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Analysis of control design of quadruped robot motion based on motion stability theory

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Abstract. Quadruped walking robot can not only walk on uneven ground and complex terrain by static walking, but also realize high speed walking with dynamic walking. The development of quadruped walking robot has been paid much attention to by all countries. In order to study the factors that affect the dynamic walking stability of quadruped robot, the ADAMS virtual prototype software was used to simulate the dynamic walking of quadruped walking robot. In this paper, MATLAB data was input into ADAMS by using trajectory planning of robot. According to the force and constraint imposed by ADAMS, the specific method and steps of virtual prototype of walking robot were established. The research results and the combined simulation method of MATLAB- and ADAMS have guiding significance for the design and research of quadruped walking robot and the simulation experiment.

Key words. Motion stability theory, four groups of robots, motion process.

1. Introduction

Mobile robot technology is one of the most important and active research fields in the field of robot research. A quadruped robot is a robot that mimics the form of quadruped locomotion. It not only exceeds the stability of biped robot, but also avoids the redundancy and complexity of six legged robot mechanism. It can walk slowly on complex terrain in static walking mode, and can walk at high speed with dynamic walking. It has a very attractive prospect in many fields such as military or civilian materials transportation, field exploration, star exploration, disaster rescue, agricultural production, education and entertainment in complex terrain environment. In order to realize the highly dynamic, strong adaptability and high stability of the quadruped robot, the motion control strategy is the focus and difficulty of

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the study, especially the multi-joint coordination control, environmental adaptability control and dynamic stability control. At present, the motion control method of biped robot is based on kinematics model and dynamics model. It adopts the idea of modeling, planning and controlling. Firstly, the robot body and environment are modeled accurately. Then, the optimal trajectory of the robot is obtained by artificial programming. The feedback mechanism is used to control the deviation between the actual motion and the ideal trajectory of the robot, so that the motion of the robot can reach the ideal trajectory as much as possible. The control method can achieve complex and precise motion of the robot. However, it needs complicated kinematics and dynamics modeling with complex motion planning, discontinuous planning process and poor real-time control, so it is difficult to improve the robot's environmental adaptability.

2. State of the art

In the aspect of CPG bionic control of quadruped robot, the research of The University of Electro and Communications is the most typical. A pioneering research on the adaptive dynamic walking of quadruped robot in unstructured environment by using neural system model was studied, and a series of quadruped robots were developed [1]. The researchers used the improved Matsuoka neuron oscillator model to construct the robot's CPG control network [2], which was the basic rhythm generator movement. The stretch reflex, vestibular reflexes, extensor flexor reflex and other biological reflection mechanisms were integrated into the CPG control network. The adaptive dynamic walking of Patrush series quadruped robot under complex terrain and the running motion on the road surface was realized. In the gait transformation of quadruped robot, researchers have made some attempts and explorations [3]. The quadruped robot with a lumbar joint was investigated, and the gait transitions were achieved by varying the robot's motion speed and the muscle tension at the lumbar joint. In addition, the researchers verified the existence of hysteresis in robot gait transformation by simulation and experiment [4]. The research on quadruped robot in our country started late, and there is still a big gap compared with foreign countries. However, in recent years, with the national attention to the robot industry and increased investment, great progress in this area has been made and a series of results have been achieved [5].

2.1. Methodology

The movement control system of higher animals is a complex network involving higher nervous centers, lower nervous centers, skeletal muscles, executive systems, receptors, and sensory organs, as shown in Fig. 1.

In Fig. 1, the high central nervous system consists of a series of motor centers, including the cerebral cortex, the basal ganglia, the brainstem and the cerebellum. Their main function is to send movement instructions, control the rhythmic motion, select sport mode, and control the movement through the central comprehensive CPG feedback, proprioceptive and visual information, so as to realize the advanced

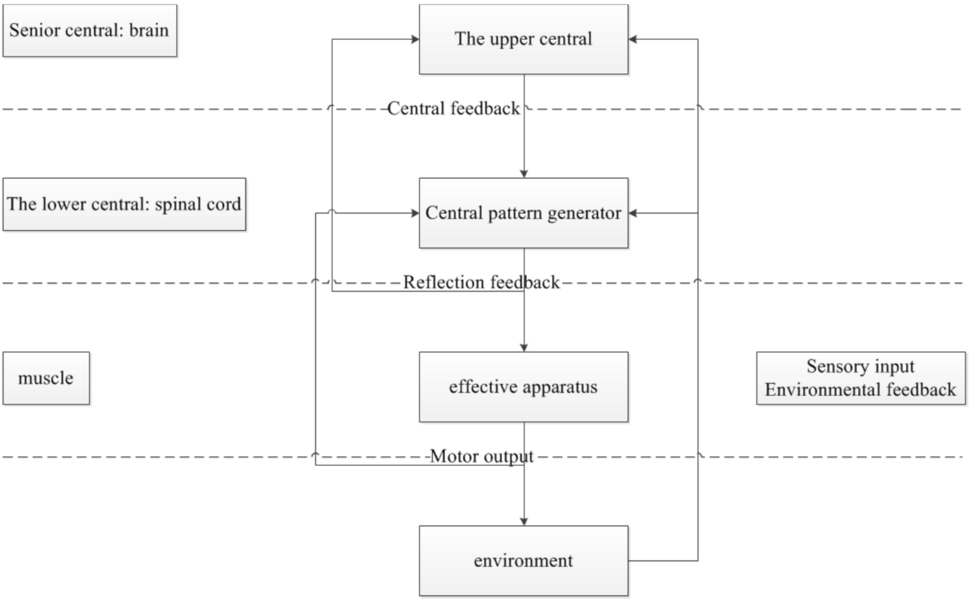

Fig. 1. Animal movement control network

movement function of obstacle avoidance and path planning in complicated environment [6]. Central mode generator (CPG) is the central control unit of rhythmic movement. The main function is to produce rhythm signals and control effector to realize motion. CPG is a distribution network composed of intermediate neurons with multiple oscillating centers. The self-oscillation is realized by mutual inhibition between neurons, and a multi-channel or one way periodic signal with stable phase interlocking relation is generated to control the rhythmic movement of the limbs or related parts of the body. In CPG, synaptic connections between neurons are malleable and a variety of output behaviors are exhibited to control animals' multiple motor patterns. Effector, the musculoskeletal system, is responsible for limb movements. There is a complex feedback network in the whole control system, including central feedback, reflective feedback and environmental feedback. These feedback loops are used to achieve biological reflex function. Central feedback is the replication of the CPG output, and the central nervous system uses central feedback to understand the control process of CPG. The feedback provides the upper body motion state or position information by using various proprioceptive sensors, and adjusts the output of CPG through the reflection mechanism, and coordinates the relationship between CPG and ontology and environment [7]. Environmental feedback monitors the relationship between the environment and the body mainly through visual and tactile sensory, so that the upper control system can ensure the appropriate command issued according to the environmental conditions or adaptive response.

In order to study the high speed walking quadruped trotting gait to achieve stable, trajectory planning and motion control curve were generated by using MAT-

LAB software firstly. And the virtual prototype was built by the ADAMS virtual prototype software [8].

In order to reduce the impact of the ground motion of the quadruped walking robot when swinging the legs to the ground, a high-speed dynamic and stable walking was carried out, and the trajectory of the foot was planned with the compound cycloidal trajectory planning method. The displacement expression in inertial coordinate system is as follows

$$x = s\left[\frac{t}{T_y} - \frac{1}{2\pi}\sin\frac{2\pi_t}{T_y}\right], \tag{1}$$

$$Z = 2H\left[\frac{t}{T_y} - \frac{1}{4\pi}\sin\frac{4\pi_t}{T_y}\right], \tag{2}$$

where, X is the displacement of the advancing direction, Z is the displacement in the high direction, S is the step length (the moving distance of the center of gravity in the unit cycle), H is the lifting height of the swinging foot, and T_y is the swinging cycle of the swinging leg.

The movement pattern of a foot animal is represented by "gait". Gait is the walking pattern with fixed phase relation between legs. The main characterization parameters of gait are defined as follows [9].

Gait cycle T: the time taken for a complete motor cycle.

Step length S: within one gait cycle, the distance that the body center of mass moves relative to the ground.

Load factor: the time at which the leg is supported on the ground, which accounts for the proportion of the entire motion cycle.

Supporting phase and oscillating phase: leg movement is divided into two processes: support and swing. The supporting phase refers to the state in which the leg meets the ground, supports the body and pushes the body forward. A swinging phase is the state of the leg lifting in the air. Load factor and phase difference are the two most important parameters of gait description. Different gait has different load factors, and the same gait can also have different load factors at different speed [10].

According to the load factor of each leg, gait can be divided into regular gait and irregular gait. Regular gait is the gait with the same load factor, the same motion rule, and the same phase difference between the legs. The typical gait of a four legged mammal has the following four kinds [11]. Walking gait: also known as "wave gait", each leg rises and falls in turn, and the phase difference is a. Trotting gait: diagonal legs rise and fall in pairs, and the phase difference between two pairs is b. Walking with the same side: the same side of the legs up and down in pairs, the difference between two pairs of c. Running gait: front and rear legs rise and fall in pairs, and the phase difference between two pairs is d. According to the rhythm of the movement, the above can be divided into double beat gait (trot gait, walking gait with the same side, running gait) and four beat gait (walking gait). The phase gait of the typical gait of a quadruped is shown in Table 1.

Table 1. Typical gait phase relation of quadruped

Gait	Leg phase			
	Left foreleg	Right foreleg	Right rear leg	Left rear leg
Walking gait	0	1/2	1/4	3/4
Trotting gait	0	1/2	0	1/2
Walking with the same side	0	1/2	1/2	0
Running gait	0	0	1/2	1/2

Nios II embedded CPG supports 32 bit instruction set, 32 bit data line width, 32 general-purpose registers, 32 external interrupt sources, and 2GB addressing space, including up to 256 user-defined CPU custom instructions [12]. The optional on-chip JTAG debug module is a debug logic based on boundary tests that supports hardware breakpoints, data triggers, and debug within an off chip. In this system, according to the corresponding requirements, the design of the system was based on the kernel, and all kinds of basic F units were added to the system development and application. The actual system design diagram is shown in Fig. 2.

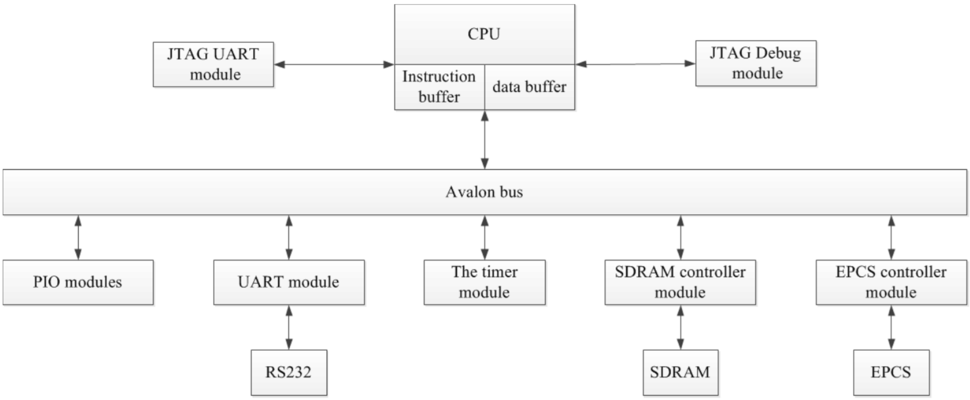

Fig. 2. Nios II system chart

It can be seen from the above diagram, the kernel of Nios II system designed in this paper includes Nios II CPU, JTAG UART module, JTAG Debug module, PIO module, UART module, timer module, SDRAM controller module, and EPCS controller module [13]. All data and programs in the system are transmitted via the Avalon bus. The whole kernel is built on the software implementation by using Altera's Quartus software and the SOPC builder tool. The whole design process adopts the SOPC technology proposed by Altera Company. SOPC technology is a flexible and efficient design scheme for on chip system SoC. Its working environment is SOPC builder in Altera of Quartus. Compared with other SoC designs [14], it has the advantage of programmability and uses the programmability of FPGA for SoC design. By using the SOPC builder tool, the user can easily connect the processor, memory and other peripherals to form a complete embedded system. SOPC mainly consists of 2 parts: graphical user interface (GUI) and system generator from the internal point of view. Each component within the graphical user interface can also provide its own configuration graphical user interface, and GUI creates the system PTF file to describe the system. The build program creates a system HDL description for the target device [15].

3. Results analysis and discussion

In this paper, by changing the ground friction factor to simulate the movement of the robot on different ground, the paper analyzes the adaptability of the quadruped robot with different configurations to the terrain. In Adams, the static friction coefficient static coefficient and the dynamic friction coefficient dynamic coefficient are set as the design variables DV-1 and DV-2 respectively, and the different ground contact conditions are simulated by changing the values of the two design variables. DV-1 is more and less prone to relative sliding, the robot in a larger range of changes in the DV-1 stable walk reflects better terrain adaptability; DV-2 larger, the relative sliding, the robot foot and ground The greater the friction, the more easily off, the range of the two as shown in Table 2.

Table 2. Simulation data of different starting

	Design variable	Standard values	Minimum value	Maximum value
Static friction factor	DV-1	0.65	0.25	0.75
Dynamic friction factor	DV-2	0.55	0.15	0.65

It is found in the simulation experiment that when walking machine adopted symmetrical starting (the supporting foot was symmetrical at the beginning of the support and the end of the support relative to the airframe), the body soon collapsed toward the rear as the robot walks along. After careful observation and analysis, it is determined that the robot flips around the diagonal of the support (the line between two diagonal braces), which is not observed in previous physical prototype experiments. After analysis, it was determined that the value of the step size was very small in the physical prototype test, the original value was 12 cm, and the values in the simulation experiments were greater than 100 cm. The larger the step length, the greater the corner, and the more disadvantageous the walking stability was. With the subsequent step lengths were 600 mm, 450 mm and 225 mm, and the simulation results proved this point. When the step size was 600 mm, the robot fell 1 cycle after the start of the walk. When the step lengths were 450 mm and 225 mm respectively, the robot did not fall during the 20 experimental periods. When the step length was 225 mm, the attitude stability of the robot was better than that of

450 mm (see Table 3).

Table 3. Simulation data for unsynchronized length

Step size (mm)	Root mean square values of the roll angle in walking	Root mean square value of pitch angle in walking
450	1.3	3.1
225	1.2	2.9

In order to study the influence of robot walking cycle on walking stability, the robot cycle was simulated by 1.4 s, 1.0 s and 0.7 s. When the walking cycles were 1.4 s and 1.0 s, the robot fell after less than two cycles after the start of the walk. When the walking cycle was 0.7 s, the whole test cycle (20 cycles) did not fall. Obviously, smaller cycles are good for stability. The longer the cycle, the larger the change of the body of the walker's body, thus resulting in increased collisions and easy fall of the robot.

In order to solve the stability control problem of quadruped robot subjected to lateral impact, a lateral stability control strategy based on CPG and lateral step reflection was proposed. A CPG control network model considering lateral motion of robot was constructed. A trigger mechanism for the quadruped robot was introduced by constructing a trigger with a triggering property for the lateral pendulum of the hip joint. The block studies and reasonable values of CPG network connection weight matrix R were carried out, so as to make the output signal of the front and back rotation of the hip joint and the lateral oscillation oscillator keep the correct phase relationship at any time. Based on the ZMP theory and the linear inverted pendulum model, the magnitude of lateral stride of quadruped robot was predicted from the dynamics point of view. Finally, the joint simulation method of MATLAB/Simulink and ADAMS was used to verify the feasibility and effectiveness of the proposed control scheme. The simulation results show that under the influence of CPG and lateral step reflection, when the quadruped robot is subjected to lateral impact, its lateral acceleration can be restored to the threshold within a relatively short time, and then it terminates the reflection and matches the normal linear walking control scheme. The robot can successfully realize the stability control after the lateral impact of the normal walking, and its ability to resist lateral impact is improved significantly.

The principle prototype of the quadruped robot is shown in Fig. 3. The total mass of the prototype is about 100 kg. It is composed of a frame type airframe and four articulated leg mechanisms. The machine consists of 45 parts, 27 kinds of standard parts and purchased parts, totaling more than 1000 parts. The material is mainly made of 2A12 alloy aluminum, the key connection which needs to be strengthened adopts super hard aluminium 7050, and the joint shaft adopts No. 45 steel. It is mainly made up of robot, thigh side, knee joint and leg assembly, single leg and leg module.

In order to ensure the stability of the quadruped robot control system, it is

Fig. 3. Principle prototype of quadruped robot

necessary to ensure that the data communication of the control system has certain reliability, that is, the data cannot be misrepresented and lost. The purpose of this experiment is to verify the data accuracy of the CNA bus network composed of two main boards through continuous transmission and reception of large amounts of data.

The experimental principle: the gait generator sends 8 bytes to the execution drive as a set of consecutive data, and the execution driver sends the received data back to the gait generator after each data is received. The gait generator compares each received feedback data. If it is the same as the send data, count the correct variable plus 1. If it does not match the send data, count the wrong variable plus 1. Then, through the number of correct data and errors the process of sending, the correct rate of sending data can be obtained.

The prototype of quadruped robot was built in this chapter. Firstly, the CAN bus communication experiment between the gait generator and the executive driver was carried out to verify the reliability and real-time performance of the communication protocol. Secondly, with one leg experimental platform of quadruped robot, the single leg motion control experiment of robot was carried out to verify the rationality of gait generator design and the accuracy of CPG based multi-joint coordinated control method. The frequency response and load characteristics of the single leg were obtained by testing. Finally, based on the test and control performance of hydraulic drive unit, the gait planning test of the prototype was carried out to verify the correctness and effectiveness of gait generation algorithm for Quadruped Robot Based on CPG, so as to lay a foundation for the further movement of the experimental prototype.

4. Conclusion

From the point of view of design and planning, the main factors that affect the dynamic walking stability of quadruped robot were simulated and analyzed. The simulation test method was carried out using ADAMS. Through a large number of comparative analysis and theoretical analysis of simulation experiments, it can be found that there are many factors affecting the dynamic walking stability of quadruped walking robot, which are divided into the following aspects:

Stride length and walking cycle have important influence on walking stability. In order to achieve stable walking of walking robot, both stride length and walk cycle have a maximum limit value. The smaller the step size and the longer the walking cycle, the better the stability of the robot. The quality of walking robot has an obvious influence on the stability of walking. The quality of each component is reduced by employing lightweight material and reducing the size of each component, which can effectively reduce the collision between the ground and the ground when the swinging leg touches the ground, so as to improve the different effects of machine elements, such as the swing leg trajectory planning, supporting the ground, the robot's DOF configuration, damping system design and specific control plan.

However, there were still some shortcomings in this study, such as further improving the robot's ability to adapt to the environment. In this paper, the vestibular reflex and the flexor reflex have been studied, but other biological reflex mechanisms should be introduced to make the robot more abundant.

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