Development of a Humanoid Biped Walking Robot Platform KHR-1
- Initial Design and Its Performance Evaluation

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Abstract

In this paper, we describe the design philosophy that should be considered for developing a humanoid robot platform and the actuator selection method of the lower limbs by introducing a simple model and specific motion patterns in the sagittal and lateral plane. This paper also presents the mechanism, controller architecture and force toque sensor of the developed humanoid robot KHR-1. As a performance evaluation, a standing up and sitting down motion control with one leg has been performed by experiment since the role of the knee joint is the most important in walking and going up the stairs. By this experiment, we verified the validity of our actuator selection method. As a basic experiment on a sensory feedback control, we performed a balance control experiment using ZMP feedback at double support phase. An experimental result shows that the robot is capable of keeping its ZMP at its center position in spite of any disturbance and also suppressing the inherent vibration due to a mechanical structure.

1 Introduction

With the help of technological growth including better actuator and increased computing power, many researchers have studied walking machines, hopping robots, acrobatic robots, humanoids, pet robots, and other variations during the last twenty years. These developments have a common goal: the eventual realization of a robot that can help and cooperate with humans. Among these, the humanoid biped walking robot will be a foundation for the robot which is human friendly, human interactive and human interfacible. Recently, many researches have been focused on a development of humanoid biped robot which is similar to human being. Honda R&D's humanoid robots[1], WABIAN of Waseda University[2], ASIMO[3], H6[4], H7 and are well known humanoid biped robots. Since the humanoid biped robot has very complicated structure, it is very hard to realize a real-time motion control based on the sensory feedback like real humans. Some researchers have just conducted a playback motion using a predefined joint profile obtained from a off-line learning process[2][9][10]. Others have adopted a partial on-line modification of robot motion based on sensory feedback[1][12].

A goal of our research is to realize a complete on-line motion control of the biped walking robot based on a sensory feedback control. The biped walking robot has to keep its balance during walking motion in spite of an existence of external forces. As a fundamental step for the final goal, we developed a biped walking robot platform composed of 22 DOF (12 DOF for lower limbs, 8 DOF for arms and 2 DOF for waist that has yaw and roll motion) based on our own design concept.

We will begin with introducing the design philosophy of our humanoid robot platform including mechanisms, specifications, selection method of actuators, electrical hardware and force/torque sensor. In the performance evaluation part, we checked the knee joint capability and performed a balance control based on the sensory feedback in the double support phase. For this balance control, a force/torque sensor was installed on the sole of the robot. When we applied the external force to the robot, it always tried to preserve ZMP at its geometric center position between two feet by moving its hip horizontally despite the external force. Through these two experimental evaluations, we tried to verify the validity of our design approach and the balancing capability of developed humanoid biped robot.

2 KAIST Humanoid Robot platform-1 : KHR-1

2.1 Design Philosophy

When we decided to develop our humanoid robot platform, we were faced with a very preliminary question – what will be our design philosophy? In this section, we describe several design factors which should be considered for developing a humanoid walking robot platform.

Size and weight

Several different types of humanoid robots have been developed for the last decade. Heavy adult size robots which are over 180cm in height and weigh over 100kg have been developed by Honda and Waseda University[1][2]. Child size robots whose heights are about 120cm have also been developed by Honda(Asimo)[3] and Tokyo University (H6 and H7)[4]. Sony has developed a small toy size robot whose height is only 50cm(SDR-3X)[5]. Through the benchmarking investigation for the current humanoid robots, we decided to develop a child size robot in order to use it for both entertainment and service purpose. A child size robot is appropriate for performing a certain practical task while interacting with human. We designed each body segment length based on an average set of human segment length shown in the reference[6].

Fig.1 and Fig.2 show a schematic drawing and photograph of KHR-1, respectively. The total weight is 48kg including master controller, motors, amplifiers, sensors and batteries. Its height without head is 119cm.

Kinematically simple structure

To obtain a closed-form solution of inverse kinematics, the KHR-1 was designed to have a kinematically simple structure. For instance, the hip joint was designed to have a three DOF whose axes intersect at one point without offset distance. The ankle joint also has 2 DOF whose roll and pitch axes intersect at one point.

Light, Compact and zero backlash joint

We adopted a harmonic drive gear as a main reduction gear for each joint. The harmonic drive gear is a well-known for light, compact and zero backlash reduction gear. Depending on joint types, we added several transmission devices such as pulley-belt, bevel gear between motor and harmonic drive gear.

Full DOF to imitate human motion

The KHR-1 has 22 DOF in total. Each leg has 6 DOF – 2 DOF for ankle joint, 1 DOF for knee joint and 3 DOF for hip joint. Actually, the hip joint consisting of 3 revolute joints imitates a human hip joint in the form of a ball joint. Waist has 2 DOF - a yaw and a roll motion. Each arm is composed of a shoulder having 3 DOF and an elbow having 1 DOF. Up to now, head and hand mechanism were not implemented yet.

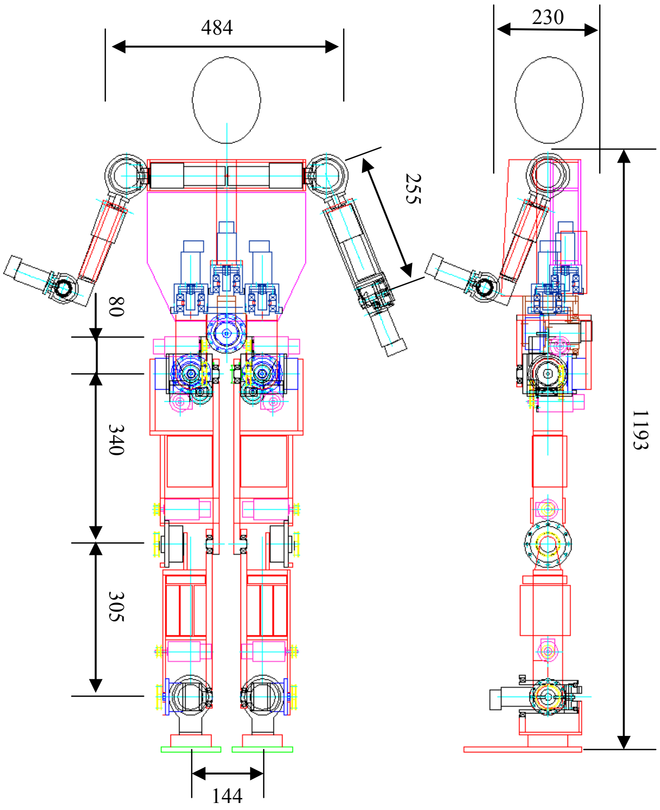

Figure 1. Schematic drawing of KHR-1 (unit:mm)

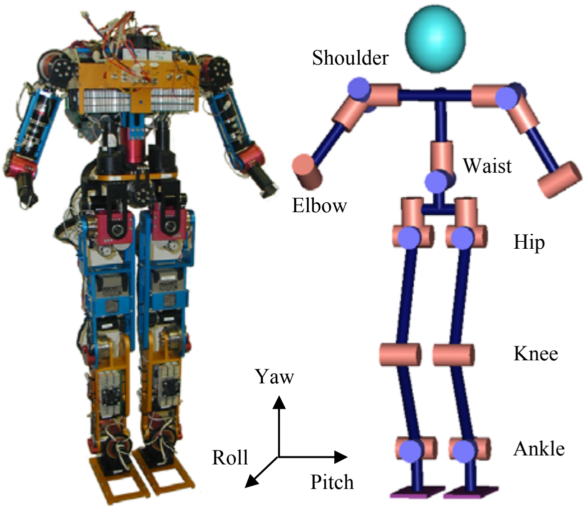

Figure 2. Photograph and joint structure of KHR-1

Self contained controller

All the necessary electrical components such as master controller, motor amplifier, battery, etc. are installed in the robot body itself so that it can walk in working environments without having any wiring connection with external controller.

Low power consumption

To ensure an autonomous walking motion for a required time period without supplying electrical energy via wiring connection from external source, power consumption should be maintained in a minimum level. Our design target is to keep the autonomous walking motion for about one hour. Thus, we designed the electrical system in order that its total power consumption should be kept in less than 100W at standby mode and 150-240W at walking mode.

2.2 Driving System

We designed three basic types of driving system for each joint depending on required motion and space limitation. These driving systems can be conveniently used as a basic component to design a specific joint based on a modular design concept.

In-line axis driving system

The harmonic drive gear is able to realize an in-line axis driving between input and output axes. For the joint without having space constraints along driving axis, we are able to apply the in-line axis driving system using harmonic drive gear. For instance, shoulder, waist joints, yaw axis of hip joint and roll axis of ankle joint were designed by adopting this type of driving system.

Parallel axis driving system

When the in-line axis driving system is not able to be fitted in a joint because of a space limitation, a belt-pulley mechanism can be added between output axis of motor and input axis of harmonic drive gear. The belt-pulley mechanism is an efficient driving system in terms of compact size, light weight and low cost.

We used this type of driving system for knee joint, pitch axis of ankle joint, pitch and roll axis of hip joint.

Intersecting axis driving system

As for an elbow joint, it requires very compact size and light weight for the driving system. We used a bevel gear between output axis of motor and input axis of harmonic drive gear. Fig.3 shows a schematic diagram of elbow joint adopting bevel gear and harmonic drive gear.

3 Selection of Actuators and Reduction Gears for the Lower Limbs

The lower limbs of KHR-1 which consists of 12 DOF support the upper body of robot. The selection of actuators and reduction gears used for the lower limbs is one of the important tasks for the robot design to ensure a stable walking motion.

In this section, we conduct a simulation using a simplified modeling as shown in Fig.4 in order to estimate a required torque and speed for each joint. We simply describe the lower limbs as links and lumped masses attached at the end of each link. We calculate a required torque and speed to perform a specific pattern of robot motion in the sagittal(X-Z) and the lateral(Y-Z) plane[7].

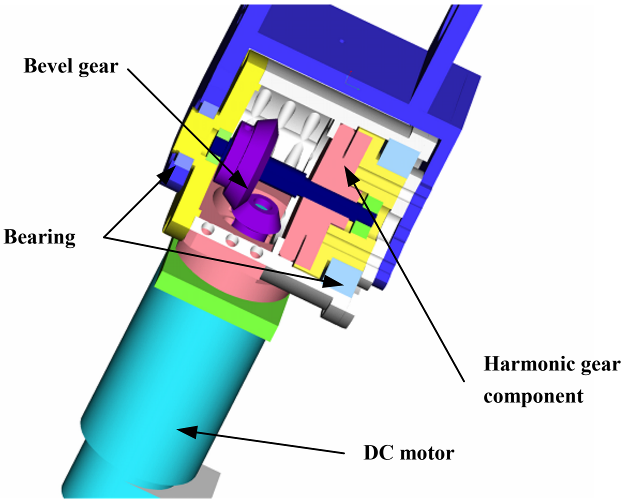

Figure 3. Design of the elbow joint

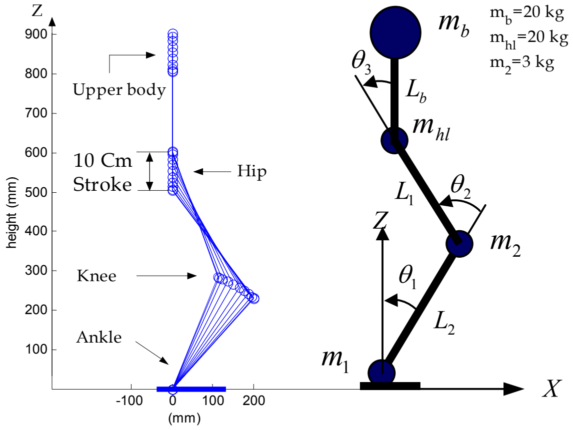

Figure 4. Standing up and sitting down motion in the sagittal plane

3.1 Pitch motion

A simulation for standing up and sitting down motion in the sagittal(X-Z) plane as shown in Fig.4 was conducted to calculate the required torque and speed of each joint actuator for pitch motion. We supposed that this kind of motion pattern could be needed for going up or down the stairs. The robot was assumed to be supported by one leg and the upper body motion was commanded by 1 Hz cosine function with 10cm stroke in vertical direction. We considered this condition under the assumption that the robot was going up and down the stairs of 10cm at walking period of 1sec/step. The hip mass is supposed to be 20kg including the swing leg on the opposite side. The lumped knee mass is 3kg and the upper body mass is 20kg.

Fig.5 and Fig.6 shows the time response of each joint torque and speed, respectively. The simulation results show that the knee joint is the most critical one to perform the pitch motion and it needs maximum torque of 82Nm and angular speed of 20rpm. If we calculate power from the torque and speed curves, the maximum required power of knee joint is turned out to be about 120W.

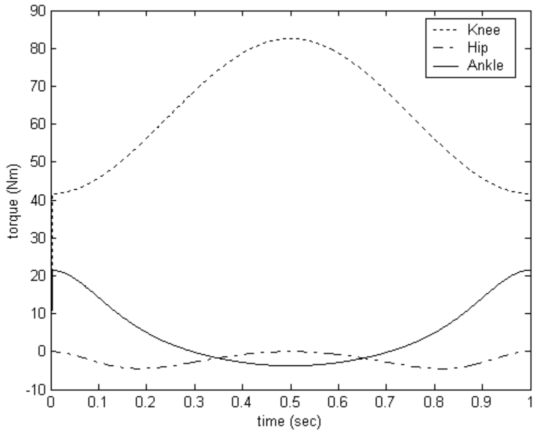

Figure 5. Pitch joint torque
- Standing up & sitting down motion

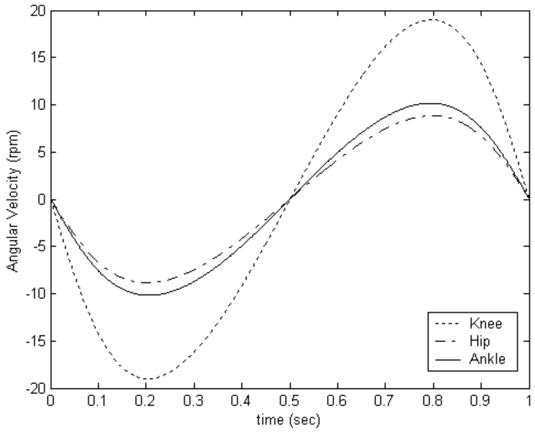

Figure 6. Pitch joint Speed
- Standing up & sitting down motion

We also noticed that more torque was required for hip and ankle joints when the upper body inclined in a forward direction. Through a simulation, we concluded that the maximum required motor power of hip and ankle joints didn't exceed 70W when the upper body inclined by about 35 degrees in a forward direction and the hip moved by 6cm in a backward direction.

Based on the simulation results, we selected an appropriate motor specifications and reduction ratio of harmonic drive gear and belt-pulley system. Fig.7 and Fig.8 show a comparison between the required torque/speed and selected ones.

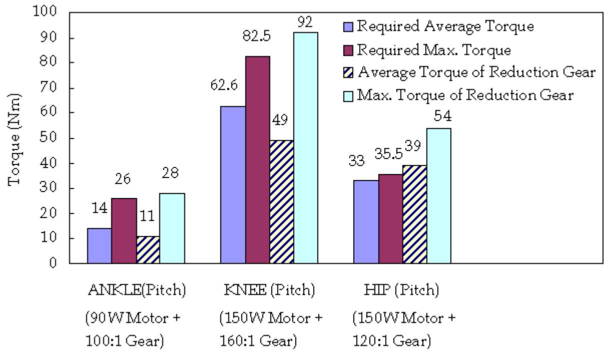

Figure 7. Comparison between required joint torque and permissible torque of selected reduction gear

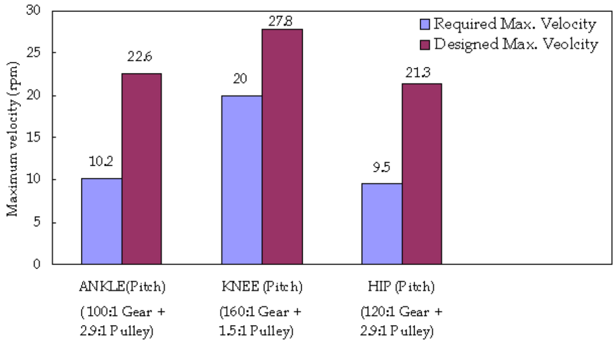

Figure 8. Comparison between required joint velocity and designed velocity

3.2 Roll motion

We consider a specific motion pattern in the lateral(Y-Z) plane described in Fig.9 in order to calculate the maximum required torque of actuators for roll motion. While one leg is stationary on the ground, the other leg swings from left to right. We suppose that this kind of motion pattern can be found when the robot tries to keep its balance during the single support phase or it moves the position of landing foot to the lateral direction.

At the initial posture, the upper body is shifted by 70 mm in a leftward direction. One leg is commanded to swing by 1Hz sine function with amplitude of 20 degrees. The lumped masses shown in Fig.9 are m_1=6kg, m_2=3kg, m_3=5.5kg, m_b=20kg, respectively.

From the simulation result shown in Fig.10, a maximum torque was turned out to be 38 Nm for the roll axis of hip joint, J_2, which is the most critical joint for roll motion.

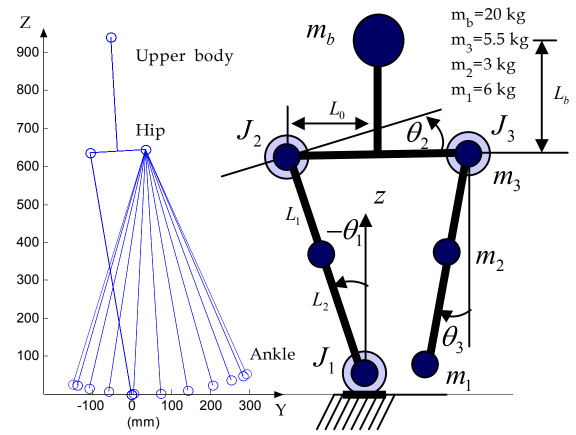

Figure 9. Rolling motion from left to right in the lateral plane

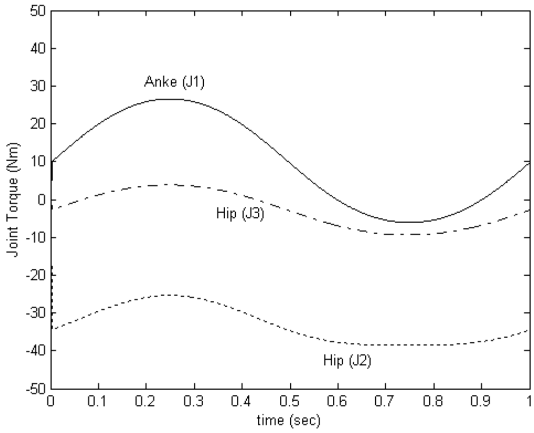

Figure 10. Roll joint torque - Rolling motion from left to right.

3.3 Yaw motion

A yaw motion of hip joint is required to turn walking direction of robot. Actually, since the hip joint is only required to resist a rotational inertia of swing leg, a high power actuator is not needed for yaw motion.

Since compression and tension loads are repeatedly applied to the yaw axis of hip joint during a walking cycle, the consideration of the loading capacity along the yaw axis is more important rather than the power of actuator. To ensure an enough axial loading capacity, we inserted an angular contact ball bearing whose dynamic load rating is 12 kN. To increase the loading capacity further, two bearings are arranged in a back-to-back duplex type.

4 Electrical Design

4.1 Controller Architecture

Fig.11 shows the overall block diagram of robot controller architecture. We adopted Pentium III-500 embedded computer with PC104 interface as a master controller. The master controller is interfaced with two peripheral interface boards(PIB) which control 12 DC motors of upper and lower body of robot, respectively. The PIB is equipped with 12 PWM generators and encoder counters. It also has a built-in microcontroller which receives the measured force and torque data via RS-232 communication from the force/torque sensor attached to the sole of robot. This microcontroller communicates with the master controller via parallel interface implemented by 8255 chip. The force and torque data are updated at 100Hz. The master controller performs a robot motion control algorithm based on the sensory feedback and generates joint commands at 100Hz. A linear interpolation at the joint coordinate and digital PD controllers for DC motors are running in the background program at 1KHz.

An 8-channel A/D converter is also prepared for reading analog signals from additional sensors such as rate gyro and accelerometer, etc. But, these sensors are not implemented yet.

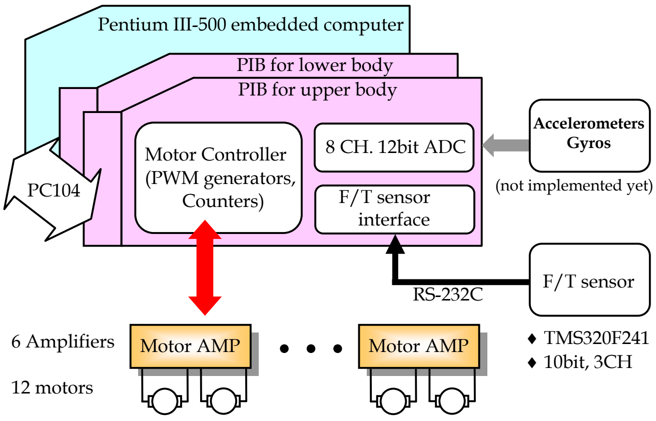

Figure 11. Hardware architecture

4.2 DC motor amplifier

We developed DC motor amplifier equipped with 4 N-channel power MOS-FETs driving in a full H-bridge configuration in PWM mode at 20KHz. It is capable of controlling 24V DC motor up to 18A. It is also equipped with overcurrent protection circuit. Since its size is very compact(120×70×18mm for two channel), it is suitable to be installed into the robot body adjacent to joints.

4.3 Force Torque Sensor

It is necessary to measure force/torque of foot in order to calculate actual ZMP(Zero-Moment-Point) for dynamic walking motion. We developed a force/torque sensor which is capable of measuring two moments up to 34Nm along roll and pitch axes and one normal force up to 95kgf in the vertical direction. Due to a compact size(80×80×25mm) and light weight(200g), it can be easily mounted to the sole of a foot. The electronic circuit has a built-in microcontroller (TMS320F241) which transmits the measured signal to the master controller via RS-232 communication.

5 Performance Evaluation

5.1 Knee joint Actuator

An experiment was conducted to verify the performance of the knee joint actuator selected by a pitch motion simulation described in the section 3.1. Actually, the test condition shown in Fig.6 is too severe for the experiment without using a balance control at single support phase. So we reduced the frequency of the repeated motion to 0.5Hz. Here, our objective of the experiment is to verify the feasibility of the proposed simulation method.

Fig.12 shows the experiment result comparing with the simulation one. We note that the time response of torque of knee joint can be well estimated by the proposed simulation method.

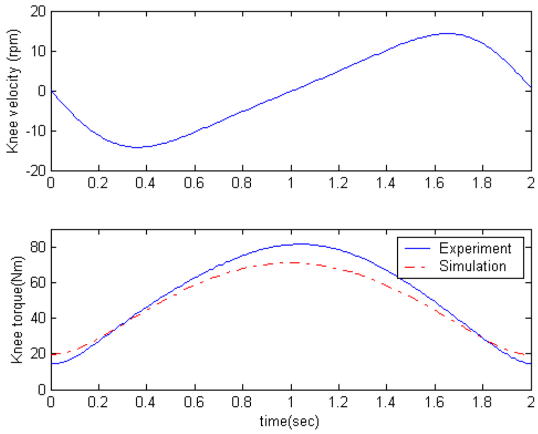

Figure 12. Experimental result (0.5Hz 10cm stroke)

5.2 Balance Control based on ZMP Feedback

A realization of dynamic stability is an indispensable task for a biped walking robot. Many researchers have proposed a walking motion generation algorithm based on ZMP(Zero Moment Point)[8] to ensure the dynamic stability. The ZMP is defined as the point on the ground where the total moment of the active forces equals to zero[9]. If the ZMP is within the convex hull of all contact points between the feet and the ground, we can achieve a dynamically feasible walking motion.

Most of researches are focused on how to determine whole body motion to realize a desired ZMP trajectory.

Some researchers try to design a desired ZMP trajectory first and find a waist or hip motion to realize it using lots of different algorithms[2][10]. On the other hand, other researchers try to obtain a hip motion with smooth trajectory first. After that, they modify the hip trajectory iteratively to satisfy the ZMP constraints by using an exhaustive search computation method[11].

When we want to calculate the desired ZMP trajectory, it is actually hard to know about precise information of robot dynamic parameters such as mass, location of center of gravity, moment of inertia of each link, etc. As a matter of fact, the calculated ZMP trajectory usually contains the deviation from the actual ZMP trajectory. Therefore, it is necessary to modify the prescribed joint trajectory based on the actual ZMP calculated from force/torque sensor integrated with the sole of foot[1][12].

Now, our strategy for walking motion control can be summarized with the following two main parts.

- *Gross motion control part*: We adopt a simple model of robot to perform a trajectory planning in a real-time based on ZMP concept.

- *Balance control part*: In order to compensate the deviation between the calculated and actual ZMP, we design a balance controller based on a simple modeling and a sensory feedback from force/torque sensor.

As an initial step for the realization of the whole system, we designed, first, a balance controller based on ZMP feedback.

In order to represent a robot motion at double support phase, we introduce a simply inverted pendulum having a linear actuator with a lumped mass, *m*, at its end[13][14]. The hip motion is used to keep a balance of robot based on ZMP feedback. For simplicity, the hip motion is restricted to only a horizontal direction while keeping its height constant[2][10]. The measured ZMP, y_{zmp}, in the lateral(Y-Z) plane from force/torque sensor can be obtained by the following equation[15].

$$y_{zmp} = \frac{F_{zr} y_r + F_{zl} y_l}{F_{zr} + F_{zl}} \qquad (1)$$

where, y_r (y-component of ZMP for right foot) can be approximately calculated by only normal force and moment because the distance between the force/torque sensor and the sole is very short.

$$y_r \cong \frac{M_{yr}}{F_{zr}} + Y_{foot\_r} \qquad (2)$$

Y_{foot_r} : y-component of position for the right foot

Fig.13 shows an overall block diagram of the balance control system which consists of a controller and a robot represented by the inverted pendulum. The control objective is to regulate the measured ZMP at zero by means of hip motion. The performance of proposed balance controller is shown in Fig.14. An external force is initially applied to shift the robot in the horizontal direction by about 5.5 degree of roll angle of ankle joint. When the external force is removed suddenly, the robot starts to oscillate approximately with its natural frequency and this continues for about 10sec. However, when we used the balance controller, the actual ZMP rapidly reached to zero within 1sec.

We believe that the concept of the proposed balance controller can be extended to the balance control at single support phase.

6 Conclusion and Further Study

In this paper, we developed a humanoid biped walking robot platform, KHR-1 based on a series of design philosophy. Our development activities were focused on the followings.

1) We proposed a general design guideline for the development of humanoid biped walking robot platform.
2) We classified a driving system into 3 basic types which can be conveniently adopted for designing each joint of robot based on a modular design concept.
3) We proposed a simple way to select actuators and reduction gear for each joint of the lower limbs by introducing a simple modeling and a specific motion pattern.
4) We developed an electrical control system which consists of master controller using Pentium III-500 embedded computer, PWM DC motor amplifier and 3-axis force/torque sensor.
5) We designed a balance controller based on simple modeling at double support phase and ZMP feedback.
6) Several experiments were performed to verify the performance of KHR-1.

Our further study will focus on the realization of overall walking motion including a balance control at single support phase and a gross motion control. We will also upgrade the overall electrical control system by adopting a distributed control architecture based on CAN network.

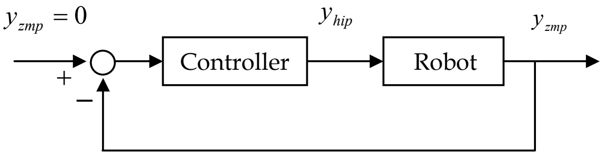

Figure 13. Block diagram of balance control

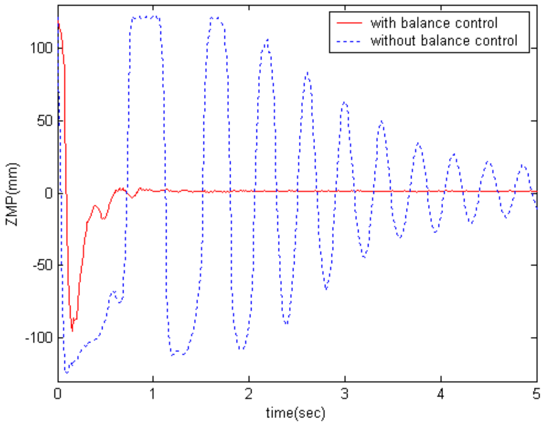

Figure 14. Time response of measured ZMP (Experimental result)

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