QUADRUPED ROBOT CONTROL ALGORITHM AND ITS FIELD TEST

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ABSTRACT

This paper introduces a legged bionic quadruped robot developed by the China North Vehicle Research Institute. Based on virtual leg algorithm, we studied different gaits and the stability control algorithm which established a three element model, the height of the body, the stability of the attitude and the forward speed. Firstly, a single bionic leg prototype was set up. By adjusting control parameters, the dynamic tracking effect of plantar force could meet desired requirements. After that, the model was merged into TROT gait with the full scaled quadruped robot. With the lateral disturbance, the experiment showed the robot could recover the balance after several closed loop cycles. This proved not only the effectiveness of the control algorithm, but also the effectiveness of the principle prototype integration. The aim is to provide engineering and theoretical support for the optimization of the robot and the control algorithm on uneven surface in advance.

1. INTRODUCTION

Compared with other types of ground movement, foot walking has unique and superior performance. In nature, most mammals adopt the method of foot–walking so that they can reach any desired place on the .ground [1, 2]. Compared with wheeled and tracked vehicles, foot-walking mode shows obvious advantages of flexibility, fluency, adaptability and effectiveness in uneven terrain conditions [3]. The quadruped robot has excellent loading capacity and stable performance. It has not only good dynamic performance, but also strong adaptability to the terrain [4]. At the same time, since the mechanism design and control algorithm in terms of difficulty and redundancy are moderate, it is very suitable in the application of exploration, disaster rescue and other fields. As a result, the research field of quadruped robot has become one of the hottest spots and the leading edge of the legged robot.

We started quadruped robot research project in2011. This paper mainly introduces the prototype of a quadruped robot made by our project team and the research process.

2. GENERAL INTRODUCTION TO THE DEMONSTRATION CONCEPT AND PROTOTYPE

The quadruped mobile platform is a new project following several wheeled UGV projects, because it is a new area of bionic intelligent mobile. Wheeled and tracked vehicles have been well known as the king of the land, but after nearly a hundred years of efforts, people failed to make wheeled or tracked vehicles to get a fundamental improvement in the performance of soft ground. This was why we began to study quadruped mobile platform.

In nature, the walking, running and climbing ability of mammals is very strong and powerful. For example, goat walks in the steep cliff comfortably by choosing the correct footholds to keep stance and balance. Therefore, we studied the leg structure of quadruped mammal and analyzed its joint degrees of freedom. We got a bionic reasonable simplification, and then proposed design concept named as BR120G, see Fig. 1.

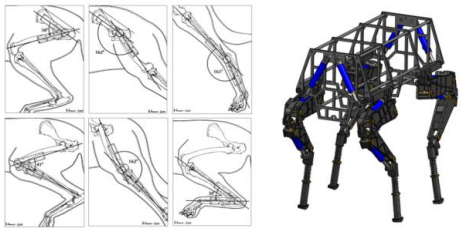


Figure 1. The design concept of quadruped robot

The BR120G robot adopts the front and back symmetrical topology structure, which means that the mechanism and the structure of the four bionic legs are consistent. Each leg consists of four joints, namely, hip lateral expansion joint (HAA), hip swing joint (HFE), knee (KFE) and ankle (AFE), so this is a Bigdog-like structure. The prototype we have been built see Fig. 2.

Figure 2. Quadruped mobile robot prototype

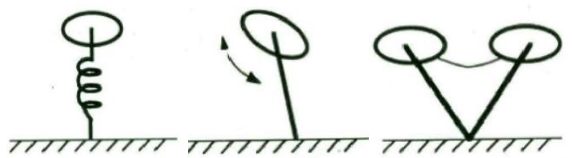
Each joint is driven by a hydraulic cylinder provided with a servo valve and a linear displacement sensor to form a hydraulic servo system. The force feedback mechanism is used to realize the stability control of the robot resulting in a pressure sensor installed at the end of each hydraulic cylinder. In addition, an IMU unit which can measure the pitch angle roll angle and yaw angle of the body in real time to provide the signal to the control system for closed-loop operation is also arranged on the body.

3. STUDY ON GAIT AND STABILITY CONTROL METHOD BASED ON VIRTUAL LEG

The gait and stability control algorithm of legged robot are the basis of stable walking on uneven terrain. A large number of gait and stability control algorithms have appeared since the birthday of the legged robot. Common control methods are: Based on the kinematic model of the method, the central mode generator control method, dynamic model method, etc. Among them, the virtual leg control algorithm proposed by Marc Raibert has been successfully applied to single legged, bipedal, and quadruped robots, helping the realization of legged robot walking and running really like animals [5]. BigDog robots developed by Boston Dynamics, Scout II robot developed by Stanford University were developed from this control algorithm. The success of these robots proved the effectiveness of this control algorithm for legged robot system. Here, we will introduce the basic principle of this control algorithm. In next chapter, we will make further introduction based on the algorithm to carry out the results of the single leg and the whole machine test.

3.1. Three elements about walking

The main idea of the virtual leg control algorithm is to assume the robot as a spring loaded inverted pendulum system (named SLIP), and its behavior can be decomposed into three basic actions [6]: body height support, body attitude stabilization and forward speed control, see Fig. 3.



(a) Height support (b) Attitude stabilization (c) Forward speed control

Figure 3. Three elements about walking control principle

3.2. Body height support control

Body height support control is a kind of energy compensation mechanism. We can imagine a non-powered SLIP system the bounce height will gradually reduce to zero with the energy loss. Therefore, if we want to keep it in motion, we must estimate the energy loss in each bounce cycle and compensate it. In order to estimate the size of the force, if its dynamic behavior is simplified as a spring [7], see Eq. 1.

$$F = k \cdot \left(\left\| \vec{r}_0 \right\| - \left\| \vec{r} \right\| \right) \tag{1}$$

In Eq. 1, k is the virtual spring stiffness, $\vec{r}_0$ is a direction vector from hip joint point to foot touch-down point at zero time, $\vec{r}$ is a direction vector from hip joint point to foot touch-down point at current time.

3.3. Body height support control

In the course of walking, the body posture is difficult to be guaranteed due to the disturbance of the terrain and external forces. For this purpose, it is necessary to calculate the unbalanced force and torque in each bounce cycle. At the same time, in order to ensure that the calculation is not too complex to ensure the real-time control system, Marc Raibert used a PD controller to estimate the force and torque needed to maintain the balance, see Eq. 2.

$$\begin{bmatrix} {}_B F^d{}_B \\ {}_B T^d{}_B \end{bmatrix} = k_p \left(q^d{}_b - q_b \right) + k_d \left(\dot{q}_b^d - \dot{q}_b \right) \tag{2}$$

In Eq. 2, ${}_B F^d{}_B$ 、 ${}_B T^d{}_B$ is the virtual external force and torque needed by the body coordinate system. $q^d{}_b$ 、 q_b is the desired position & attitude and actual position & attitude of the body. $\dot{q}_b^d$ 、 $\dot{q}_b$ is velocity and angular velocity of body. k_p 、 k_d is the parameters of PD controller.

At the same time, based on the force analysis of the robot, the relationship between the virtual external force and torque and the force of the supporting leg can be obtained by Eq. 3.

$$\begin{bmatrix} I & I & \cdots & I \\ \vec{r}_{leg,0} & \vec{r}_{leg,1} & \cdots & \vec{r}_{leg,m} \end{bmatrix} \begin{pmatrix} F_{leg,0} \\ F_{leg,1} \\ \cdot \\ \cdot \\ F_{leg,m} \end{pmatrix} = \begin{pmatrix} F^d{}_B \\ T^d{}_B \end{pmatrix} \tag{3}$$

In Eq. 3, $F_{leg,i}$ is the force of *i*-th leg, *i* from 0 to *m*, *m* is the number of legs.

By Eqs. 2-3 and combined with the optimization control algorithm, the support force of the leg can be got.

3.4. Forward speed control

Another important element of control is to control the touch-down-point position of the swing leg to realize acceleration and deceleration of the robot.

The swing leg's touch-down-point can be obtained by [8], see Eq. 4.

$$r_f = \frac{\dot{r}_f T_s}{2} + k_{r_f}\left(\dot{r}_f - \dot{r}_{f\_d}\right) \tag{4}$$

In Eq. 4, r_f is touch-down-point position, $\dot{r}_f$ is the velocity of the point, $\dot{r}_{f\_d}$ is the desired velocity of the touch-down-point position, k_{r_f} is the gain, T_s is the time of each bounce cycle.

4. VERIFICATION OF VIRTUAL LEG CONTROL ALGORITHM ON SINGLE LEG TEST BENCH

The key of the virtual leg control algorithm is to control the robot's swing phase and the supporting phase during the bounce cycle [9,10]. In order to verify the control effect, the above analysis can be carried out in a single leg test bench. The verification of the swing phase can obtain the touch-down-point position of the foot according to the preset three-spline curve by observing its closed loop effect. Then, the foot's sensor will detect the state of the leg, and switch to the support legs' control to enter the supporting phase. By recording desired value and actual foot force, we can verify the closed loop effect through the comparison. It can be seen from the Fig. 4 that the single leg is switched from the swing phase (the foot force is 0) to the support phase, the desired foot force shows a step from zero to almost 500N.The close loop effect of each joint angle is basically good, while the knee closed loop shows a slight lag.

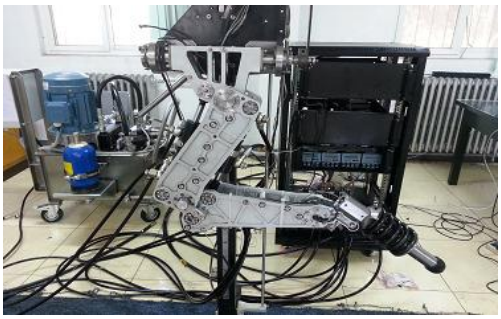
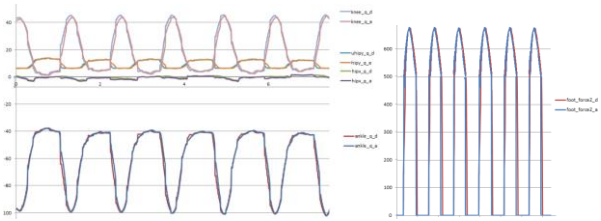


Figure 4. Single leg test bench

As shown in Fig. 5, it is in the test period, we intercepted a section curves about the joint angle and the foot force during the closed loop as the object to analysis. Among them, Fig. 5(a) is the closed-loop state curve of each joint angle, and Fig. 5(b) is the closed loop state curve of the foot force. The rising time of the foot force closed loop is basically controlled in the four closed loop cycle, about 20ms. At the same time; it is also very practical to achieve the desired foot force tracking. The overall control effect has been proved, then we will validate the control algorithm on the prototype of the four legged robot.



（a）Joint positional closed loop curve （b）Foot force in the Z direction

Figure 5. Closed-loop state curve of each joint angle

5. VERIFICATION OF VIRTUAL LEG CONTROL ALGORITHM ON ROBOT PROTOTYPE

In order to verify the effectiveness of the control algorithm in a quadruped robot prototype, we first made the quadruped robot using trot gait walk stably on flat ground. Then we imposed a force in the lateral position and recorded the changes of the body attitude angle to validate the effectiveness of control algorithm.

Test scenes can be got in Fig. 6, as known from the picture: when suffering lateral force the supporting leg was able to withstand the force and the swing leg immediately took a step toward the direction of the force, reducing the force and keeping stability.

Figure 6. Lateral disturbance test scenes

These results can also be seen from the value of the body pitch and roll angle, as shown in Fig. 7. Note that the red line area represented the biggest regional disturbance moment, the maximum rolling angle was about 15°, the maximum pitch angle was about 10°, but the whole disturbance process was in very short time. The whole process of recovering to the balance position from disturbance was rapid enough, so it proved that the control algorithm was effective.

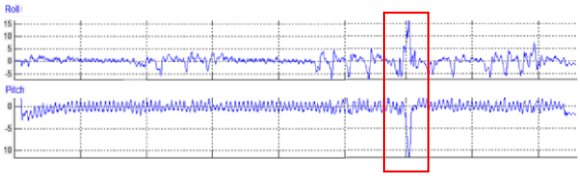


Figure 7. Roll and pitch control result when lateral disturbing

6. CONCLUSION AND PROSPECT

Research on quadruped robot technology in this paper is a positive exploration of legged robot and the intelligent control. In this paper, based on the perspective of bionic walking, we designed and developed a kind of bionic quadruped robot. Then, we set up a controller duty for the gait and stability of the robot by researching the virtual leg control method principle. In order to verify the effectiveness of the control algorithm, we used the single leg prototype and the quadruped robot to carry out the performance test judging from the results of experiment, which proved the method, was satisfactory.

Nevertheless, the robot research will continue: How to solve the hydraulic servo system of small problems, how to improve the system response speed; how to solve the system integration and reliability, how to enhance the ability of mechanical system to reduce the complexity of the control system; how to solve the problems in outdoor road movement and improve the ability of adaptation to the terrain. We believe that with the continuous development of research work on the quadruped robot, those problems will be solved, and the quadruped robot will have more powerful capacity. In future it will become a good assistant of mankind.

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