pipeline inspections and underwater archaeology. In this paper, we present a novel amphibious spherical robot system, and the dynamic simulation is made by virtual prototyping technology. The design structure and research significance of amphibious robot in this thesis are put forward. According to the features of the motion of the amphibious robot, the Lagrange dynamic model is established, which offers theoretical foundation for the following simulation analysis based on virtual prototype technology. In order to improve design efficiency and reliability, the mechanical arm for the joint rotation angle, angular velocity and angular acceleration and moment kinetic parameters can be obtained in the ADAMS (Automatic Dynamic Analysis of Mechanical Systems) model of dynamic simulation analysis. Finally, according to previous dynamics equation derived, we can calculate the joint torque through the equation. Compared with the measurement data by using ADAMS, the correctness of Lagrange dynamics equation can be verified. The results verify the rationality and exactness of design plan and structure design as well as provide valuable data information for further research on improving control quality of the amphibious robot.**

Index Terms* - *Amphibious Spherical Robot, virtual prototypes, dynamics simulation analysis, ADAMS (Automatic Dynamic Analysis of Mechanical Systems)

I. INTRODUCTION

During the past decade, robotic technology, which has advantages of good surrounding adaptability and move agility, is applied to a variety of directions such as mineral, adventure, entertainment and military affairs, etc. At present, underwater vehicles can mainly be included remote operated underwater vehicles (ROVs) and autonomous underwater vehicles (AUVs) [1]-[3]. Different shapes and the sizes of autonomous robots obtained rapid development, due to different applications and tasks require. The prospecting, development and utilizing the ocean resources have become the focus of the international concern, thus amphibious robot has become a hot topic of academic research.

Amphibious robot is a multi-purpose construction, reconnaissance, communication and reclamation unit, which can walks on land as well as in rivers, lakes and oceans configured GPS, gyroscope, accelerometer and avoiding blocker sensor. The robot has advantages of long endurance, stable high speed, and large load capacity [4]. Meanwhile, it can release some tiny underwater robots to complete tasks in a narrow, confined space [5].

Recently, more and more researchers from some colleges and research institutes pay attention to the spherical underwater robots and obtained some achievements. In 2013, Pohang University of Science and Technology developed a spherical underwater robot, Cyclops, which focused on precise localization and maneuverability to acquire accurate visual data. Using the nearly constant dynamic surge, sway, heave, and yaw performances, the vehicle can scan a wide subsea area in a short mission time [6]. In 2014, U-CAT, underwater robot was developed by Tallinn University of Technology [7]. U-CAT is an autonomous, small-size and low cost vehicle, currently under development, for shipwreck penetration. The robot uses a novel 4-fin actuation that gives the vehicle high maneuverability for operating in complex environments and can assist archaeologists during possibly dangerous and expensive shipwreck exploration missions.

Compared with foreign countries, the research of robot started relatively late in China. During the past decade, Chinese scientists and researchers had paid attention to the development of underwater robot. In 2007, Harbin Engineering University developed a spherical robot. According to architecture and kinematic characteristics of this vehicle, they obtained the dynamic model of the water-jet propeller. Finally, the dynamic model of a spherical underwater robot was set up and the speed of the submarine was simulated˙ In 2012, Beijing University of Posts and Telecommunication designed a new amphibious spherical robot [8], which was equipped with sensor devices and sent the real-time information back to the ground control system. The robot can roll on land or underwater freely and also can move in the water.

In summary, the research and development of amphibious robot have both high academic value and practical significance. Among them, solving the dynamics of robot is a key but problem in mechanism theory. However, the traditional means, which makes use of mechanical prototype experimentation to design robot, not only spends long time, high cost, a number of calculation during design, but also is very poor in its visualization. The innovation points of this paper lies in investigating the dynamics simulation for amphibious robot on virtual prototyping technology, and the results of simulation provide important guidance to

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mechanism design and parameters preference for the amphibious robot.

The organization of the paper is outlined as follows. In section II, according to proposed amphibious spherical robot structure, the robot system structure and basic properties is described. In section III, a motion reference coordinate system of this robot and its simplified-structure of the physical body dynamics model are described. After dynamic analysis, the Lagrange dynamic equation group for simplified-structure of the amphibious robot's body system is achieved, which offers theoretical foundation for the following simulation analysis base on virtual prototype. Then, a great number of simulations are finished based on virtual prototype technology. In section IV, the results from theoretical analysis and simulation are compared to demonstrate the performance and analysis module for control. It proves the mechanical design and the feasibility of gait planning producing useful data and conclusions, which offers references for the research of the real prototype. Finally, conclusions are given.

II. SYSTEM STRUCTURE OF AMPHIBIOUS SPHERICAL ROBOT

A. *The Amphibious Robot System Structure*

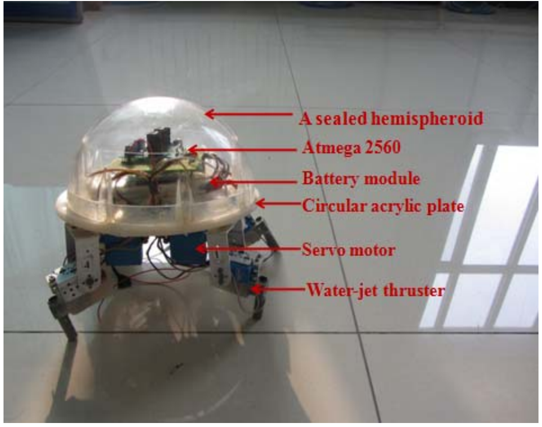


Fig.1 The structure of proposed spherical amphibious robot

The proposed amphibious spherical robot is shown as in Fig. 1. The proposed amphibious spherical robot consists of a circular acrylic plate, a sealed hemispheroid and four actuating units. Each unit contains two servomotors and one water-jet propeller. Therefore, robot has a total of eight servo motor and four water-jet propellers. The two servomotors are installed perpendicular to each other, one in the horizontal plane, and the other in the vertical plane. Each water-jet propeller is installed with the servo motor in the vertical plane. In addition, the direction of water-jet propeller can be changed both in horizontal plane and vertical plane, either sequentially or simultaneously. In order to make the whole robot waterproof, all control units and batteries are installed in the sealed hemispheroid, which is transparent and waterproofed [9].

The robot uses the four water-jet propellers as driving legs and changes gait by adjusting the sequence of the leg movement [10]. In Fig. 2, there are two degrees of freedom in the hip joint(Joint 1) and knee joint(Joint 2) of the robot, which refer to hip flexion and knee flexion.

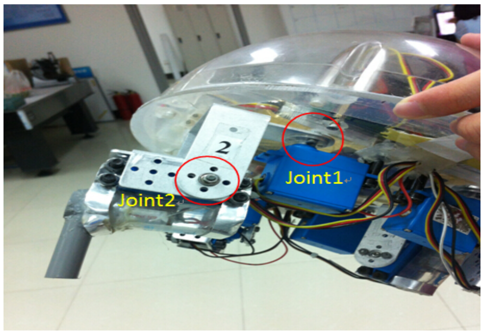


Fig.2 The single leg joints of the spherical amphibious robot

B. *Dynamics Modeling*

During the preceding two decades many dynamic researches have been done [11]. Dynamics plays an important role in the control of parallel robots for some applications like track simulators or pick-and-place operations involving fast manipulators. Thus, deriving dynamical equations for amphibious robot is an essential step prior to controller design.

To derive the dynamics mathematical modeling of mobile manipulator system, two approaches can be considered [12]. The first method is the Newton-Euler equation. It can deal with the coupling correlation of forces acted on the joints and displacement of links, but it is not efficient to solve when there are many joints. The second method is the Lagrange dynamics equations, which is the equilibrium equation of energy and more accurate to analyze the links' motion constrained each other. In this paper, we consider the Lagrange dynamics equations.

The Lagrange equation [13] is:

$$L = E_k - E_p \tag{1}$$

In which: L-Lagrange function; E_k -total kinetic energy of system; E_p -general potential energy of system.

The Lagrange equation is expressed the under formula by generalized coordinate q_i and Lagrange function L:

$$F_i = \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_1} - \frac{\partial L}{\partial q_i}, i = 1, 2, \cdots, n \tag{2}$$

In which: F_i is external force along that generalized coordinate direction, which can be determined by coordinate. n is the number of links.

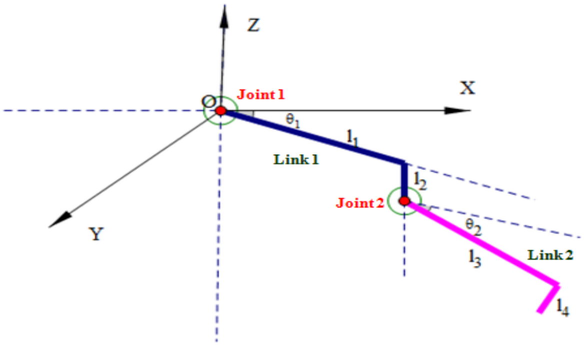


Fig.3 The single leg structure diagram of amphibious robot

According to Fig.3 selected coordinates, each leg consists of two links (Link 1 and Link 2) and two rotation joints (joint 1 and joint 2). Link 1 in the swing plane XOY consists of two sections: l_1, l_2. The qualities were m_1 and m_2, respectively. Link 2 consists of two section: l_3, l_4. The qualities were m_3 and m_4, respectively. θ_1 and θ_2 represent as generalized coordinates variables.

Lagrange equation of motion is obtained:

$$L=(K_1+K_2)-(P_1+P_2)=[\frac{1}{2}(m_1+m_2)\upsilon_1^2+\frac{1}{2}(m_3+m_4)\upsilon_2^2]+(m_1+m_2)gl_2$$
$$+(m_3+m_4)g(l_2+l_3\cos\theta_2+l_4\sin\theta_2) \tag{3}$$

By a series of complex derivation and arrangement to the formulas, then solving algebraic equation can receive the dynamic equations of flexible robot finally.

$$T_1=\frac{d\partial L}{dt\partial\dot{\theta}_1}-\frac{dL}{d\theta_1}=[(m_1+m_2+m_3+m_4)l_1^2+(m_3+m_4)(l_3^2\sin^2\theta_2+l_4^2\cos^2\theta_2$$
$$+2l_1l_3\sin\theta_2-l_3l_4\sin2\theta_2-2l_1l_2\cos\theta_2)]\ddot{\theta}_1+[(m_3+m_4)(l_3^2\sin2\theta_2-l_4^2\sin2\theta_2$$
$$+2l_1l_3\cos\theta_2-2l_3l_4\cos2\theta_2+2l_1l_4\sin\theta_2)]\dot{\theta}_1\dot{\theta}_2 \tag{4}$$

$$T_2=\frac{d\partial L}{dt\partial\dot{\theta}_2}-\frac{dL}{d\theta_2}=\frac{1}{2}(m_3+m_4)[(2l_3^2\sin^2\theta_2+2l_4^2\cos^2\theta_2-2l_3l_4\sin2\theta_2)\ddot{\theta}_2-(l_3^2\sin2\theta_2$$
$$-l_4^2\sin2\theta_2+2l_1l_3\cos\theta_2-2l_3l_4\cos2\theta_2+2l_1l_4\sin\theta_2)\dot{\theta}_1^2+(2l_3^2\sin2\theta_2-2l_4^2\sin2\theta_2$$
$$-4l_3l_4\cos2\theta_2-l_3^2\sin2\theta_2+l_4^2\sin2\theta_2+2l_3l_4\cos2\theta_2)\dot{\theta}_2^2-2g(l_4\cos\theta_2-l_3\sin\theta_2)] \tag{5}$$

These general equations have been simplified and represented by their simple matrix forms as follow:

$$\begin{bmatrix}T_1\\T_2\end{bmatrix}=\begin{bmatrix}D_{11}&D_{12}\\D_{21}&D_{22}\end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\\ddot{\theta}_2\end{bmatrix}+\begin{bmatrix}D_{111}&D_{122}\\D_{211}&D_{222}\end{bmatrix}\begin{bmatrix}\dot{\theta}_1^2\\\dot{\theta}_2^2\end{bmatrix}+\begin{bmatrix}D_{112}&D_{121}\\D_{212}&D_{221}\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\dot{\theta}_2\\\dot{\theta}_2\dot{\theta}_1\end{bmatrix}+\begin{bmatrix}D_1\\D_2\end{bmatrix} \tag{6}$$

In which, D_{11} and D_{22} are the effective inertia ; D_{12} and D_{21} are the coupling inertia; D_{111} , D_{122} , D_{211} and D_{222} are the coefficient of centripetal acceleration effect; D_{112} , D_{121} , D_{212} and D_{221} are coefficient of centripetal acceleration effect; D_1 and D_2 are the gravity terms.

$$D_{11}=[(m_1+m_2+m_3+m_4)l_1^2+(m_3+m_4)(l_3^2\sin^2\theta_2+l_4^2\cos^2\theta_2$$
$$+2l_1l_3\sin\theta_2-l_3l_4\sin2\theta_2-2l_1l_2\cos\theta_2)] \tag{7}$$

$$D_{22}=\frac{1}{2}(m_3+m_4)[(2l_3^2\sin^2\theta_2+2l_4^2\cos^2\theta_2-2l_3l_4\sin2\theta_2) \tag{8}$$

$$D_{12}=D_{21}=0 \tag{9}$$

$$D_{111}=D_{122}=0 \tag{10}$$

$$D_{211}=-\frac{1}{2}(m_3+m_4)(l_3^2\sin2\theta_2-l_4^2\sin2\theta_2+2l_1l_3\cos\theta_2-2l_3l_4\cos2\theta_2+2l_1l_4\sin\theta_2) \tag{11}$$

$$D_{222}=\frac{1}{2}(m_3+m_4)(2l_3^2\sin2\theta_2-2l_4^2\sin2\theta_2-4l_3l_4\cos2\theta_2-l_3^2\sin2\theta_2+l_4^2\sin2\theta_2$$
$$+2l_3l_4\cos2\theta_2) \tag{12}$$

$$D_{112}=D_{121}=\frac{1}{2}(m_3+m_4)(l_3^2\sin2\theta_2-l_4^2\sin2\theta_2+2l_1l_3\cos\theta_2-2l_3l_4\cos2\theta_2+2l_1l_4\sin\theta_2) \tag{13}$$

$$D_{212}=D_{221}=0 \tag{14}$$

$$D_1=0 \tag{15}$$

$$D_2=-2g(l_4\cos\theta_2-l_3\sin\theta_2) \tag{16}$$

The related parameters of the robot are shown as follow: $m_1=16g$ $m_2=21g$ $m_3=144.39g$, $m_4=1.7g$ $l_1=4cm$, $l_2=5cm$, $l_3=4cm$, $l_4=7cm$

The dynamics equation offers theoretical foundation for the following simulation analysis base on virtual prototype. According to the model is deduced Lagrange dynamics equation, through the formula to calculate the joint torque and using the ADAMS of measurement data to verify the correctness of the dynamics equation [14].

III. DYNAMICS SIMULATION

A. *Virtual Prototype Model of Spherical Robot*

ADAMS (Automatic Dynamic Analysis of Mechanical System) is dynamic simulation analysis software which has powerful dynamics solver (ADAMS/Solver) [15]. As the world's most widely used robot system, ADAMS helps engineers and researchers to study the dynamics of moving parts, how loads and forces are distributed throughout mechanical systems.

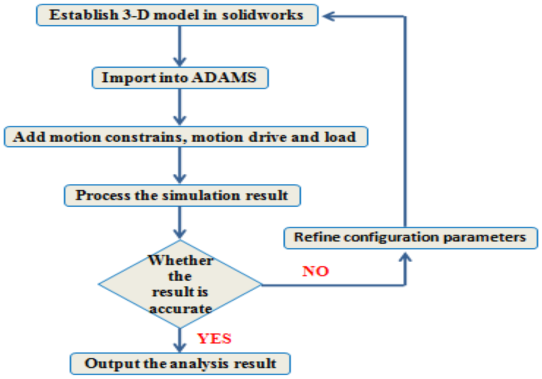


Fig.4 The procedures of simulation analysis in ADAMS

The simulation analysis procedures of amphibious spherical robot are presented in Fig.4. To verify dynamics equations and the performance of the foot trajectory, and get some important parameters, dynamics simulations are made based on ADAMS. First, the 3-D model of robot should be built in Solidworks software and needs to be imported into ADAMS by using Adams/Exchange module. Fig.5 shows the virtual prototype in ADAMS [16]. Then, after the connection way is specified, we add some motion constrains, motion drive and load. In the robot, each of the legs has two-rotation-freedom and we need to add corresponding revolute constrains into the mechanism components of the joints. Through many times debugging and modifying, feasibility and correctness of the virtual sample robot model is guaranteed.

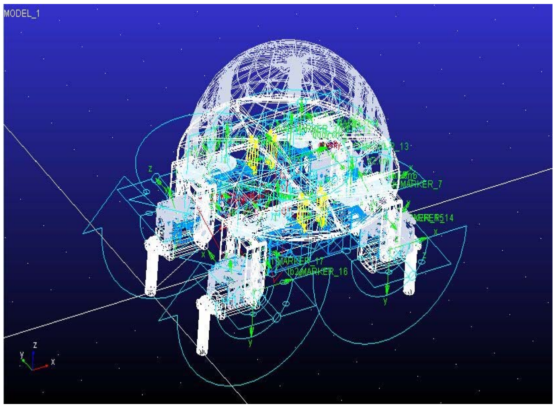


Fig.5 The virtual prototype of amphibious robot in MSC.ADAMS

B. *Dynamics Simulation In ADAMS/View Environment*

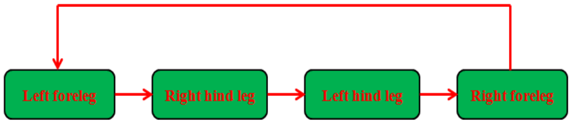


Fig.6 Crawl gait sequence of amphibious robot

It is generally acknowledged that there are only two states (stand phase and swing phase) when the robot is conducted the leg movement. In particular, the crawl gait is typical periodic walking crawling pattern of quadruped animals in a low speed walking. In this paper, we use the step sequence of LF → RH → LH → RF (L: left, R: right, H: hind leg, F: foreleg) in Fig.6 [17]. In crawling, at least three legs are contacted on the ground and such conditions make it possible to generate statically balanced walking. Therefore, the implementation of this gait pattern is a better choice for the low-speed movement.

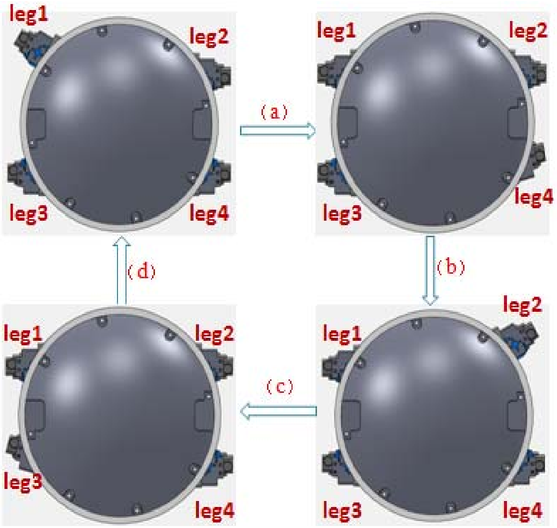


Fig.7 Crawling motion diagram of the spherical robot

As shown in Fig.7, based on this criterion, in the swing phase of single leg, the support triangle is formed by the tips of the other three supporting leg. In the crawl gait all four feet are on the ground for the body translation and the body is stopped for the leg swing motion, hence it increases the stability. In consideration of the energy consumption caused by frequent acceleration and deceleration, the crawl gait pattern is suitable for the walking on terrain.

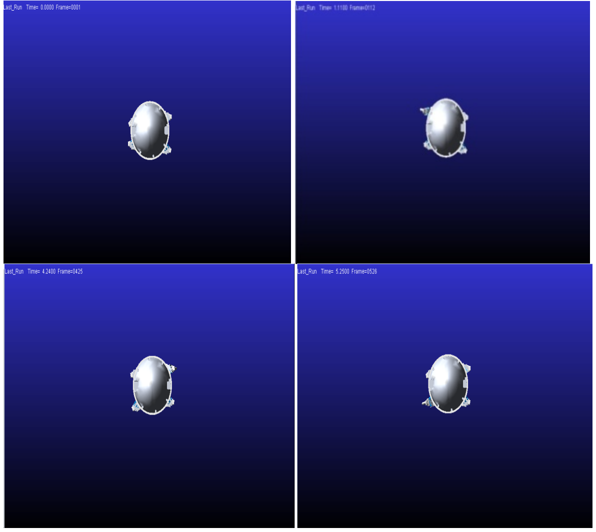
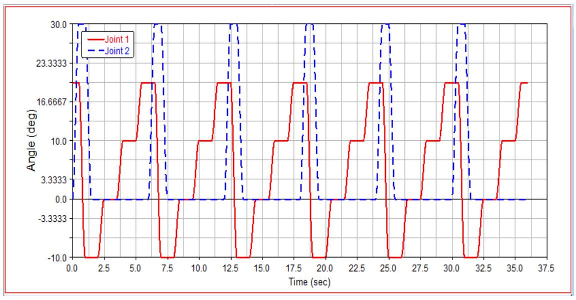


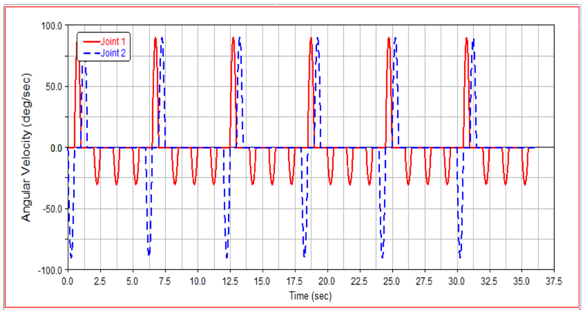
Fig.8 The crawling motion simulation of the amphibious robot

The aim of the crawl motion simulation is to verify each communication device whether to match and exchange information correctly. To achieve the best results, we try to make the setup as real as possible by setting the friction parameters in this paper.

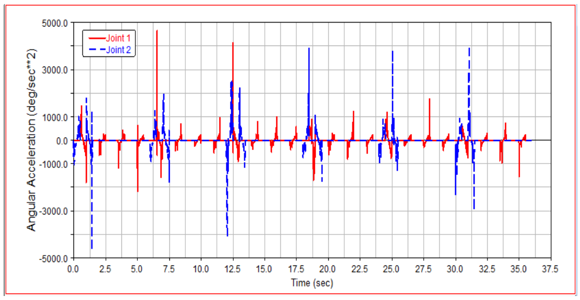
In this case, we only analyze the single left foreleg. The hip joint drive function of left foreleg is inputted as "STEP5 (time, 0.2, 0, 0.6, -18d)+STEP5(time, 1.0, 0, 1.4, 36d)+STEP5 (time, 1.8, 0, 2.2, -36d)+STEP5(time, 2.6, 0, 3.0, 36d)+STEP5 (time, 3.4, 0, 3.8, -36d)+STEP5(time, 4.2, 0, 4.6, 36d)+STEP5 (time, 5.0, 0, 5.4, -36d)+STEP5(time, 5.8, 0, 6.2,36d)+STEP5 (time, 6.6, 0, 7.0, -36d)" and the knee joint drive function of left foreleg is inputted as "STEP5(time, 0, 0, 0.2, 9d)+STEP5(time, 0.6, 0, 0.8, -9d)+STEP5(time, 1.6, 0, 1.8, 9d)+STEP5(time, 2.2, 0, 2.4, -9d)+STEP5(time, 3.2, 0, 3.4, 9d)+STEP5(time, 3.8, 0, 4.0, -9d)+STEP5(time, 4.8, 0, 5.0, 9d)+STEP5(time, 5.4, 0, 5.6, -9d)+STEP5(time, 6.4, 0, 6.6, 9d)+STEP5(time, 7.0, 0, 7.2, -9d)", which is a 7.0s movement. Fig.8 shows a video sequence of the walking motion on the floor with crawl gait under the simulation of true environment in ADAMS.



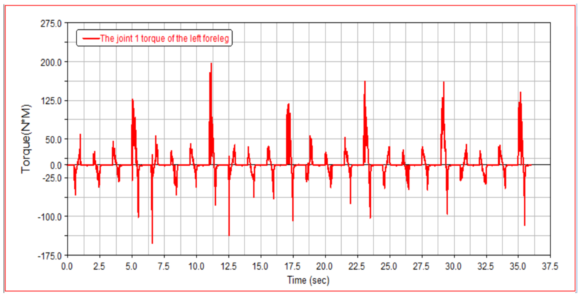
(a) The angle of the left foreleg



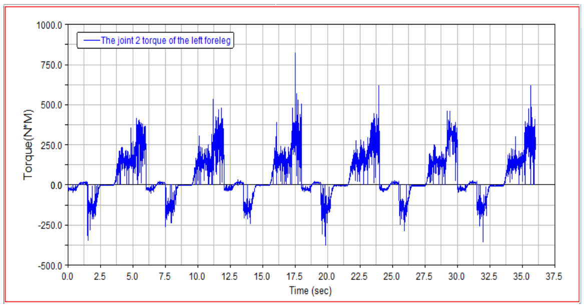
(b) The angle velocity of the left foreleg



(c) The angle acceleration of the left foreleg



(d) The joint 1 torque of the left foreleg



(e) The joint 2 torque of the left foreleg

Fig.9 The image of the simulation result of the amphibious robot

Through simulation experiment, the robot can realize stable walking following crawling gait. As shown in Fig.3, joint 1 and joint 2 represent hip joint, and knee joint of single left foreleg, respectively. In ADAMS postprocessor module of dynamics simulation analysis [19], the mechanical leg for the joint rotation angle, angular velocity and angular acceleration and moment kinetic parameters are shown in Fig.8 (a)-Fig.8 (e).

IV. RESULT ANALYSIS

In the previous dynamics equation derived, the rotation angle, angular velocity and angular acceleration can be used in calculate the torque of each joint. From the result, 30 sampling time points here is selected in Fig.8 (a)-Fig.8 (c), keeping the compatibility of the parameters, respectively [20]. Next, it puts collected corresponding data (the rotation angle, angular velocity and angular acceleration) into dynamics equation and the computed torque can be calculated using MATLAB [21]. Finally, compared with the torque in Fig.8 (d)-Fig.8 (e), the error curves of the two values can be generated in Fig.9.

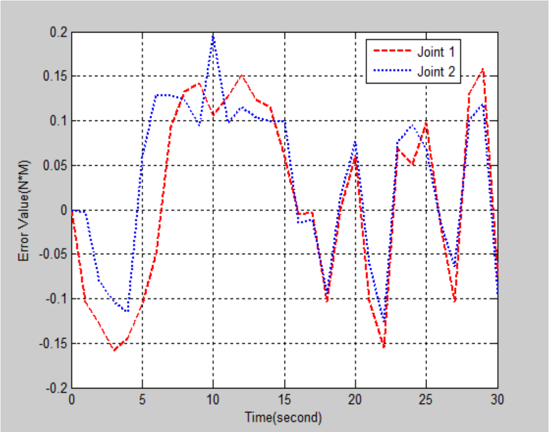


Fig.9 The line graph of error value

The horizontal axis stands for the measure time, and the vertical axis stand for the error value between the calculated torque and simulation torque. The red line and blue line represent the error value of joint 1 and error value of joint 2, respectively.

The result manifest: the calculated torque in dynamics equation is closed enough to the simulation torque and the tolerance keeps within a reasonable range of less than 0.2N*M. The correctness of Lagrange dynamics equation can be verified and dynamics model can provide the accurate characteristics and theoretic foundation of robot design control research.

From the result, it can see that:

(1).The driving torque of the joint can be positive or negative and the torque in supporting phase is large than it in swing phase.

(2).The torque of the hip joint 1(hip joint) is limited to the 50N*M range mainly except singular state.

To design machine structure of the amphibious robot successfully, the mechanical characteristics should be analyzed and evaluated after design but before prototype being made. Firstly, according to maximal value of each joint torque (750N*M) in simulation, we can select the suitable servo motors to eliminate the oscillation. Besides, we can see that continuous impact force generated by the pressing of robot feet and road surfaces. The mechanical leg alone can't give a satisfactory motion, and the shock absorbers should be used with the feet.

Therefore, Virtual Prototyping Technology can improve the mechanical design and the feasibility of gait planning producing useful data and conclusions, which offers references for the research of the real prototype

IV. CONCLUSION AND FUTURE WORK

The paper proposes an amphibious spherical robot configuration driven by water-jet propellers and servo motors. Lagrange dynamics equation of the robot is established and the simulation crawl gait experiment conducted in ADAMS. Last, the error curves between calculated torque and measurement torque can be given. From the above, researches, some conclusion are summed up as follow:

1) A dynamics model was established by Lagrange method. The Lagrange equation is formulation which captures the whole dynamics, linear and angular in one equation. And this formulation offers theoretical reasons for the following gait simulation analysis base on virtual prototype.

2) Based on ADAMS software as the foundation, the design of a simplified amphibious spherical robot virtual prototype model to study the dynamics equation of validation. In the ADAMS model of dynamics simulation analysis, the joint rotation angle, angular velocity and angular acceleration and torque, etc of each joint can be achieved.

3) According to previous dynamics equation derived, we can calculate the joint torque through the equation. Compared with the measurement data by using ADAMS, the correctness of Lagrange dynamics equation can be verified.

In future work, some experiments are performed in order to verify these simulation results by using inductor dynamometer, and we will design a composite foot trajectory composed of cubic and straight line. Meanwhile, the control method will be considered to add in the model, and dynamics co-simulation is given with MSC.ADAMS and MATLAB. Then, add more sensors such as gyroscope, hydraulic capsule etc and do more simulations and experiments.

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