A Design of Humanoid Foot Control System

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Abstract. Humanoid robots can be used in high-risk operations or to replace human repetitive tasks. The basis of its various subsequent functions is the stability of biped walking. A humanoid foot structure which adapts to the ground condition and changes the contact mode is designed. The mechanical structure of robot foot is divided into two parts: front sole and rear sole. Using flexibility force transducer array and temperature transducer to monitor landform and ground data. The mechanical structure of this humanoid robot foot is such that the robot can realize passive deformation of the foot. The active deformation of the robot foot is realized by STM32 controlling servo. The structure contains four kinds of working modes, can make the robot achieve semi-passive walking, with certain robustness. In this paper, we design the mechanical structure of the robot foot and its control method. Finally, the feasibility of the foot structure is verified by experiments.

Keywords. Robot foot; flexible sensors; humanoid robot.

1. Introduction

The foundation of humanoid robot is bipedal walking, which make varieties of subsequent functions realize. Bipedal robots are designed to imitate human behavior, so it can integrate into the environment of human work and life, replace or work with human beings, and use many tools designed for human beings. The ultimate goal of the humanoid robot application is to replace human to complete various repetitive labor or dangerous operations. Therefore, it is of great significance to improve the ability of bipedal walking for robot work. Thus it is an urgent task to improve the environmental adaptability of robot feet and deal with all kinds of unexpected situations that may occur when working in a complex unknown environment.

Numerous researchers in related fields have focused on the humanoid robot stability control of walking and proposed many effective methods. A robot without any elastic mounted parts was designed, and an intuitive control method was proposed to balance foot contact forces [1]. The space crawling robots was studied, and an adhesive microarray structure was proposed. The contact area on the adhesion characteristics of the microarrays in zero-gravity space environment were analyzed [2]. The high flexibility and high adaptability of the biped robot is the natural advantage compared with the mobile robot of the track type, the wheel type, the crawling type and other mobile robots [3]. A fusion method was proposed to predict the falling over of humanoid robots using inertia measurement unit and gyroscope (IMU), foot pressure sensor (FPS), etc. [4]. Since the biped robot contacts the ground through the sole of its foot, the dependence of the path selection on the external environment is small, and a discrete landing point motion can be selected under a complex non-structured environment [5]. A static analysis-based method through establish the energy consumption model of the robot is proposed. To obtain the low-energy postures of the robot an equilibrium solution based on energy consumption and maximum step size was analyzed [6]. Therefore the double-foot robot can not
only be used for walking on the flat, but also adapt to various non-structured environments such as accident site, narrow space, step and slope, etc. [7]. Active contact terrain perception was adopted and a contact force/torque control method was proposed to traversing unstructured environment based on the viscoelastic model which avoids to a difference between planned foot landing positions and actual foot landing positions [8]. The hopping performance evaluation on three types of terrain sand novel foot pad was designs for efficient traverse of hopping rovers [9]. At present, the design of foot structure of robot mainly focuses on the design of different subsystems, including ankle joint structure, front and rear palm structure, arch structure and Achilles tendon structure [10]. Through the design and optimization of the subsystem, the motion ability and environmental adaptability of the whole foot mechanism can be improved. In this study, a kind of humanoid robot foot is designed and implemented. The validity and practicability of humanoid robot foot is verified by experiments.

For walking robots with complex foot control system, this project designs the functions of real-time perception of contact surface, ground environment recognition and attitude adjustment to provide environmental information for the robot, which can be extended to the autonomous field robot. It can help the robot to move stably and efficiently on the changeable terrain.

2. Flexible Foot Mechanism Design

Elongation within a sub-tendon did not differ level with the foot in neutral, inversion and eversion [11]. The elongation differences between the sub-tendons were not affected by foot position. Therefore, this paper designs a foot structure which can adapt to the ground condition and change the contact way. The structure contains four kinds of working modes.

1. When the pressure or temperature of the front sole is too high, the steering gear turns clockwise through the rigid rope to pull the front sole and lift the front sole.
2. When the pressure or temperature of the back sole is too high, the steering gear turns counterclockwise through the rigid rope to pull the back sole and lift the back sole.
3. When the robot walks on the uneven ground, the front sole can be lifted because it is hinged with the rear soles. At this point, the front sole will pull the spring on back sole stretched by the rigid rope, and the elastic potential energy of the spring will restore the front sole to the same when the foot is lifted again.
4. When the temperature of the sole of the whole foot is too high, it is suggested to lift the foot, and the robot overload will give a warning.

2.1. Structure of Foot

The mechanical structure of robot foot is divided into two parts: front sole and rear sole. The front sole consists of palm steel wire, torsional spring, shaft, motor, flexible temperature and pressure sensors. The rear sole is composed of tension spring, steel wire, and flexible temperature and pressure sensors.

Front sole: When the force on the bottom of the forefoot is too large due to stepping on the uneven ground, the front foot soles can be lifted passively through the rotating shaft, and the lower foot surface will pull the steel wire at the same time. When the foot soles pressure sensor detects that the pressure is too large or the temperature is too high, the electric opportunity drives the rotating shaft to pull the front soles of the front feet through the steel wire. In order to prevent the front and rear soles from lifting the front foot because the angle is too large, so the upper foot surface and the lower foot surface will have a certain angle.

Rear soles: Flexible temperature sensors and flexible pressure sensors will be discharged in array on the soles of the rear soles of the feet. When the temperature is too high or the pressure is too high or the pressure is too high, the foot can be raised. When the soles of the feet are lifted, the steel wire will pull the tension spring, and when the front soles need to fall, the stretched spring will restore the front soles to the original by pulling the steel wire. The top view of the foot mechanical structure is shown in figure 1.
2.2. Pressure and Temperature Sensitive Module
Using flexibility force transducer array and temperature transducer to monitor landform and ground data. When facing the high temperature or high pressure, the foot needs to feedback the information to robot to avoid instability or even breakdown. If the data is inaccurate, the foot will not adjust the ground ideally. Therefore, the design of sensor array also decides the accuracy. The array of temperature and pressure sensors is shown in figure 2.

Figure 1. Top view of the foot end structure.

Figure 2. Sensor array.

2.3. Motor Control Module
The foot movement is controlled by STM32 control step motor. Considering the stability when robot walking on the ground, the foot need change its shape to adjust the different condition. For example, lifting forefoot immediately when robot detects the temperature of forefoot is too high. To adjust the foot accurately, the control of stepping motor is of vital importance. The side view including the steering gear is shown in figure 3.

Figure 3. Side view of the foot end structure.

3. Foot Movement Control Method

3.1. Feedback and Sampling
The foot movement in different terrain needs to be adjusted accordingly. The ground information must be obtained by sensors, and then the foot movement can be controlled by feedback system. Feedback system, the nerve center of robot, decides the sensibility of react. So the feedback of information is also the key of realization. Robot cannot walk placidly or protect itself without feedback. Closed loop control system of foot is shown in figure 4.
3.2. Control Method
The program block diagram of foot end control system is shown in figure 5. The maximum pressure of forefoot is ‘P fmax’. The maximum pressure difference between hindfoot and forefoot is ‘P dmax’.

![Figure 4. Closed loop control system.](image_url)

![Figure 5. Side view of the foot end structure.](image_url)

4. Prototype Experiments and Results Analysis

4.1. Foot Sensor Statics Numerical Test
In order to control the movement of the foot, the pressure threshold needs to be determined. Beyond this threshold, the robot is unbalanced and prone to fall in the current gait. In this experiment, by changing the height of the obstacle, the walking pressure of the forefoot at the foot end was measured, and the pressure at the time of tipping was recorded as the pressure threshold. According to the experiment, the maximum pressure of the forefoot is 10 N, and the sensor and its output voltage are shown in table 1.

4.2. Robot Foot Static Attitude Test
When the robot is walking, it will lose its balance because of the uneven ground, and cannot walk normally. Therefore, it is necessary to measure the pressure difference of the sole pressure sensor when it will be unbalanced. Because the center of gravity of the robot is on the back foot in static state, this experiment makes the robot stand in two kinds of postures, and increase different height on the back foot. When the robot loses balance, the pressure difference between the front foot and the back foot is measured. Take the minimum value of the two pose data as the maximum pressure that can be
borne. From the experiment, it can be concluded that the maximum pressure difference that the foot can bear is 20 N, and the static pose is shown in figure 6.

Table 1. Foot sensor static numerical test.

| Pressure sensor | Sole pressure (N) | Voltage of sensor (V) |
|-----------------|-------------------|-----------------------|
| Forefoot        | 0                 | 0.24                  |
|                 | 10                | 2.10                  |
|                 | 20                | 2.70                  |
|                 | 30                | 2.79                  |
|                 | 0                 | 0.24                  |
| Hind foot       | 10                | 1.74                  |
|                 | 20                | 3.00                  |
|                 | 30                | 3.60                  |

(a) Standing on one foot  (b) Standing on two feet

Figure 6. Robot feet landing positions.

4.3. Static Numerical Test of Foot Temperature Sensor

In order to protect the foot from damage when the foot moves, the output voltage threshold of the temperature sensor needs to be determined. Beyond this threshold, the robot’s feet will be damaged, and its stability and safety cannot be guaranteed in the current gait. In this experiment, by changing the temperature of the foot contact environment, the voltage of the foot temperature sensor is measured when the foot is walking, and the output voltage of the sensor is used as the output voltage threshold when the temperature reaches the maximum temperature that the foot device can bear. The sensor and its output voltage are shown in table 2.

Table 2. Temperature sensors statics numerical test.

| Temperature (°C) | Voltage of sensor (V) |
|------------------|-----------------------|
| 23               | 2.0                   |
| 90               | 2.2                   |
| 130              | 2.8                   |
| 200              | 3.2                   |

4.4. Dynamic Walking Calibration Experiment

In order to ensure that the robot can achieve the desired function when walking, it is necessary to calibrate and modify the measured data through experiments. In this experiment, the robot moves and records the output voltage to calibrate the measured data. The walking process is shown in figure 7.
5. Conclusions
A humanoid foot structure which adapts to the ground condition and changes the contact mode is designed. The mechanical structure of robot foot is divided into two parts: front sole and rear sole. Using flexibility force transducer array and temperature transducer to monitor landform and ground data. Feedback system is the nerve center of robot, which determines the sensitivity of response. The foot movement is controlled by STM32 control step motor. Considering the stability when robot walking on the ground, the foot need change its shape to adjust the different condition. In this paper, the control method of the structure is designed. And the foot can perform four action modes. Finally, the feasibility of the foot structure is verified by experiments.

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