

Torque Feedback Control of the Humanoid Platform KHR-1

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Abstract. In this paper, we describe the design philosophy that should be considered for developing a humanoid robot platform. This paper presents the mechanism, controller architecture and force torque sensor of the developed humanoid robot KHR-1. As a basic experiment on a sensory feedback control, we first perform a balance control experiment using ZMP feedback at double support phase. As a model during single support phase, we consider the inverted pendulum model with flexible link, since the legs of a humanoid robot are relatively long and they are serially connected with compliant force-torque sensor at ankle. For this model, the torque feedback control method that increase the system damping is presented. Experimental results show that these two controllers can keep its ZMP or torque in spite of any disturbance and also suppress 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 interfacing. 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, WABIAN of Waseda University, ASIMO, H6, H7 and are well known humanoid biped robots:[1],[2],[3],[4]. 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 21 DOF (12 DOF for lower limbs, 8 DOF for arms and 1 DOF for waist that has yaw motion) based on our own design concept.

We will begin with introducing the design philosophy of our humanoid robot platform including specifications, electrical hardware and force/torque sensor. In the control method part, we deal with the sensory feedback using F/T sensor for both double and single support phase. For these, a force/torque sensor was installed on the sole of the robot. When we applied the external force to the robot during double support phase, it always tried to preserve ZMP at its geometric center position between two feet by moving its hip horizontally despite the external force. For the single support phase, the inverted pendulum model with flexible link was presented and its performance of decaying out inherent vibration was shown. Through these experiment, we tried to verify the basic 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) and Tokyo University (H6 and H7):[3],[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 shows the photograph of KHR-1. 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.

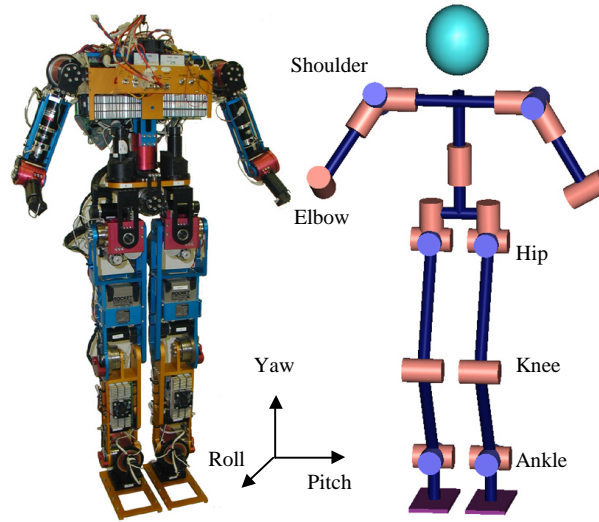


Fig. 1. Photograph and joint structure of KHR-1

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 21 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 1 DOF for yaw motion. The roll motion of waist was implemented at the initial design but it was omitted later because its working range was somewhat small. Rolling motion of hip can generate the similar motion instead of waist. 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.

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 Mechanical Design Specification

The dimension and the D.O.F of KHR-1 are shown in Table 1. The total weight including batteries, computer, controllers and amplifiers is 48 kg and the height is about 120cm. Up to now, head mechanism has not been implemented.

The selection of actuators and reduction gears for the lower limbs is one of the important tasks for the robot design to ensure a stable walking motion. We selected the actuators and reduction gears of the lower limbs by introducing a simple model and simulating specific motion patterns in the sagittal and lateral plane:[7],[16]. Based on the simulation result, we selected an appropriate motor specifications and reduction ratio.

Table 1. Specification of Humanoid Robot

Weight	Total: 48 kg	
Dimension	Height:(without head)	1193 mm
	Width:	484 mm
	Depth :	230 mm
	Length of upper arm :	255 mm
	Length of upper leg :	340 mm
	Length of lower leg :	305 mm
D.O.F	Arms	Shoulder 3 D.O.F \times 2 Elbow 1 D.O.F \times 2
	Waist	1 D.O.F(Yaw)
	Legs	Hip 3 D.O.F \times 2 Knee 1 D.O.F \times 2 Ankle 2 D.O.F \times 2
	Total	21 D.O.F

3 Electrical Design

3.1 Controller Architecture

Fig.2 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 con-

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.

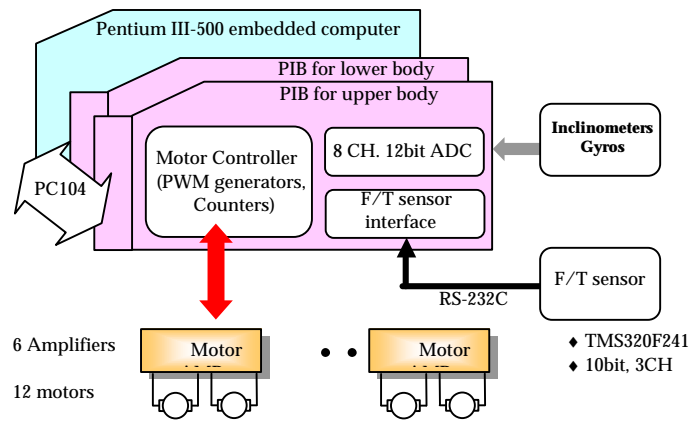


Fig. 2. Hardware architecture

3.2 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.

3.3 Force Torque Sensor

The sensors that are generally used in a humanoid robot is categorized by their level in Table 2. The fundamental 1st sensor level is the kinesthesia such as the current that is generated in each joint motor and the force/torque information at ankle or wrist. The 2nd sensor level corresponds to the vestibular organ of a human that senses the equilib-

rium of body. Accelerometers, inclinometers and rate gyros belong to this 2nd level. The stabilization of walking is possible with 1st level sensor (F/T sensor) on the flat ground. The 2nd level sensors will improve its performance when the disturbances exist. The 3rd level sensors are the vision sensor, which is related with space perception, and tactile sensor. These sensors enable the highly advanced recognition and expand the ability of interaction with human. In this study, we will focus on the posture balance rely only on the F/T sensor in advance. After maximizing the performance with minimum sensor, we will improve the performance with the additional sensors.

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 that 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.

Table 2. Sensor level that is generally used in the humanoid robot

Level	Sensory organ	Sensor
1 st level	Muscle, tendon (Kinesthesia)	Force/Torque Sensors at ankle and wrists Current Sensors for each motor
2 nd level	Vestibular organ (Sense of equilibrium)	Accelerometers / Inclinometers Rate Gyros
3 rd level	Eye (Space perception) Tactile organ	Vision System Tactile Sensors Etc.

4 Balance Control based on ZMP Feedback during Double Support Phase

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) to ensure the dynamic stability.: [8] 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].

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

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.

$$y_r \cong \frac{M_{xr}}{F_{zr}} + Y_{foot_r} \quad (2)$$

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

Fig.3 shows an overall block diagram of the balance control system that 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.4. 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. This type of balance controller including the integral action can be used in initialization of robot when the origin is not perfect and asymmetry of the weight distribution is occurred.

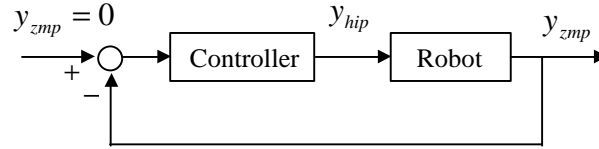


Fig. 3. Block diagram of balance control

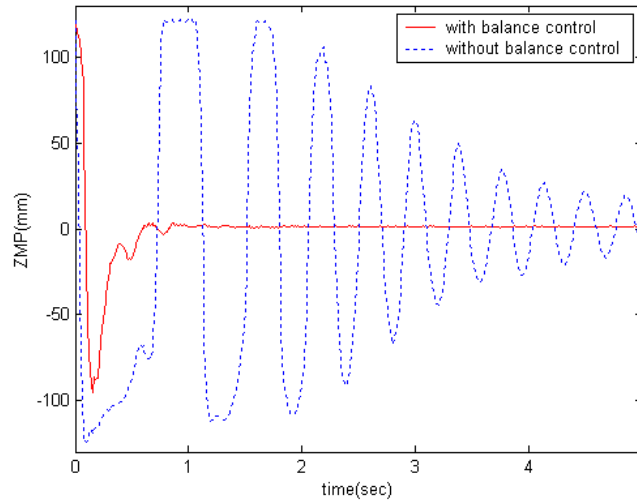


Fig. 4. Time response of measured ZMP (Experimental result)

5 Torque Feedback Control at Ankle Joint during Single Support Phase

As a model of bipedal walking during single support phase, inverted pendulum model, flywheel model and acrobat model can be assumed:[13]. The link is generally assumed to be rigid in many cases, but in real situation, it is flexible because the foot is connected with a compliant force-torque sensor and the leg length is relatively long compared to its cross section. For this flexibility, the humanoid robot exhibits the characteristics of a lightly damped structure. For example, when the ankle is under the

position control during single support phase, the external force easily generates the sustained oscillation even though the position error is nearly zero. If the biped walking robot system has this inherent problem, we cannot succeed in position control of biped walking in real environment, even if we get the exact trajectory that satisfies the desired reference ZMP by simulation. This phenomenon is much more critical in the fast gait. Therefore, it is desirable to perform the position control by torque feedback considering the stiffness of links. In this paper, one mass inverted pendulum with flexible link is considered as the suitable model as shown in Fig. 5. In the figure, u denotes the ankle joint angle and q denotes the actual inclined angle produced by the flexibility. The output is the torque T from the F/T sensor and the input is u . For the model shown in Fig.5, the equation of motion is derived as

$$y = T = mglq - ml^2 \ddot{q} \quad (3)$$

$$T = K(q - u) \quad (4)$$

The transfer function from the ankle joint angle to the torque is derived from the above two equations.

$$\frac{y}{u} = K \frac{-s^2 + \frac{g}{l}}{s^2 + (\frac{K}{ml^2} - \frac{g}{l})} = K \frac{-s^2 + (b - a)}{s^2 + a}, \quad (5)$$

where $a = \frac{K}{ml^2} - \frac{g}{l} > 0$, $b = \frac{K}{ml^2}$, u is the position of the ankle, K is the stiffness of the leg, g is the gravity, l is the length of pendulum, and m is the mass, respectively.

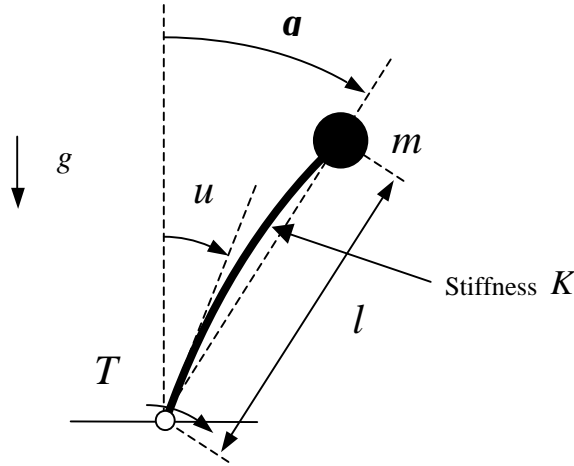


Fig. 5. Simple inverted pendulum model with flexible link

If the damping coefficient C of the link is considered together with stiffness K in the equation (4), torque can be expressed as $T = K(u - q) + C(\dot{u} - \dot{q})$. However, damping coefficient is neglected for simple calculation, since the value is relatively small compared with stiffness.

Practically, the ankle joint angle u is generated by the reference command u_{ref} in the PD position feedback configuration of Fig.6. The transfer function T/u_{ref} in the diagram of Fig. 6 has almost same dominant poles and zeros with T/u , and also has negligible fast poles over 600 rad/s which correspond to the motor dynamics. Thus, it is valid to regard u_{ref} as u . So, the transfer function is approximated by the following equation.

$$\frac{T}{u_{ref}} ; \frac{T}{u} = K \frac{-s^2 + (b - a)}{s^2 + a} \quad (6)$$

It is also valid to design the feedback controller for equation (6), if the closed loop pole is assigned near to the dominant system poles. The parameters of the equation (6) can be found by experimental identification. As shown in the equation, the pole is near to the imaginary axis of s-domain, and the system is a non-minimum phase plant of which zero is located in the right half plane.

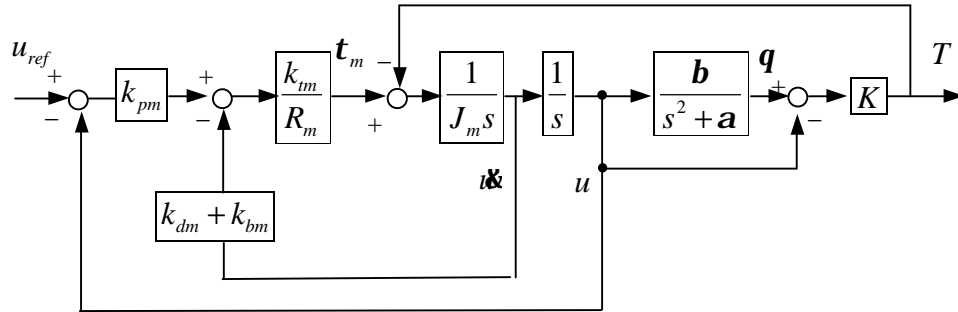


Fig. 6. Transfer function from the reference position of an ankle to torque output including the motor dynamics (under assumption that the effect of a inductance and a damping term of a motor is small and negligible)

k_{pm} = Proportional gain of position control

k_{dm} = Derivative gain of position control

R_m = Terminal resistance

t_m = Torque output of an ankle actuator

k_{bm} = Back-EMF constant

k_{tm} = Torque constant

J_m = Inertia of an ankle axis

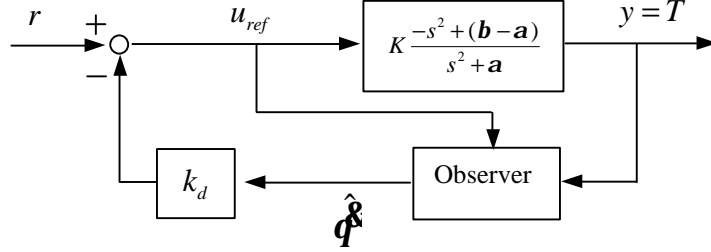


Fig. 7. Block diagram of damping controller

Even though the system is the lightly damped system, we can increase its damping ratio using the following feedback law in the configuration of Fig.7.

$$u_{ref} = r - k_d \dot{\hat{q}} \quad (7)$$

With the damping controller, we can reduce the oscillatory torque induced by the external force when the PD position control is applied at the ankle joint.

From equation (3),(4),(6),(7)

$$\frac{q(s)}{r(s)} = \frac{K}{ml^2 s^2 + k_d K s + (K - mgl)} = \frac{\frac{K}{ml^2}}{s^2 + 2\mathbf{x}\mathbf{w}_n s + \mathbf{w}_n^2} \quad (8)$$

We can assign the damping ratio freely and the oscillatory motion can be suppressed effectively by changing k_d gain in the following equation.

$$k_d = 2 \frac{\sqrt{ml^2 (K - mgl)}}{K} \mathbf{x} \quad (9)$$

The steady state value of this transfer function is

$$\lim_{s \rightarrow 0} \frac{q(s)}{r(s)} = \frac{K}{K - mgl}, \quad (10)$$

and it is independent of k_d gain. If we add the proportional gain k_p , the steady state value is different according to the gain.

In the equation (7), $\dot{\hat{q}}$ should be calculated from the following observer equation.

$$\dot{\hat{q}} = \frac{1}{K} w + \frac{l}{K} (y + Ku) \quad (11)$$

$$\dot{\mathbf{x}} = -L_o \mathbf{w} - (L_o^2 + \mathbf{a})(\mathbf{y} + K\mathbf{u}) + K\mathbf{b}u, \quad (12)$$

where the observer pole is L_o .

For a practical implementation of damping controller, the compensator transfer function in Fig.8 is derived by substituting for u in the observer equation (10),(12).

$$K_c(s) = p_c \frac{s + p_b}{s + p_a} \quad (13)$$

$$\text{with } p_a = \frac{l + (\mathbf{b} - \mathbf{a})k_d}{1 + k_d l}, \quad p_b = -\frac{\mathbf{a}}{l}, \quad p_c = \frac{k_d l}{K(1 + k_d l)}$$

Therefore, increasing damping ratio in the light damped system can be regarded as making the simple first order polynomial compensator that stabilizes the torque oscillation. The same damping controller can be applied to the control of sagittal plane, but its stiffness is different.

Fig.9 shows the experimental result of the proposed damping controller during single support phase. When only PD control is applied in holding the ankle without damping controller, it cannot decay out the oscillation caused from external torque. However, after the damping term is applied by damping controller, the oscillation is decayed out within 0.8 second. In the compensator, assigned observer pole L_o is 6 rad/s and damping ratio \mathbf{x} is 0.707. This compensator works as a basic controller during single support phase of biped walking.

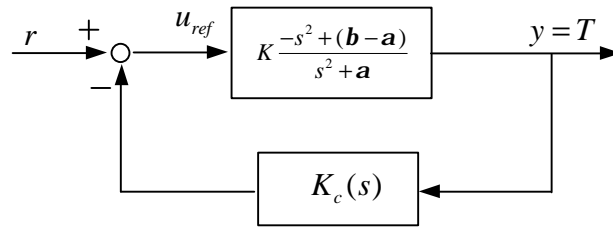


Fig. 8. Block diagram of practical damping controller

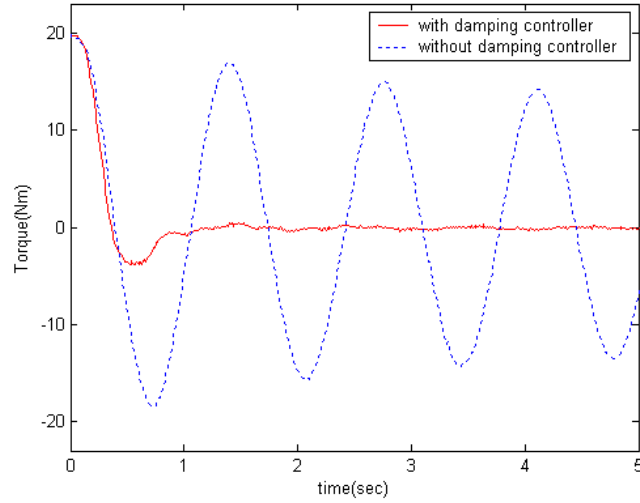


Fig. 9. Time response of measured torque (Experimental result)

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 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.
- 3) We designed a balance controller at double support phase and performed ZMP feedback by experiment.
- 4) As a suitable model during single support phase, the inverted pendulum model with flexible link was proposed and the compensator design method was described for the model. The torque feedback experiment was performed to verify the performance of controller.

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

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