Paper:

Design Methodology of an All-terrain Autonomous Quadruped Robot

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Abstract. The design and control method of a quadruped robot is presented for autonomous cruise over complex terrain. The unique leg design paired with specially modified motors allows the robot to accomplish various tasks with simpler control method and minimum cost. According to a series of real-life tests including hill-climbing, rope-crossing and obstacle-crossing, performance of the robot is proved to be able to meet its design objectives. By verifying performance on real-world prototypes, a new design method of quadruped robot is proposed as an alternative, cost-effective way of achieving certain types of goals.

Keywords: Quadruped Robot; Autonomous Cruise; Image Recognition; Tilt Control; Obstacle-crossing

1. INTRODUCTION

Wheeled robot has been widely used in production and life. It has the ability to move at high-speed and shows stable performance on roads without vertical obstacles. However, on uneven road surface, the wheeled robot might not work as expected, so it is necessary to study the legged robot which is better suited for locomotion on irregular terrain.

Balance is the most important problem in robot motion control. The center of mass position, the zero moment point[1] and the center of pressure[2] are used to measure the balance of robot.[3] points out that the research on the control of the centroid angular momentum enables the legged robot to make a variety of postures to complete the required tasks. Virtual admittance control proposed in [4] is used to control the whole-body angular momentum of the robot, providing an approach for trot gait control. In [5], the hybrid motion mode of the legged robot is achieved, enabling the legged robot to move across steps.

However, the robots in above studies are not designed to execute multiple tasks, therefore the kinetic models are simplified and the dynamic performance of the robots are limited. In [6] and [7], the ZMP index is used to study the translational control of the centroid of the legged robot in 2-D and 3-D space respectively. Although their ignorance of the mass of the leg makes the research results not fully applicable, it provides a new idea for the research of robot's centroid translation. In [8], a new adaptive wheel motion generator is proposed to track the centroid motion of the whole robot, and the dynamic control of the foot robot is achieved with the inverse kinematics model. The high-speed motion of quadruped robot is achieved based on a spring loaded, pantograph mechanism with multiple segments in [9].

There is a common problem in the above design: it is difficult to control because it needs to complete the foot trajectory control through complex solution. And the cost of the robot is very high. A new design method of quadruped robot is proposed as an alternative, cost-effective way of achieving certain types of goals in this paper. The remainder of this paper is organized as follows. 2 introduces the hardware design of the robot, including the structure design and circuit design. 3 introduces the control algorithm of the robot, including tilt control, gait planning and image recognition. The physical test is carried out and the performance of other robots is compared in 4. The design is summarized and the future work is introduced in 5.

2. HARDWARE DESIGN

2.1. Overall Design

The overall structure design is shown in **Fig.1**.

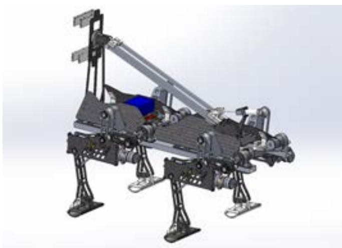

Fig. 1. Overall Design

The mechanical structure of the quadruped robot should be able to meet the design requirements of walking, turning, climbing and crossing obstacles. The strength and stiffness should meet the design standards. All parts of the robot have to be robust and error free. The complete robot is supposed to be easy to assemble and disassemble. It should also have a platform for installing other modules for additional function and leave space for adjustment and setting.

2.2. Chassis Design

Considering the requirements of strength, stiffness and ease of manufacturing, the chassis is made of hollowed aluminum square tube and carbon fiber plates. The chassis is made of ladder shaped frame of aluminum square tube to provide strength. Two 40x20x1 aluminum square tubes are used for longitudinal beams, while 40x20x1 and 20x20x1 aluminum square tubes are used for cross beams. The upper and lower layer of 2mm carbon fiber plates are mounted on the ladder chassis, giving the complete chassis assembly high strength and torsional stiffness. At the same time, carbon fiber plates also provide the platform for legs, motors and other components, as well as a platform for additional modules.

This structure of tube chassis and carbon fiber panels can be cost-efficient and lightweight compared to other manufacturing methods like a machined chassis. For early prototyping stages, carbon fiber plates can be switched to glass fiber plates for even lower cost.

Fig. 2. Chassis Design

2.3. Leg Design

2.3.1. Motion Trajectory Design

To meet the requirements of stable trajectory and good control of thigh, a crank-rocker four link fixed trajectory design for thigh is used. The calf is driven by a screw drive mechanism, and the nut drives the connecting rod to control the angle of the calf. **Fig.3** shows the leg structure design, and **Fig.4** shows the trajectory simulation results.

Using a fixed four-link design can guarantee a stable trajectory and a better load distribution. A large proportion of load is distributed on the rocker, therefore less stress is applied to each motor output shaft.

Dimensions of the four link mechanism are calculated so that their trajectory can satisfy normal walking requirements. The trajectory has adequate amount of foot lift to prevent rubbing and have a steady drive stroke to propel the robot forward.

Fig. 3. Leg Structure Design

Fig. 4. Trajectory Simulation Results

2.3.2. Selection of Motor and Gearbox

The eight motors on the robot are RM3508 motor with high output, good stability and low weight. Both thigh and leg should use gearbox to reduce speed and increase torque.

Fig. 5. Motor and Reducer

The screw drive and connecting rod are used as the decelerating device on the calves. The screw with a lead of 8mm is selected to match the motor speed and the designed motion of the leg.The thigh motor uses a self-made planetary gearbox to decelerate. By changing the gears and outer rings, an additional stage is added to the original two-stage planetary gearbox of RM3508, and the final gear ratio is 71:1. The detailed specifications of gearbox are as follows:

Three reduction ratios are respectively $(46/17+1)$, $(46/17+1)$, $(46/11+1)$, that is 3.7, 3.7, 5.1. The total reduction is 71.

The reduction ratios of the original two-stage gearbox of the motor are $(46/17+1)$, $(46/11+1)$, that is 3.7, 5.1, The total reduction is 19.

The modulus of gears in gearbox is 0.5.

Considering the relative low load of the robot, a simple design like this can satisfy the need of this robot. The cost of each motor after the modification can be less than 1000CNY, which is only a fraction of what most quadruped robots use currently. Therefore, for light load applications, the method above can be more economical than a custom-built motor.

2.3.3. Leg Structure Design

To achieve good strength, stiffness and weight, the upper and lower legs are made of carbon fiber plates cut to a specific shape and assembled with 3D printed parts. Through optimized shapes and combination of different thickness plates, the legs can achieve a great strength-to-weight ratio. The leg design is shown in **Fig.6** below.

Fig. 6. Leg Structure Design

The mechanical structure of a leg using fiberglass panels during an early stage of development is shown in **Fig.7**.

Fig. 7. Leg Physical Figure

To meet the requirements of torsional stiffness, the axles in thigh, rocker and calf is oversized hollow aluminum axles with a minimum of 15mm in diameter. Different models of deep groove bearings are used in each pivot to provide smooth rotation and good tolerance. To ensure the stability of the robot, the foot has a extended width to keep the robot steady, and also a arc shape makes it easier for the robot to cross the obstacle.

2.4. Accessory Design

A battery holder is mounted on the chassis to ensure the stability of the battery and adjust the center of mass. Similarly, the chassis also has an emergency stop switch together with an remote control emergency stop switch to ensure the safety of the robot and operators. A camera and a Mini PC are installed at the bottom of the chassis for the robot to sense the environment.

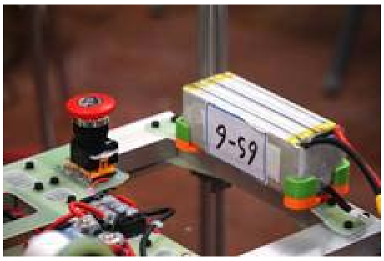

Fig. 8. Attachment Design

2.5. Circuit Design

The electrical system of the quadruped robot consists of main control circuits, four leg subsystems containing 8 motors and 8 motor speed controllers, a power distribution module, and a solenoid valve control system.The electrical system design is shown in **Fig.9**.

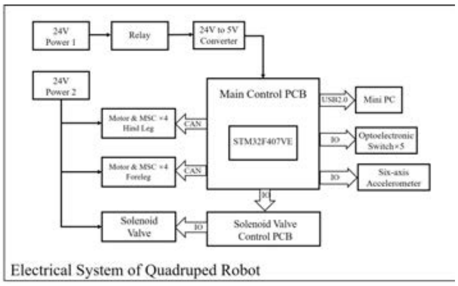

Fig. 9. Electrical System Design Overview

To avoid back EMF caused by DC inductive loads such as solenoid valve and motor at the moment of power on and off, a power distribution module is adopted to isolate the power supply of motor and solenoid valve from that of MCU. The main control PCB and solenoid valve control PCB are designed respectively.

The main control PCB is designed based on STM32f407VE with adequate peripheral interfaces to ensure its flexibility and extensibility. The solenoid valve PCB is powered by a 24V battery different from the main control PCB. Its control signal is provided through the main control PCB's GPIO.

Power MOSFET IRF540NS in **Fig.**10 controls the make-and-break of solenoid valve, and optical coupler TLP785 realizes high/low-voltage isolation.

Main peripherals include: M3508 P19 Brushless DC Gear Motor, C620 Brushless DC Motor Speed Controller(MSC), Mini PC, and sensors such as optoelectronic switch, six-axis accelerometer, camera. A relay is connected between the 24V batteries and the main control circuit with a push button to serve as an emergency stop to disconnect power to the robot.

To realize distributed control and real-time control of the system mentioned above, CAN bus is selected as the communication mean of the communication link.

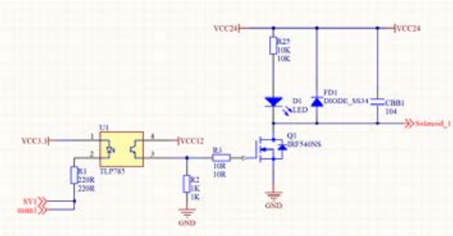

Fig. 10. Schematic Design of Solenoid Valve Control PCB

3. CONTROL ALGORITHM

3.1. Control Block Diagram

The quadruped robot designed in this paper is a fully automatic robot.The robot takes STM32 single chip microcomputer as the control core. The external information data is obtained by the camera, and the analysis results are sent to the single chip microcomputer after being processed by mini PC. At the same time, the single chip microcomputer can also capture the attitude angle information sent by the gyroscope and the distance information sent by the infrared sensors. After analyzing and processing the above data, the single chip microcomputer makes control decisions, gait planning. It carries out tilt control to ensure its own posture balance. The overall control block diagram is shown in **Fig.11**.

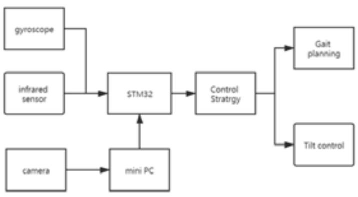

Fig. 11. control-block

3.2. Tilt Control

The attitude of quadruped robot can be expressed by roll angle, pitch angle and heading angle. JY61 sensor is used to feed back the angle information of the quadruped robot. The precision range is within 0.1° and the data is sent to MCU through serial port.

To prevent the robot from turning over, the upper plane of the robot is required to be horizontal all the time. Therefore, it is necessary to control the center of gravity and tilt of the quadruped robot. The four legs of the quadruped robot are $L1, L2, L3$ and $L4$. The distance between the front and rear legs is $2b$, and the distance between the left and right legs is $2a$. The schematic diagram is shown in **Fig.12**.

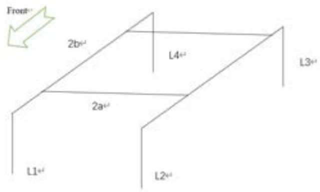

Fig. 12. Structure of Quadruped Robot

Suppose the tilt angle of the front and rear tilt is θ_{FR}. To keep the upper plane of the robot horizontal, according to the structure diagram and the front and back tilt side view, $2b$ is the distance between the legs of $L1$ and $L4$, and $L1 + L4 = m$. M is a constant, then:

$$L1 = \frac{8b^2(1-\cos\theta_{FR}) + 4bm\sin\theta_{FR}}{2m + 4b\sin\theta_{FR}} \tag{1}$$

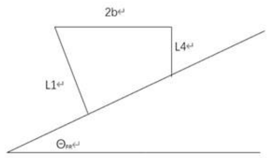

Fig. 13. Front and Rear Tilt Side View of Quadruped Robot

Suppose the tilt angle of the left and right tilt is θ_{LR}. To keep the upper plane of the robot horizontal, according to the structure sketch and the left and right tilt side view, 2a is the distance between the legs of $L1$ and $L2$. $L1 + L2 = n$, n is a constant, then:

$$L1 = \frac{n + 2a\tan\theta_{LR}}{2} \tag{2}$$

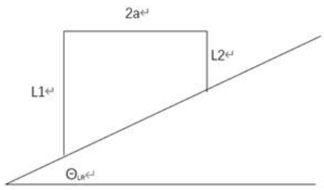

Fig. 14. Left and Right Tilt Side View of Quadruped Robot

In this design, the arc trajectory formed by the leg motor driving the leg motion is the optimal trajectory. So the balance can be achieved only by controlling the leg motor to reach the corresponding height.

3.3. Gait Planning

At present, the functions of the quadruped robot include:

1. The robot can move straight and turn in various gaits. Straight walking can be divided into two modes: trot gait and walk gait. The stride mode of trot gait is: $L1$ and $L3 \rightarrow L2$ and $L4$; walk gait is: $L3 \rightarrow L2 \rightarrow L4 \rightarrow L1$.Turning depends on adjusting the walking distance of left and right legs and turning by differential method.

2. The robot can cross obstacles, including crossing steps and ropes.According to the identified rope or step height, adjust the leg height to cross. If the step is too wide, you will choose to climb the step first and then make subsequent judgment.

3. The robot can up and down the slope.According to the above adjustment method, the maximum upward slope is 20 degrees.

4. The robot can jump. The jumping can be realized by moving both hind legs at the same time and landing with the front legs, but there is a certain mechanical loss.

5. The robot can judge its own attitude information and realize autonomous attitude correction.

3.4. Image Recognition

Scale-invariant feature transform (SIFT), is a computer vision algorithm which can detect and descript local features in a figure. The features are extreme points in the spatial scale and the SIFT can extract position, scale, rotation invariants of features. This algorithm has its own patent whose owner is the University of British Columbia. As in Lowe [10], SIFT was divided into four steps.

1. Scale space extreme value detection. Build image pyramid and look for image positions on all scales. Then, use Gaussian differential functions to identify potential points that are invariant to scale and rotation.

2. Keypoints positioning. SIFT use a precise model to determine the position and scale at each candidate position. The choice of key points depends on their stability.

3. Direction determination. Every SIFT keypoint has its own one or more gradient direction. The invariance to transformations such as direction, scale and position can be obtained by these directions.

4. Keypoints description. Around each keypoint, the local gradient of the image is measured at the selected scale. These gradients are converted into representations which allow large local shape deformations and light changes.

SIFT is used to detect obstacle like ropes and stairs in this module. The coordinate of each feature point would be recorded and once a row of linear feature points is detected, the system directs the robot to make cross-obstacle actions.

As shown in **Fig.16**, it is clear that feature point focuses on the edges of the rope which is the signal of obstacle detection. This method depends much on the stability of the camera views even high frame rate can be realized with using SIFT. Besides, the texture of floor would also increase uncertainty. In our experiment, this module performs well in a clear environment and disordered texture background.

Fig. 15. Original Rope Image

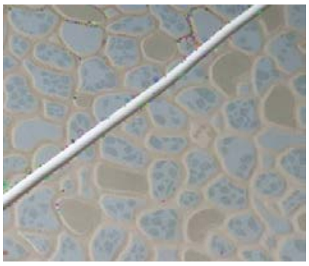

Fig. 16. SIFT Detection Results

4. PHYSICAL TEST

Series of basic tests are carried out on an even terrain to test the mechanical robustness of the quadruped robot, and the performance of different motion pattern is tested, as shown in the following figure, where **Fig.17** is the maximum speed test of trot gait, **Fig.18** is uphill test, **Fig.19** is step test, and **Fig.20** is rope crossing test.

Fig. 17. Maximum Speed Test of Trot Gait

Fig. 18. Uphill Test

Fig. 19. Step Test

Fig. 20. Cross Rope Test

The robot is then placed on an obstructed terrain. When an obstacle is detected in front of the robot, the camera can not detect the height of the step or rope. At this time, the robot will switch from trot gait to walk gait, slowly approaching the rope or step through small step fine adjustment, and then measure the height of the step or rope through the infrared distance measurement module under the front of the vehicle. Raise the lower leg to the corresponding height for crossing. At the same time, the front of the quadruped also contains a ranging module, if the measured step height is higher than the body height, it chooses to detour. If the measured rope height is higher than the body, it adjusts the leg height to lower the body and pass from below.

We compare quadruped robot with Boston Dynamics produced by internationally well-known Boston company and the best performance AlienGo in Chinese market at present. The performance metrics of those robots are shown in **Table.1**.

Table 1. Performance Comparison

category	Ours	ALIENGO	Boston Dynamics
Maximum walking speed(m/s)	1.5	1.5	2.8
Maximum rope crossing height(m)	0.2	0.15	0.2
Maximum angle of uphill	20°	15°	20°
Maximum height of steps(m)	0.15	0.15	0.2
Environmental awareness	Poor	Medium	Strong
Anti disturbance capability	Medium	Medium	Strong
Maximum load(kg)	5	$5 \sim 10$	26
Endurance time(h)	$1 \sim 2$	2	Unknow
Price(K)	15	100	530

According to the above comparison, the performance of the quadruped robot designed in this paper is similar to the quadruped robot sold in the Chinese market in terms of walking speed, rope crossing height, uphill, weight-bearing and endurance, but the control difficulty is far lower than other robots Compared with the internationally famous robot companies, although the proposed robot does not reach the performance of Boston Dynamics, the manufacturing cost is far lower than that of the robots on the market. Except for weight-bearing capacity, there are no significant gap in other performance metrics.

5. CONCLUSIONS AND FUTURE WORK

This paper provides an overview about an autonomous quadrupedal robot that is capable of navigating on obstructed terrain. The efficiency of the proposed design was shown through several actual experiments.

The main achievements are summarized as follows:

1. The proposed combination of system design, actuation and control principle enable robust locomotion of the quadrupedal robot.

2. From a design aspect, the use of fixed four-link design simplifies the control of the robot. Hardware modularity and extensibility allow fast maintenance and convenient function adjustment in each iteration.

3. The cost of the robot is far lower than that of other robots on the market under the premise of completing various tasks.

While we have shown that the proposed quadruped robot is able to execute different gaits and meets commercialized quadrupedal robot in certain performance metrics, there are some remaining issues. Further work focuses on achieving higher dynamic motions as well as dexterity to handle greater mechanical impacts.

Acknowledgements

The authors thanks anonymous reviewers for their valuable suggestions and comments that have helped improve the presentation of this paper. This work was supported by the Beijing Municipal Natural Science Foundation under Grant No.3192028.

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