A Novel Design of Flexible Foot System for Humanoid Robot

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***Abstract*—The Large-scale uneven ground is mostly unsmooth and in the irregular state in which the irregularity is usually unknown (such as footway, carriageway, unexplored desert, mountainous area, surface of the Mars). In order to walk steadily and rapidly on such ground, a chief problem to overcome is that the humanoid robot's foot is not matching with the unknown model of the ground. Therefore, the humanoid robot's foot should have the flexibility mimic the human's foot, and can adapt to and steadily interacted with any unsmooth ground. Also interferences and disjoints between soles and irregular unsmooth ground should be avoided. Aiming at solving the key problem for humanoid robot to steadily and rapidly walk on the large-scale and three- dimension uneven ground, we've set up a new multi-degree-of-freedom flexible foot mechanism which can make the humanoid robot's walking gesture and gait automatically adapt to the terrain, and then carry out the research of the globally stable control of the gait. The flexibility can obviously improve the humanoid robot's walking stability and speediness on the large-scale uneven ground.**

***Keywords*—humanoid robot, flexible foot system, locomoting on uneven ground**

I. INTRODUCTION

The foot structures in the research of traditional humanoid robot are mostly rigid and flat. Also these structures have not characteristics and functions of automatically adapting to the uneven terrain. In existing research results[1,3], when a humanoid robot is walking on the uneven ground according to the pre-designed gait, as shown in Fig.1, its flat soles could not maintain the large-scare four-point contact on the uneven ground while its foot meets obstacles. Because the contact points between sole and ground are less than four and the contact area between sole and ground is less than the sole area, the ZMP stable point is outside the support region. Therefore, it directly causes that the humanoid robot can not walk successfully on the rough ground. Here, we propose a new flexible foot system that can automatically adapt to the three dimensional terrain. Our proposed system will serve as the foundation for future research on making humanoid robot steadily walk on the large-scale and three- dimension uneven ground.

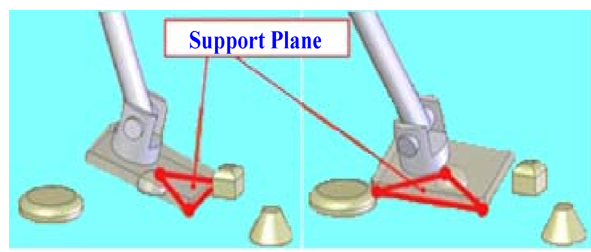

Figure 1 The Contact Condition of Humanoid Robot Rigid Plate Foot with the Smooth less Ground

Up to now, most research institute's research on humanoid robot's steady walking on the large-scale and three-dimension uneven ground mainly aim at walking on regular steps, regular slope or ground that has only uniform unsmooth mode. Under such circumstance, we can make the humanoid robot steadily walk on the uneven ground through several methods, such as: 1) Installing rubber pads[5] or other energy-absorbing materials[6] on the rigid and flat sole to reduce vibration; 2)Making non-degree of freedom structural improvement such as human-like foot arch and the front part of foot curving upward; and 3)Effectively controlling the dynamic walking. Till recent years, along with the research on humanoid robot's steady walking on the indoor uneven ground gradually grow up, more complicated research on humanoid robot's steady walking on the large-scale outdoor uneven ground is gradually involved. We could only find few foot systems for walking robot in recent years that can avoid the interference and disjoin between the soles and irregular unsmooth ground[7,8]. In 2005, Hashimoto developed a new foot system of biped walking robot capable of maintaining four-point contact[2,8]: adding four supporting legs which have cam-type locking mechanism and can move along Z-Axis to the rigid and flat sole, it assures that the biped walking robot can maintain four-point contact on the ground while walking, and the contact area between sole and ground can be the same as the sole area. It has been proved that under the new foot system the biped walking robot can walk steadily on the real uneven ground. The development of the new foot system of biped walking robot capable of maintaining four-point contact has proved that the innovation institute can greatly boost the development of the walking capability of the humanoid robot. But the middle part of foot in the new foot system is still rigid and flat, so the highest point of the uneven ground that humanoid robot's foot can adapt is restricted, and it should less than 20mm. In 2006, Yoon[7] developed a new 4-DOF foot system which separates the rigid and flat sole into front-left, front-right, and rear platforms, and the front-left stands for big toe and front-right platforms stands for four other toes. And then the new 4-DOF foot system uses rigid connective mechanism to allow the front platform generate pitch motion and allow the rear platform generate roll motion, and the two platform will bear the whole weight of the humanoid robot. Such human-like design of sole makes the humanoid robot walk more naturally and the humanoid robot's walking gesture to be more close to the human beings. Frenchman Sellaouti[4] developed a humanoid robot named ROBIAN. ROBIAN's foot architecture has one degree of freedom of motion, and its front part of sole can move around the middle axis of the foot. Thus, it forms the function of curving and supporting just like the human's front part of foot. Such foot system designed by Yoon and Sellaouti still has limitations that there is large scale flat area and the motion direction is single (the sole can not curve horizontally downward). The foot system just makes the foot feature similar to human beings, but it can not assure that humanoid robot steadily walk on the large-scale uneven ground.

Through comprehensively analyzing we find that many researchers are trying to increase the number of the DOF in order to improve the flexibility of the foot as to achieve the goal of adapting automatically to the three dimensional uneven terrain. By using the merits of the above foot systems for reference, improving the limitations that the max DOF is only four, there is still large scale flat area, and the adaptability to the three dimensional terrain is restricted, and referring to the degree of freedom of the human sole and then making greatly and multi-directionally improvement, we propose a new flexible foot system that has more DOF to realize the multi-dimensional attachment and stable contact on the unsmooth ground in the space scope.

II. THE ESTABLISHMENT OF NEW FLEXIBLE FOOT SYSTEM

A. The design principles of new flexible foot system

- in the structure, it consists of flat pieces of small area;
- in the function, each flat piece can independently move up and down or left and right, and it can also generate pitch motion, the contact point between sole and ground can move back and forth so the sole can perfectly attach to the unsmooth ground.

In order to avoid excessing degree of freedom, make the mechanism less complicated and reduce the difficulty of control, we choose the number of flat pieces on each foot as four, and the front two pieces are utilized for mimic the motion of human toes and the backside ones are used for improving the adaptability of the rear part of foot to the ground.

B. The structure of the flexible foot system

The four flat pieces of the flexible foot system are connected with each other by the coupling and revolute joint. The motion principle is shown in Fig.2. In the figure, the rubber nail under front part of each flat piece can move back and forth and the rubber nail under back part of each flat piece is fixed. The fixed rubber nail generates the pitch motion while the movable rubber nail moves and realizes the adjustment of the supporting point. These motions can avoid the interference between the rubber nail and the ground. Those four flat pieces' movement and pitch motion based on the ground features will ensure that each flexible foot could has at least four contact points on the ground, and the contact area could be as large as possible. When there are convex obstacles on the ground, the four flat pieces form a conical pyramid shape package. When the robot meets concave obstacles, those four flat pieces contact with the ground just like the funnel.

In relative to the traditional rigid flat sole and the flexible foot systems developed by Hashimoto or others, our new foot system has several merits: the max number of DOF of motion on each foot is 12, the motion ability is multi-directional and more flexible than human feet, thus it can really automatically adapt to the complicated terrain.

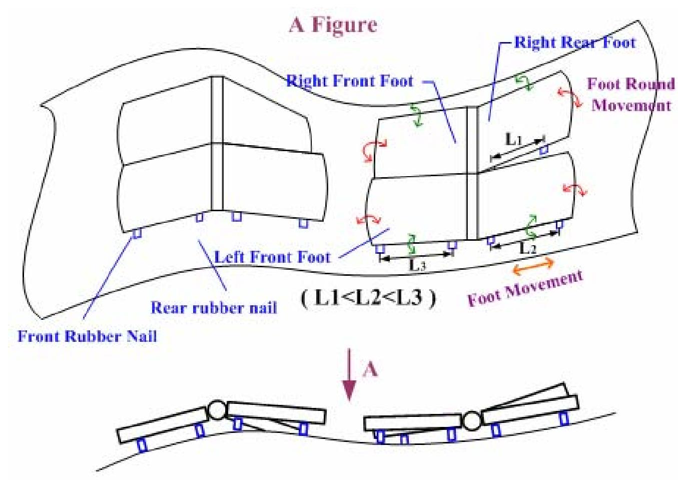

Figure 2 Flexible foot and ground stable contact movement principle

III. THE REALIZATION OF THE FLEXIBLE FOOT SYSTEM'S ADAPTABILITY TO THE GROUND

The flexible foot system is the base to carry out functions for dynamic walking of humanoid robot. Fig.3 shows the configuration and schematic diagram of our primary design. In the following section the flexible foot system will be explained respectively.

Each flexible foot is composed of four tiny fore- and rear-feet, which can pitch up and down independently. Also it has a wring between the tiny fore-foot and rear-foot so as to make sure the whole foot can keep a certain original gesture and strength, as view A in Fig.3. Every tiny foot has a spring below it. Driven by micro-electric motor through flexible cable, the front touchdown rubber nails which are connected with springs can move backward and forth. Thus distal supporting points under each tiny foot can properly adjust its touch point according to the ground concave and convex condition.

Driven by another micro-electric motor inside leg through flexible cable, each tiny foot's front upper end enables feet to adjust its up-down pitching angle (according to the information collected by sensors fixed in four corners and the middle of the sole), thus enable the front rubber nails to touch the ground with proper force. All micro-electric motors are installed inside legs in order to lighten the weight of feet. The compact configuration can reduce the complexity of foot mechanism, improve the controllability, and lift robot's mass center. The flexible foot has eight degrees of freedom, among which four pitch motions around Y axis and the other four along X axis. These ensure that each tiny foot has at least one point to touch steadily with the concave convex ground. Besides, wrings can be added between tiny left and right front-feet, and then another two flexible cables and micro-electric motor can be added, thus to increase rotation degrees of freedom around X axis and further achieve to pitch around X axis. As a result of 12 degrees of freedom, the flexible foot can steadily touch spherical or quasi- spherical obstacles.

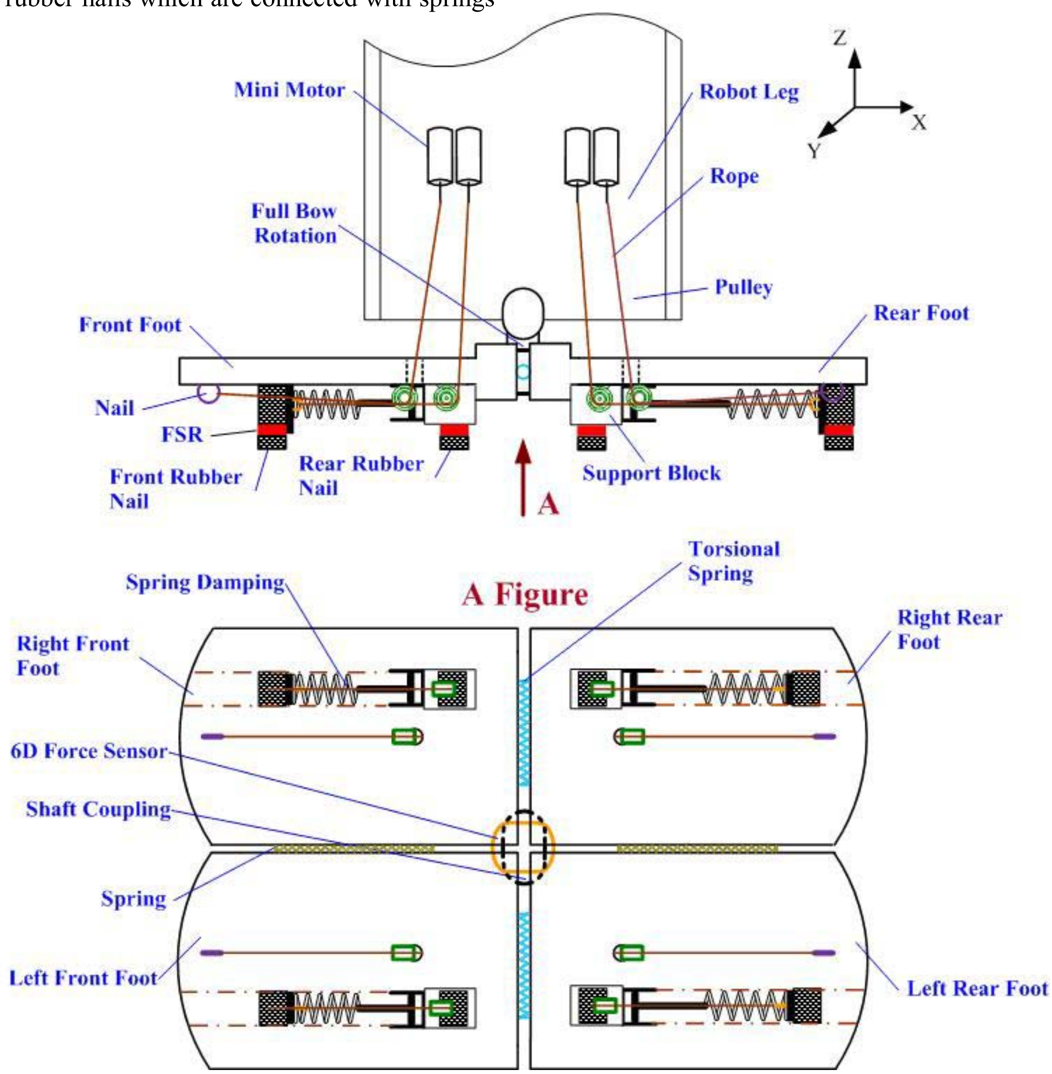

Figure 3 Flexible Multi-DOF Foot System

Eight thenar rubber nails cooperate to form stereo three-dimensional spatial four points (or more) ground touch. It keeps to have the projected area of the fore stereo points in horizontal plane as large as possible, so as to ensure the mass center of the apery robot to be in the area of ZMP Area. Tiny feet can adjust its support points to proper stereo place according to the curvature data of the concave convex ground. Every degree of freedom movement is driven by motor to avoid couplings. The volume of motor is small (diameter: about 1.2cm, length: about 3 cm). Though it increases the number of actuator, it decreases transmission components and reduces the complexity extent of mechanism and control as a whole. *Fig.2* is a schematic diagram showing the flexible foot steadily touches the three-dimensional concave convex ground.

IV. KINEMATICS

For design flexible foot system, the kinematics of the flexible foot mechanism is analyzed. The kinematic parameters in equations are illustrated in Fig.4. The fixed base reference

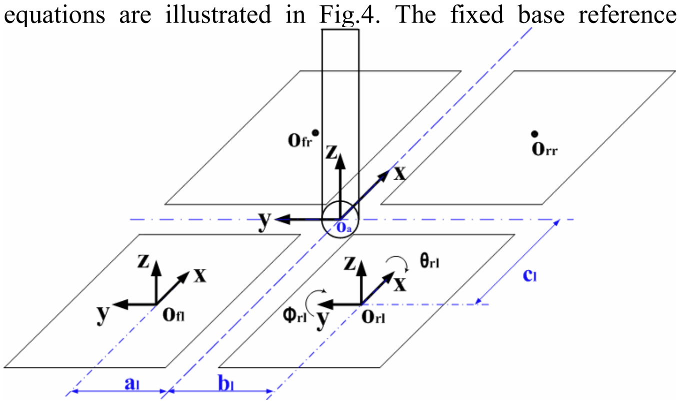

Figure 4 The kinematic model of the foot mechanism

frame, $O_b = (X_b, Y_b, Z_b)$, is located at the ground. Local reference frame for the two rear platforms, $O_{rl} = (X_{rl}, Y_{rl}, Z_{rl})$, $O_{rr} = (X_{rr}, Y_{rr}, Z_{rr})$, is located at the center of the rear left and right platforms. Local reference frames for the front-left $O_{fl} = (X_{fl}, Y_{fl}, Z_{fl})$ and the front-right $O_{fr} = (X_{fr}, Y_{fr}, Z_{fr})$ are centered at each front platform, respectively. The ankle, $O_a = (X_a, Y_a, Z_a)$, mobile reference frames is located at the center of the flexible foot system.

Firstly, the rear left foot plate is discussed as following. The orientation (θ_{rl}, ϕ_{rl}) is given for the rear left tiny foot plate, where θ_{rl} is the pitch motions at rear left plate, and ϕ_{rl} is the roll motion of plate. Position O_{rl} can be represented in the base reference frame $O_b = (X_b, Y_b, Z_b)$ as:

$$O_{rl} = O_a + R_y(\phi_{rl}) R_x(\theta_{rl}) T_{rl}^a(-c_L, -b_L, 0) \quad (1)$$

Similarly, coordinate positions (O_{rr} O_{fl} , O_{fr}) of the other three mobile reference frame can be represented in the base reference frame $O_b = (X_b, Y_b, Z_b)$ as:

$$O_{rr} = O_a + R_y(\phi_{rr}) R_x(\theta_{rr}) T_{rr}^a(c_L, -b_L, 0) \quad (2)$$

$$O_{fl} = O_a + R_y(\phi_{fl}) R_x(\theta_{fl}) T_{fl}^a(-c_L, a_L, 0) \quad (3)$$

$$O_{fr} = O_a + R_y(\phi_{fr}) R_x(\theta_{fr}) T_{fr}^a(c_L, a_L, 0) \quad (4)$$

where R is the rotation matrix, $T_{rl}^a(x, y, z)$ is the translation matrix from local reference frame $O_{rl} = (X_{rl}, Y_{rl}, Z_{rl})$ of the rear left plate to the ankle mobile reference frame $O_a = (X_a, Y_a, Z_a)$, c_L is the distance of y-axis from center position O_a of the ankle to coordinate position in each plate's mobile reference frame, b_L is the distance of x-axis from the ankle position O_a to the coordinate positions O_{rl} , O_{rr} of rear plates, a_L is the distance of x-axis from the ankle position O_a to the coordinate positions O_{fl} , O_{fr} of front plates.

The inverse kinematics computes the cable driven actuator displacements $(\Delta L_x, \Delta L_y)$ of the cable mechanism for each foot plate given the orientation (θ, ϕ) for each foot plate. Take the rear left tiny foot plate for instance, the displacement of cable could be:

$$\Delta L_x^{rl} = \theta_{rl} D / 2 \quad (5)$$

$$\Delta L_y^{rl} = \phi_{rl} D / 2 \quad (6)$$

where D is the diameter of the pulley in the cable driven mechanism.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a new flexible foot system which can perform complicated dynamic motion. The whole foot system occupy 12 degrees of freedom. These motions in 12 degrees of freedom could cooperate with each other in the moment the foot contact with ground and the foot should move or generate pitch motion properly in each degree of freedom. Only by doing this can each small piece in the foot system steadily and closely contact with the proper contact point of various unsmooth ground and can it take the advantage of the flexibility and adaptability to the ground. So, in the next step of research of humanoid robot walking on the three-dimension uneven ground, we will study to set up kinetics/kinematics models of small foot system in multi-degree of freedom, and thus lay a foundation for settling the overall stability of humanoid robot.

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