System Overview of The Humanoid Robot Blackmann

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Abstract: - This paper presents a newly developed humanoid robot Blackmann by the Robot Laboratory in the National University of Defense Technology, China. Blackmann is 1.55 meters tall and 63.5 Kg weight with 36 DOFs. And it was designed to be human-like including two legs, two arms, a trunk and a head. This paper covers the mechanical design, hardware description and basic motion control schemes of Blackmann. Up to now, Blackmann has been built and tested; the embedded motion control system has been realized and assembled in the body of Blackmann; the basic control schemes based on FRI point are implemented and human-like walking has been realized and further study is in process.

Key-Words: - humanoid robot; mechanical design; control system structure; FRI point

1 Introduction

Within the world of mobile robots, the humanoid robots are of great interest these years. The humanoid robots originate from biped robots. As same as their predecessors, the humanoid robots can pass obstacles easily and move on uneven terrain optionally; and they can do more jobs besides walking with whole upper body including functional arms and fingers,. It is as obvious as interesting that anthropomorphic biped robots are potentially capable of effectively moving in all unstructured environments where humans do. Furthermore, based on their attractive appearance, they have huge potential values in house-serving, entertainment or other fields. Humanoid robots are expected to be servants and maintenance machines with the main task to assist human activities in our daily life and to replace humans in hazardous operations. On the other way, it is meaningful to develop a humanoid robot with full DOFs and integrated control system and sensors, because it is an ideal test-bed for basic robotic theory, model-based programming, multi-sensors integration research, control architecture design for adaptive behaviors and so on.

Recently, significant progress has been made in the design of a hardware platform for humanoid robots and control of humanoid robots, particularly in the realization of dynamic walking in several full-body humanoids. There are more than 50 major humanoid robot projects around the world, along with many other bipedal walking projects (an extensive list of projects is given at the site www.androidworld.com). The current representative humanoid robots include ASIMO[1] produced by the HONDA corp., SDR-3X and SDR-4X[2] by the SONY corp., Wabian by the Waseda University, H7 by the Tokyo university.

The study on humanoid robot is related to various theory research problems and technology applications of many subjects. The quality of achievement of a humanoid robot relies on a tight cooperation between researchers in mechanical design, automatic control and the architecture of real-time computer and so on[3]. Compared with other legged robot, a humanoid biped robot is more difficult to design and control. Firstly, for mechanical design of legs, so many problems need thinking about: compactness, lightness, high joint torques, large joint range, low backlash and friction. Of course, such a system is expensive. Secondly, control of such a naturally unstable system is not an easy project. Without efficient and safe control algorithm and reliable hardware, the humanoid robot may fall down and the damage is fatal. So building a humanoid robot needs to synthesize technology, cooperation, fund support and experiences.

In the Robot Laboratory of National University of

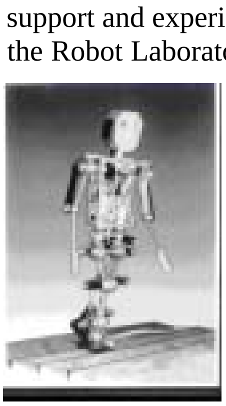

Fig.1 Humanoid Robot "Pioneer"

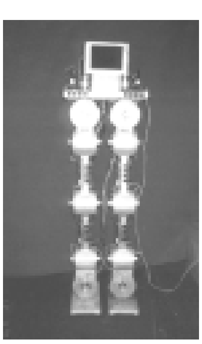

Fig.2 Biped Robot built in 2001

Defence Technology, P.R.China, the biped robot had been studied since 1989. In September 1989, the planar biped robot with 10 DOF was constructed, and spatial biped robots with 12 DOFs were built afterward[4]. In 2000, the humanoid robot Pioneer was developed (seen in Fig.1). As seen in Fig.2, a biped robot was designed as a test-bed for embedded control system and on-line motion planning research in 2001. During the long period of biped research, abundant experiences were accumulated and researchers were trained. In 2001, our lab began to study on humanoid robot system funded by Chinese High Technology Project. The ambition is to construct a humanoid robot with relatively full DOFs. The robot may designed to have an anthropomorphic appearance and to walk like human, with the capability to extract information from environment. Furthermore, we can control it through multiple ways. In 2003, the prototype was finished and was called Blackmann. In 2004, force/torque sensors and inclinometers were installed in Blackmann. Up to now, almost all essential devices are embedded in the body. Blackmann can fulfill all kinds of basic bipedal walking, and it was able to receive commands from keyboard or remote computer via wireless LAN. Several kinds of sensors were used to help Blackmann to feel the world. After training, Blackmann can even recognize simple voice instruction and act accordingly. The following part is to present the mechanical structure, sensors, control system, basic control scheme of Blackmann and our future work.

Table 1
WEIGHT, DIMENSION AND DOFS OF BLACKMANN

Weight	Total	63.5 Kg
	Head	0.50 Kg
	Trunk	25.1 Kg
	Upper arm	0.70 Kg
	Lower arm	0.70 Kg
	Upper leg	7.06 Kg
	Lower leg	3.94 Kg
	Sole	3.16 Kg
	others	6.72 Kg
Dimension	Total Height	1545 mm
	Height of Head	200 mm
	Height of Trunk	580 mm
	Height of Upper arm	250 mm
	Height of Lower arm	250 mm
	Height of Upper leg	350 mm
	Height of Lower leg	340 mm
	Height of Sole	95 mm
	Width of Shoulder	420 mm
	Width of Coxa	180 mm
	Length of Sole	270 mm
	Width of Sole	175 mm
Arms	Shoulder	2 DOF × 2
	Elbow	2 DOF × 2
	Wrist	2 DOF × 2
Legs	Hip	3 DOF × 2
	Knee	1 DOF × 2
	Ankle	2 DOF × 2
Hands	Finger	5 DOF × 2
Neck		2 DOF × 1
Total		36 DOF

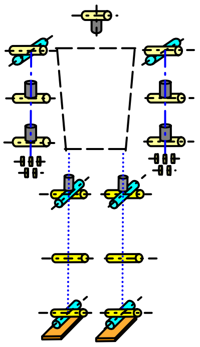

Fig.3 DOFs of Blackman

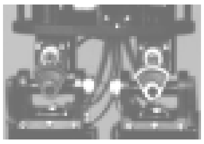

Fig.4 Orthographic design of the hips

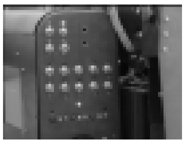

Fig.5 Back case of Blackmann

2 Mechanical Structure Of Blackmann

Blackmann is 1.55 meters tall, and 63.5 Kg weight. It has 36 DOFs with two legs of 6 DOFs, two arms of 6 DOFs, two hands of 5 DOFs, and the head of 2 DOFs. With complete upper body, Blackmann was human-like as designed, and it can imitate human walking motion in the sagittal and frontal plane[5]. In Table 1 and Fig. 3, the dimension, weight and DOFs of Blackmann are shown.

2.1 Humanoid Joints Design

For the lower limbs and joints of shoulders, the actuators are composed of DC motors and harmonic drive gears, and three kinds of transmitters were used, including the bevel gears for ankles, knees and 2 joints of hips (lateral and sagittal), spur gears for rotational joints of hips and belts for shoulders.

Synthesizing the requirement of motion planning and walking control, appropriate type of motors and harmonic drive gears with proper reduction ratios were selected through simplified simulation of the lower limbs and quondam experience. In addition, for the convenience of motion planning, 3 DOFs of the hips and 2 DOFs of the ankles were designed orthographic to imitate the human joints (seen in Fig.4.

For the other joints, the servo motors were used as actuators, and the reducers were embedded in the motors, so the pulley belts and gears were used as the transmitters.

The joints ranges were shown in Table 2.

2.2 Back Case Design

In order to offer sufficient space for the embedded control devices and power supply, a back case was designed. The whole control system was located in the back case(seen in fig.5), and the LCD(Liquid Crystal Display) used to watch the running state of Blackmann was set in the shell of the back case.

Considering the convenience of control algorithm implementation, model construction and symmetry of Blackmann, the cells were set in the room of bosom and belly to keep the center of mass just upon the waist.

Table 2
Ranges of Joints

Joint	Range(degree)
Lateral joints of hips and ankles	-30-30
Sagittal joints of ankles	-30-45
Knees	-90-10
Sagittal joints of hips	-30-80
Rotational joints of hips	-60-60
Sagittal joints of shoulders	-30-90
Sagittal joints of shoulders	-5-60
Elbows	0-90
Pitch joints of wrists	-20-70
Rotational joint of neck	-60-60
Pitch joint of neck	-30-30

3 Sensors

3.1 Inner Sensors

In the joints of lower limbs and shoulders, the analog potentiometers were mounted on the low-speed axis to detect the absolute angular position, and impulsgebers with high precision were directly mounted on the high-speed axis to measure the relative angular position of the motor output. The related angular velocity can be calculated by direct numerical differentiation of the counting pulse owing to the high quality of the digital signal.

3.2 External Sensors

Within the foot, a compact 5-dimension force/torque sensor was located between the rigid part of the sole and the plate, where the ankle cardan was attached(seen in fig.6). The sensor can measure the vertical, frontal and sagittal components of the ground reaction force and the frontal and sagittal components of the torque caused by the ground reaction. The force measurement range is 1000(N) with the resolution of 10(N), and the torque measurement range is 6000(N/cm) with the resolution of 60 (N/cm).

In order to measure the body posture, the inclinometers were installed in the upper body of Blackmann. As a kind of inclination sensors, it can detect frontal and sagittal obliquities with the accuracy of 0.01 degree.

The upper machine can get the force/torque and postural information through CAN bus.

4 Control System Design

4.1 System Requirements

Our main concern when designing the control system of Blackmann is to ensure its reliability and safety as far as possible. So the following prerequisites were proposed:

- ✓ The system should be highly integrated and of high efficiency. Interfaces between inner blocks should be well defined and easy to be maintained;
- ✓ The system can be interfered through multiple ways to ensure system safety;
- ✓ The system may rise to the emergency by design;
- ✓ The lower controllers may have good performance on response and trajectory tracing with small errors and low overshoot;
- ✓ The system should have strong capability of anti-jamming.

4.2 System Structure Design

Taking above-mentioned requirements into account, a hierarchical control system was designed based on industrial single board computer. As the upper machine, the industrial computer is connected with the multi-axis motion controllers via PC/104 bus[6] , extended PC/104 bus and extended serial bus. And Blackmann can be controlled by programs or by commands through keyboard or wireless control device(seen in fig.7). Moreover, a simple speech recognition system was established. With this system, Blackmann can receive commands from specific trainers after training. So we can terminate the motion of Blackmann at any time through multiple ways if necessary. Through CAN bus, upper machine can take in the environmental information through force/torque sensors or other external sensors[7, 11]. Through experiments, it was verified that the

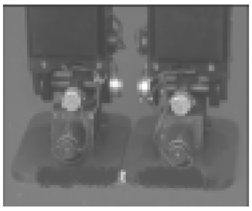

Fig.6 Force/torque sensors located in the sole

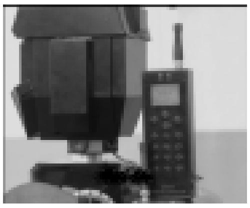

Fig.7 Remote controller

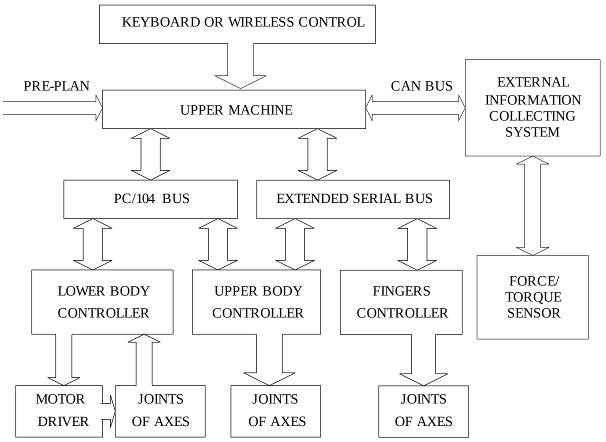

Fig. 8 Configuration of humanoid control system

designed system is easy to be expanded and maintained. Configuration of the system is shown in Fig.8.

4.3 Data Flow Description

According to the pre-plan information and the environmental information from external sensors, the upper machine makes real-time decision by modifying current angular position of several joints and sends command and data to the lower machines. Then the lower machines receive commands and data from upper machine via PC/104 bus or serial bus, and get real-time information from sensors, then send PWM(Pulse Width Modulation) signal to the motor drivers or directly to the servo motors. Thus the motion control is performed [8].

4.4 Lower Controllers Design And System Assembly

Various axes differ in the requirement of control precision, and different actuators are chosen for different joints of axes. As a result, three kinds of multi-axis motion controllers are designed, and several measures were adopted in circuit design to prevent disturbance. DSP and FPGA were used in controllers design and the precision was improved greatly. The detailed description of the motion controllers can be seen in [8].

The industrial computer, lower body controllers and upper body controllers were located in the back case, while the fingers controllers were set in the palms and the power amplifiers were built in free space near the driven motors; the remote command receiver with antenna was set on the top of the back case; and the speech recognition system was located in the frontal side of the upper body.

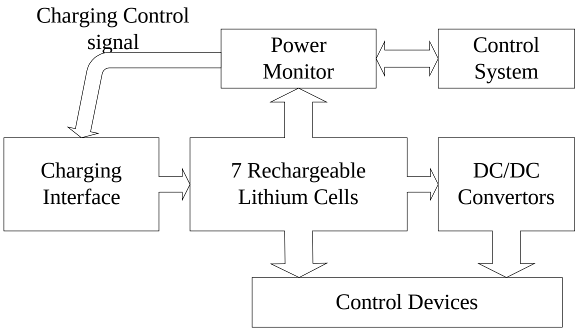

Fig.9 Power system configuration

5 Power Supply Of Blackmann

The power supply is an essential part of a humanoid robot system. Its capability is critical for stable walk of a humanoid robot, especially when it is located in the body of the robot. It is not easy to deal with the relationship among the input power of the motors, output torque of joints, the output power and the weight of the power system.

Accordingly, the criterions for design include:

1) The power capacity should be large enough to supply all the control devices to drive all the joints to perform human-like actions;

2) The power system should be light enough to be born by the lower limbs of the robot;

3) Low voltage protection and real-time characteristics surveillance are essential for the power system.

Considering the criterions and devices that we can actually get on the market, a pile with seven series-wound rechargeable lithium cells was selected to supply all the electric modules of Blackmann. And several types of DC/DC convertors were used to satisfy the requirement of different control devices. The designed power system can supply about 1 hour’s walk without recharging. Allowing for that troubles in power supply will cause falling of the robot and any fall was strictly forbidden, a power monitor was designed to watch the variation of the output voltage, output current and other characteristics so as to control the charging of the batteries. Connected with the upper machine of the control system on purpose, the power system can indicate the control system to terminate the program in emergency. The power system configuration can be seen in Fig.9.

6 Basic Control Scheme And Walking Stability

6.1 Walking Stability Analysis

The prime ambition of motion control is to realize stable walking, so walking stability of Blackmann should be ensured with the highest priority, then the other targets are considered, such as energy optimization or output torque optimization.

In our control scheme, FRI[9] point is used as a criterion for the walking stability of a humanoid robot. The off-line calculation method was used to define the stable region and control trajectory modification and the online FRI point calculation method was proposed to test the stability of real humanoid walking. The online FRI point trajectory calculation method is given as followed.

$$\begin{cases} (x_F - x_Q) = \dfrac{-M_{Sy} - z_S \cdot F_{Sx}}{F_{Sz} + m_a g} \\ (y_F - y_Q) = \dfrac{M_{Sx} - z_S \cdot F_{Sy}}{F_{Sz} + m_a g} \\ (z_F - z_Q) = 0 \end{cases} \tag{1}$$

where M_{Sx} and M_{Sy} are the ground reaction moment in the sagittal and lateral direction respectively, F_{Sx} , F_{Sy} and F_{Sz} are the ground reaction force in the sagittal , lateral and vertical direction respectively, (x_F, y_F, z_F) and (x_Q, y_Q, z_Q) are the position of FRI point and sole in world coordinates respectively, z_S is the vertical position of force/torque sensor in the world coordinates.

6.2 Basic Walking Control Scheme

The adopted walking control scheme was classified into two parts:off-line walking control trajectory generation (motion planning) and online posture control or trajectory modification[10, 13].

In the off-line motion planning part, the following requirements are thought about. Firstly, during motion planning, FRI point should be within the stable region according to the planned motion trajectory; secondly, within the remaining parametrized space of solutions, the most appropriate trajectory control can be selected.

The method of key position based locomotion planning was adopted and the technique of simplified inverse kinematics calculation was used to compute the joint angle after considering the kinematic constraints.

After the off-line motion planning, computer simulation was used to check up the feasibility of the planned control trajectory and to modify the joint angle. The calculated FRI point position based on dynamic model was the gist for trajectory modification. Then the control trajectory was downloaded to the upper machine of motion control system before walking experiments. In walking experiments, real-time FRI position calculated by information from compact force/torque sensors was used as the judge of humanoid postural stability, and the temporal position of FRI point was recorded and used to modify the pre-planned trajectory.

6.3 Walking Experiments

In humanoid walking experiments, the off-line and online trajectory modification was adopted and it has played an important role. After several reduplicative experiments and debugging, the basic walk of Blackmann was realized and the method of off-line motion planning succeeded (seen in Fig.11). The according FRI point trajectory and the vertical reaction force of each sole are also shown in Fig.10, which measured by force/torque sensors, where F_{Sz} shows the foot alternation in body support periodically and the FRI point trajectory always stay in the stable region. In this shown walking experiment, Blackmann can walk 1 step per second with step length of 200mm.

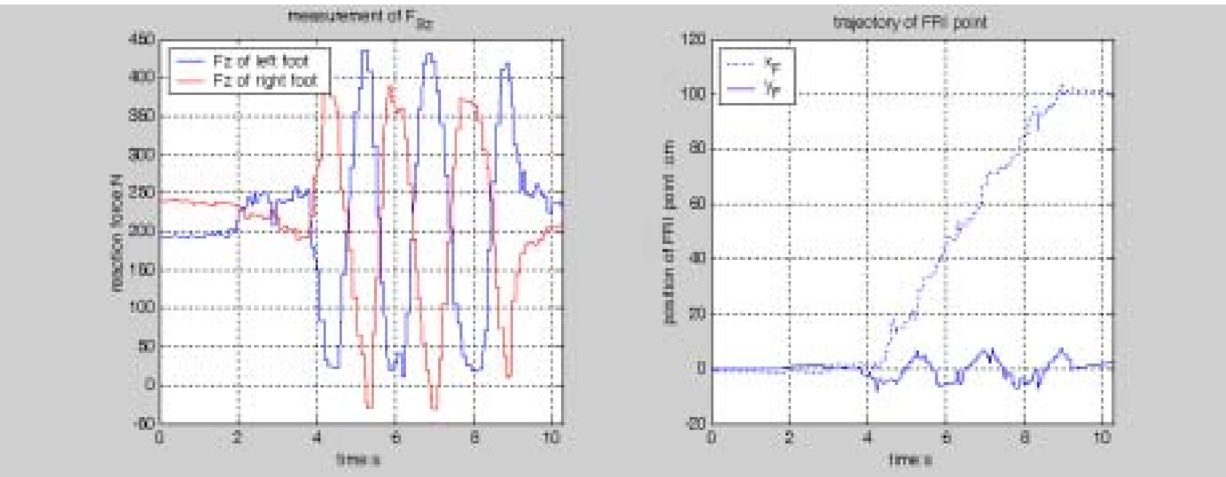

Fig.10 Measurement of F_{Sz} and FRI point trajectory

While the algorithm of real-time trajectory modification is on study now and not performed yet but humanoid standing posture control was basically realized. The algorithm of force and torque feedback control has been studied in [11] and tested in computer simulation.

7 Present State And Future Work

At the present time, the basic anthropomorphic walk including upper body actions on plane is realized without external power supply. The maximal walking speed is 1.08 km/h, and the maximal step length is 250 mm. The nominal step length is 200 mm with walking period of 1 second. All these conclude that the whole humanoid system design succeeded and further research is possible.

Our next research point is to use external information feedback, then the humanoid robot can not only walk on flat, but also adapt itself to the variation of the environment[12], especially to the mutative terrains. So, at this stage, further study on posture control based on force/torque feedback is under way and has made some progress in algorithm research. In the near future, some other external sensors will be installed and used in walking control and experiments. Furthermore, in order to improve intelligence and mobility[3] of Blackmann, some intelligent control algorithms (including genetic algorithms, fuzzy logic and neural networks) will be the keystone of our research.

8 Acknowledgment

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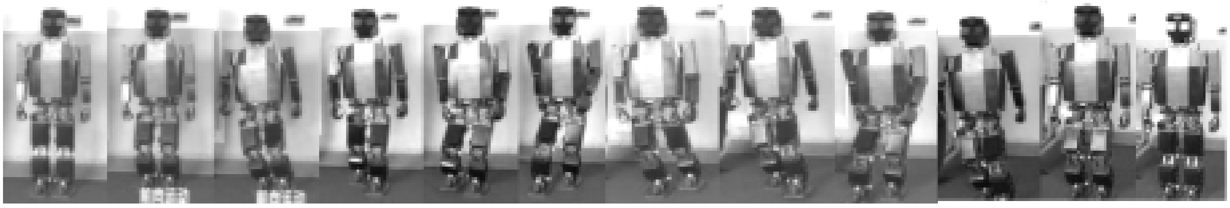

Fig.11 Photo sequence of the walking experiment