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The Development of a Mobile Humanoid Robot with Varying Joint Stiffness Waist

ZHAO Tiejun
Shenyang University of Technology
58, Xinghuanan street, Tiexi district shenyang, 110023, China
tj_zhao@tom.com

Tan Dalong , ZHAO Mingyang
Shenyang Institute of Automation of the Chinese Academy of Sciences, Shenyang 110016, China
myzhao@sia.ac.cn

***Abstract* -A mobile humanoid robot named YIREN has been developed as a platform for the research on intelligent robotics. The robot consists of 23 degrees of freedom (DOF), including the mobile platform, waist, torso, arms, neck and head, and it has two peculiarities: a waist mechanism that could adjust the mechanical compliance suitably and a mobile platform which is an omni-directional mobile robot with orthogonal-wheel assemblies. The design was mainly focused on two essential requirements of safety and mobility. This study aimed at realizing passive compliance of the mobile humanoid robot by its waist, and developing its autonomous navigation ability by its mobile platform. This paper presented a waist mechanism that could vary the joint stiffness. The influence of this waist on the compliant characteristics and the stability of the whole body were studied. The mobile humanoid robot that employs this waist is appropriate for the human-robot cooperative tasks, because it can realize safety motion by performing the waist and varying the joint stiffness while is operating.**

Index Terms - humanoid robot, stiffness, waist

I. INTRODUCTION

Many studies about humanoid robots have been conducted in recent years and most previous studies mainly aimed at realizing human-like motion of legs such as walking, jumping and dancing. But as operating closer and closer with humans, robot's interaction is an increasing research topic in robotics. Thus, the humanoid robot should be not only having high walking stability but also having high arm manipulative flexibility. Humanoid robots developed are classified so far into two categories: the biped humanoid robots and the mobile humanoid robots. The biped humanoid robots have been developed mainly to investigate the fundamental functions of biped locomotion such as walking and turning. The mobile humanoid robots have been developed mainly to study human-humanoid interaction and cooperation[1]. WABOT-1 was the world's first life-sized biped humanoid robot in the world, which was constructed in 1973 by Waseda University[2]. Its successor was named WABIAN (Waseda Bipedal Humanoid). The newest WABIAN: WABIAN-R has a completely humanoid figure with two arms, two legs and a head, and it has capabilities of normal walking, dynamic dance waving arms and hip and dynamic carrying of a load. ASIMO is a biped humanoid robot constructed by the Corporation of Honda, it can walk and turn in any direction, walk up and down stairs continuously, and maintain its balance on uneven ground surfaces[3]. H7, biped humanoid robots developed by University of Tokyo has a strong and light structure because aircraft technologies was applied to its body frame, and it can walk up and down 25cm high steps[4]. HRP was a prototype humanoid robotics project, which had been performing by Ministry of Economy Trade and Industry of JAPAN from 1998 to 2002 for five years. Its robot has an ability to cope with rough terrain in the open air and to prevent tipping over[5]. WENDY—a mobile humanoid robot is a successor of the Hadaly-1 and Hadaly-2 of Waseda University. Its performances have been evaluated by two requirements such as safety and dexterity. It can fulfill tasks such as picking up objects, breaking egg and cutting vegetable[6]. DAV—a mobile humanoid robot developed by Michigan State University has basic capabilities of human beings, such as mobility, dexterous manipulability and tactile sensation. HERMES constructed by Bundeswehr University of Germany is equipped with two arms, a bendable body, a pan-tilt head with two video cameras and an omni-directional wheelbase. Its work space can extend up to 120 cm in front of it when it bends forward 130º, and keep its balance even when the body and the arms are fully extended to the front. ARMAR developed by Karlsruhe University of Germany has anthropomorphic body with 4 DOF on a mobile platform and can be bended forward, backward and sideward. With a telescopic joint in its body the total height of the robot can be adapted.

The waist of human is the center of the whole body that could adjust the center of gravity in order to maintain the human's equilibrium and a typical super-redundancy system that has high flexibility. The waist of humanoid robot with characters of the flexibility and the stability also plays an important role on the reproduction of a human task or operating cooperatively with humans[7][8]. In 1990, Jin-ichi Yamaguchi et. al of the Waseda University used the ZMP (Zero Moment Point) as a criterion to distinguish the stability of walking of a biped walking robot. At the same time they studied the stability of biped robot on the condition that the pitch-axis and roll-axis moments were compensated for by trunk motion. In 1993, they proposed a control method of dynamic biped walking to compensate for the three axis moment by trunk motion. In 1996, they developed a whole body cooperative dynamic walking control method that could stabilize walking by using the trunk or the trunk-hip cooperative motion, which was supported by experiment. There are many studies having been conducted on the safety of humanoid robots. Many approaches of the passive compliance mechanism and the tension control method were adopted. The COG with two compliant 6-DOFs arms that have the resonant properties to perform a variety of rhythmic and discrete tasks including turning a crank and swinging a pendulum. ASIMO can realize impedance control of the robot joint by mechanical elements while is operating light switches and shaking hands.

In 2000, we began the research and development of the humanoid robot. Our goal is to design, analyze and implement a flexible and autonomous mobile robot with handling skills for non-restricted environments. Because good mechanical designs and advanced control schemes would lead to higher performance of a robot, efforts were made to set the location of the joints, their angles of rotation and dimensions of each part at first. The robot has been an anthropomorphic model to be both easy and natural for humans to interact with in a human like way. The upper body is fixed on a mobile robot with orthogonal wheel assemblies. Besides the achievements in the mechanical level of the humanoid robot, efforts were also made to study the control method of the robotic systems. In this paper authors described features of the waist mechanism, the stiffness adjustment of joints and the optimization problem for ZMP by controlling the motion of the waist while operating.

II. THE HUMANOID ROBOT YIREN

The humanoid robot system (shown in Fig.1) is an experimental platform of researching on implemental technology of humanoid robots. The robot is a 23 DOF humanoid form robot with a 3 DOF mobile platform, two 7 DOF redundancy Arms, two 1 DOF hands, a 2 DOF waist and a 2 DOF neck. In order to prevent interfere, the hollow shaft structure is adopted in its waist and arms to route all wires through the inside.

TABLE Ⅰ
SPECIFICATIONS OF YIREN

D.O.F.	Head: 2 D.O.F. (Pitch, Yaw)	
	Arms: 7 D.O.F.x2 (Shoulder: 3, Elbow: 1, Wrist:3	
	Hand: 1 D.O.F.x2	
	Waist: 2 D.O.F. (Pitch, Roll)	
	Mobile platform: 3 D.O.F.	
Movable Range of Each Joint	Head	Pitch: 40º~30º, Yaw: -45º~45º
	Arm	Shoulder Yaw: -5º~90º, Roll: -5 º~85º Pitch: 0º~95º, Elbow Pitch: 0º~95º Wrist Yaw:-150º~150º,Pitch:0º~95º, Roll: -150 º~150º
	Waist	Roll: -30 º~30º, Pitch: -5º~45º

The footprint is an important feature for the mobile robot that has to move in a cluttered environment. Thus an omni-directional mobile robot with orthogonal-wheel assemblies is adopted in the mobile platform of the robot. Many experimental results indicated that the mobile has enough mobility and smooth motion. The AC-motors, Computer, Servo Amplifier and batteries are all installed in the body of the mobile platform.

The upper body consists of waist, arms, torso and head. The waist with 2 DOF of Pitch and Roll is fixed on the mobile platform as a support for torso. The waist is important to keep balance and achieve desired precision of the robot. Thus a series of springs are fixed in the waist to provide accurate

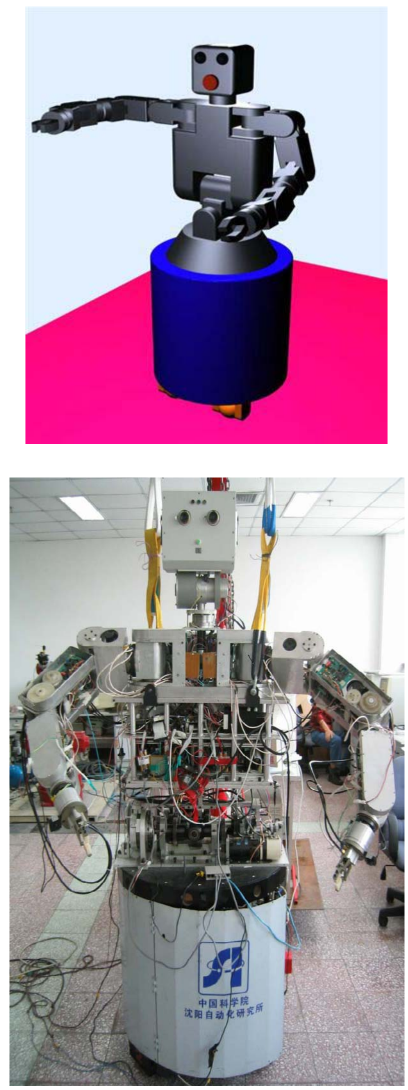

Fig.1 The humanoid robot YiRen

force feedback in each direction and absorb the shock loads from arms and mobile platform. The arms and head are fixed on the torso.

The redundancy arm configuration is similar to a broadly simplified model of the human arm with 7 DOF. The maximum radius is about 1 m with a maximum 2 kg of load. The redundancy of the 7 DOF allows the handling of situation in which additional movement constraints have to meet and avoid static obstacles. It has better adaptation to typical human environment and allows for human-like behavioral strategies in solving complex tasks.

III. DEVELOPMENT OF THE WAIST MECHANISM

A. Development Concept of the waist

There are many shortages of serial mechanism driven directly:

1) The motor and the gear are fixed on moving parts so that the motor and the gear of the rear are the load of the forepart, which increase the load of each motor and impact the dynamics property of joints;

2) The center of gravity of the robot is higher, which leads to poor stability of whole body.

The design of the YIREN humanoid robot waist is according to its special function and the load. The principle is that:

1) The workspace and the degree of freedom of it are similar to the waist of human beings;

2) It has operational flexibility and high precision at different load;

3) Motors are not fixed on joints or motive parts in order to improve the dynamic property of the robot;

4) It has the compliant characteristics to coordinate the motion of the whole body;

5) It can adjust the position of the ZMP to keep the body balance;

6) The kinetic parameters of it are pitch ($-5^0 \sim 45^0$), roll ($-30^0 \sim 30^0$), velocity (0.2 radian /s), acceleration (0.1 radian/s^2), maximum driving moment of pitch (450Nm), maximum driving moment of roll (200Nm).

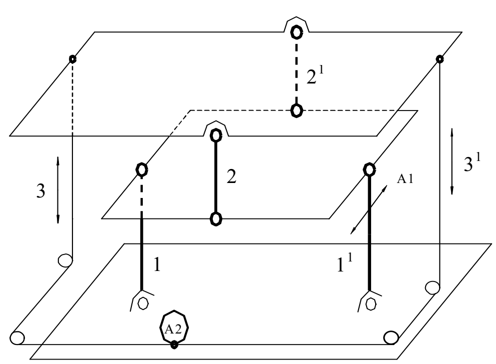

Fig.2 The sketch map of the waist

B. Waist Configure

The waist (shown in Fig.2) of the YIREN humanoid robot consists of actuating systems, differential mechanisms (shown in Fig.3), linkage mechanisms, supporting board, cable and compliant elements. Two differential mechanisms with 2-DOF are fixed in closed chains. I_1 and I_2 are motors. A_1 and A_2 are output links. The actuating systems, differential mechanisms, linkage mechanisms and compliant elements are all fixed on the base supporting board. Link 1 is fixed on A_1; Link 1，1_1 serves as the supporting axis of the middle board; Link 2，2_1 serves as the supporting axis of the upper board, which construct the pitch-axis motion. The one end of cable 3，3_1 is fixed at the axis of the upper board; The other are fixed on A_2; which constructs the roll-axis motion. The torso of the humanoid robot is fixed on the upper board.

C. Kinematics of Waist

The essence of the waist mechanism is serial-mechanism driven in parallel method. The equations of motion for this system in state space are easily computed to be:

$$
{}_2^0T = \begin{bmatrix} {}_2^0R & {}^0P_{20} \\ 0 & 1 \end{bmatrix}
$$

$$
= \begin{bmatrix} \cos q_1 \cos q_2 & -\cos q_1 \sin q_2 & 0 & l\cos q_1 \\ \sin q_1 \cos q_2 & -\sin q_1 \sin q_2 & 0 & l\sin q_1 \\ -\sin q & -\cos q & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)
$$

Where ${}_2^0T$ is the homogeneous transformation matrix of the link frame with respect to the base frame; ${}_2^0R$ is the rotation matrix of the end frame; ${}^0P_{20}$ is the vector of the end position. Where q_1, q_2 is the vector of joint variables with respect to the Pitch and Roll frame; l is the height of the waist.

The idler gears G change the turning direction of the axis, thus the angular velocity A_1, A_2 is:

$$
\dot{q}_1 = \frac{1}{i}\left|\omega_{I1} + \omega_{I2}\right| \quad (2)
$$

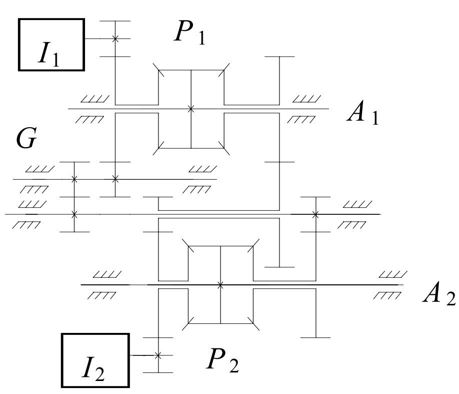

Fig.3 The differential mechanisms

$$\dot{q}_2 = \frac{1}{i}\left|\omega_{I1} - \omega_{I2}\right| \qquad (3)$$

Where ω_{I1} and ω_{I2} is the velocities with respect to the motor I_1, I_2 and i is ratio of the gears.

Because A_1 and A_2 drive the pitch-axis motion and the roll-axis motion respectively, the waist mechanism can not only implement the pitch-axis motion and the roll-axis motion separately, but also implement the resultant motion of the pitch-axis and the roll-axis.

D. Feature of the waist

We have designed two waist mechanisms according to the demand of kinematics. Comparing with the serial mechanism driven directly, this waist mechanism (shown in Fig.4) has several advantages:

1) Because the actuating systems, differential mechanisms, linkage mechanisms and compliant elements are all fixed on the base supporting board, the center of gravity falls off (from 400mm to 230mm) and the body becomes more steady;

2) The actuating systems and differential mechanisms aren't fixed on joints and motive parts directly, which decreases the load of motors and improves the dynamic property of joints;

3) Two differential mechanisms are fixed in closed chains having 2-DOF, which has a property of two motors driving the pitch-axis motion and the roll-axis motion respectively. This driven method decreases the power of motors and the consume of power and prolongs the using time of the batteries (A 500W motor and a 400W motor were replaced by two 300W motors);

4) The cable and compliant elements can adjust the stiffness of the waist to meet the needs for the complaisance and safety of the waist while are cooperating with human beings;

5) It can adjust the position of ZMP with proper compensatory motion.

IV. STIFFNESS OF THE WAIST

Using nonlinear spring characteristics possessed by the muscles themselves, humans can vary the joint stiffness. It is very important for human beings desiring for cooperative safety that the humanoid robot has the compliant characteristics. The existing humanoid robot most adopted stiffness-adjusting and controlling strategy to realize the complaisance, but the stiffness-adjusting scope of them was limited. This waist contains cable and compliant elements to driving the pitch-axis motion, so that the stiffness could change from zero to infinite in theory. The compliant elements contain cable, a liner spring, four crown blocks, two traveling blocks and a turning arm. Adjusting the stiffness of the cable by changing the angle, the turning arm could adjust the position of two traveling blocks. The research result of the compliant elements is shown in Fig.5. Because the scope of motion and moment of the pitch-axis motion is broad and the scope of motion and moment of the roll-axis motion is narrow, we adopted the compliant elements in the pitch-axis motion and adopted the tension-control strategy in the roll-axis motion.

Fig.4 The waist mechanism

V. DYNAMIC MODELING OF THE WAIST

The aim of this section is the derivation of a general dynamic joint space model of the humanoid robot waist describing the dynamic relations between the configuration coordinates, joint stiffness and the torques developed by the actuators.

To be a serial-mechanism driven in parallel method, the waist is modeled as a serial robot with two rigid links and the mixed rigid/elastic joints case[9]. Let q be the n-vector of link positions, and q_r represent the n-vector of actuator positions, as reflected through the transmission ratios. The difference q_r and q is the joint deformation. Because of the rigid joint:

$$\ddot{q}_{r1} = \ddot{q}_1 \qquad (4)$$

The complete Euler-Lagrange dynamic model of the waist can be written as:

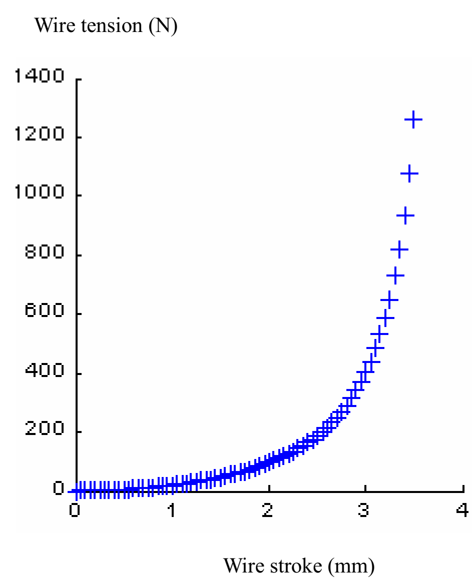

Fig.5 Result of the compliant elements

$$(J_1 + J_{r1} + J_{v1} + m_1 l_1^2 + m_2 l^2)\ddot{q}_1 - (m_1 l_1 + m_2 l) g \cos q_1 = u_1 \quad (5)$$

$$J_2 \ddot{q}_2 + k(q_{r2} - q_2) = 0 \quad (6)$$

$$(J_{r2} + J_{v2})\ddot{q}_{r2} - k(q_{r2} - q_2) = u_2 \quad (7)$$

Where m_i , J_i is the mass and the moment of inertia of the ith link, respectively; J_{ri}, J_{vi} is the moment of inertia of the *i*th motor and gears, respectively; u_i is the torque of the *i*th motor; l, l_1 is the height of the waist and the center of gravity; k is the stiffness coefficient.

VI. OPTIMIZATION PROBLEMS FOR ZMP MATCHING

According to the theory of ZMP proposed by M.Vukobratovic, the ZMP is defined as that point on the ground at which the net moment of the inertial forces and the gravity forces has no component along the horizontal axes. The balance criterion of this humanoid robot while it moving is that: for a feasible operation, the ZMP must always lie within the polygon of the mobile feet. The ZMP condition can be represented as:

$$\sum_i \{(\bar{r}_i - \bar{p}) \times m_i \bar{a}_i + I_i \bar{\varepsilon}\} - \sum_i (\bar{r}_i - \bar{p}) \times m_i \bar{G} = (0,0,k)^T \quad (8)$$

where, m_i, I_i is the mass and moment of inertia of the *i*th link, respectively; α_i, ε_i is the acceleration and angular acceleration of the *i*th link, respectively; r_i is the vectors of the *i*th link in base coordinate systems; p is the vectors of the ZMP in base coordinate systems;
when

$$\bar{G} = (0,0,-g)^T$$

$$\bar{r}_i = (x_i, y_i, z_i)^T$$

from formula (8) the position of ZMP is:

$$x_p = \frac{\sum m_i z_i \ddot{x}_i - \sum \left\{ m_i(\ddot{z}_i + g)x_i + (0,1,0)^T I_i \dot{\omega}_i \right\}}{-\sum m_i(\ddot{z}_i + g)}$$

$$y_p = \frac{\sum m_i(\ddot{z}_i + g)y_i - \sum \left\{ m_i z_i \ddot{y}_i + (1,0,0)^T I_i \dot{\omega}_i \right\}}{\sum m_i(\ddot{z}_i + g)} \quad (9)$$

Because the omni-directional mobile robot with orthogonal-wheel assemblies has horizontal and turning motion only, we regard the mobile coordinate systems as the base coordinate systems to valuate the stability. r_i can be changed by waist compensatory motion and the ZMP can be adjusted to match the desired ZMP to maintain the body balance.

VII. CONCLUSIONS

This humanoid waist overcomes some disadvantages of serial mechanism waist. Comparing with the serial mechanism driven directly, the power of motors decreases 40% and so dose the height of the waist by 50%. The scope of motion is the same as serial mechanism waist. The characteristics are the varying joint stiffness and the improvement of kinematics and dynamics property of the whole body. This waist could realize the miniaturization of humanoid robot and prolong the battery operation time also.

In the future we intend to analyze the input-output decoupling properties and feedback linearization of the mixed rigid/elastic joint model.

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