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# Controllers for Running in the Humanoid Robot, HUBO

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*Abstract*— **This paper discusses the controllers for running in the humanoid robot and verifies the validity of the proposed controllers via experiments. To realize running in a humanoid robot, the overall control structure is composed of an off-line controller and an on-line controller. The main purpose of the on-line controller is to maintain the dynamic stability while the humanoid robot runs. The on-line controller is composed of the posture balance control in the sagittal plane, the transient balance control in the frontal plane, and the swing ankle pitch compensator in the sagittal plane. These controllers were applied to the humanoid robot, HUBO, and it ran forward stably at a maximum speed of 3.24km/h.**

## I. INTRODUCTION

Running, a topic of interest in the field of humanoid robots, is being studied at various universities and institutes around the world. ASIMO of Honda is currently the best example of this type of research. According to an announcement in 2005, the newest version of ASIMO can walk at a maximum speed of 2.7km/h and run at 6km/h [1]. ASIMO is known as the fastest humanoid robot in the world. QRIO of Sony [2], HRP-2LR of AIST [5], etc. are also being used in running research.

However, in reality, the running performance of robots is vastly inferior to that of humans. The conditions of the running surface are highly restricted, the speed of humanoid robots is considerably slower than the speed of humans, and humanoid robots are more unstable than humans. Therefore, more stable and faster movements of humanoid robots are needed.

To realize running in humanoid robots, the overall control structure is composed of an off-line controller and on-line controller. The off-line controller is pre-determined, and the running pattern is included in the off-line controller. We already have developed the running pattern generation method in previous research [16]. In this research, the on-line controller for running in the humanoid robot is suggested. The main purpose of the on-line controller is to maintain the dynamic stability.

The on-line controller is composed of three controllers. First, the posture balance controller in the sagittal plane helps the humanoid robot maintain its balance and to reduce the vibration in the sagittal plane. Second, the transient balance control in the frontal plane prevents the humanoid robot from falling in the frontal plane. Third, the swing ankle pitch compensator in the sagittal plane prevents the swing foot of the humanoid robot from touching the ground while the humanoid robot runs. Through these controllers, the humanoid robot, HUBO, can run stably.

This paper is organized as follows. In Section 2, the humanoid robot used in this paper, HUBO, is explained. In Sections 3, the on-line controllers for running in humanoid robots are explained. In Section 4, the controllers are verified in experiments. Finally, the last section concludes the paper.

## II. OVERVIEW OF THE HUMANOID ROBOT, HUBO

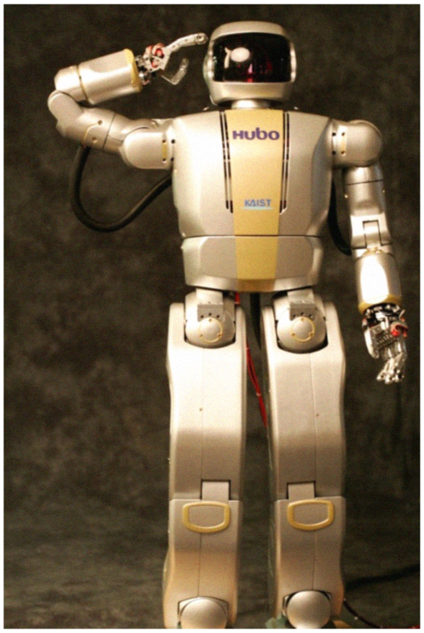

Figure 1. Humanoid Robot, HUBO

The humanoid robot used in this research is HUBO. It uses a distributed control system, the main computer managing the overall operation of the robot and the joint motor controllers

(JMCs) controlling the motor of the robot are connected through controller area network (CAN) communication. If the main computer sends position commands to a JMC, each JMC controls an assigned motor to move to commanded position. Some sensory devices are also attached. They are used for the posture control and the motion control, and they communicate to the main computer through the CAN. Since the main computer is attached inside the humanoid robot, the wireless LAN is used to access the main computer.

In this research, an inertia measurement unit (IMU), gyro, and force/torque (FT) sensors are used. An IMU sensor is attached to the upper body of the robot and measures the angled and angular velocities against the ground in the sagittal and frontal planes. The IMU sensor is composed of an inclinometer and a gyro. Other gyro sensors are used to measure the angular velocity of the stance leg in the frontal plane, which are attached to both thighs. FT sensors are also attached at the ankle joints and measure normal force and two moments. They are used to detect the landing and flying timings.

## III. CONTROLLERS FOR RUNNING

To realize running in a humanoid robot, the overall control structure is composed of the off-line controller and the on-line controller. The off-line controller is pre-determined, and the running pattern is included in the off-line controller. On the other hand, the main purpose of the on-line controller is to maintain stability while the system works.

The on-line control structure of HUBO, the robot used in this research, is composed of two control loops, as shown in Figure 2. The first control loop controls the position of motor, and it works every millisecond in the JMC. A general PD feedback controller is used here.

The second control loop works every 5 milliseconds, which is the same as the timer interrupt of the main computer. Its important role is to send the motor command calculated in the main computer to the JMCs with CAN. The running pattern generated off-line is located in this loop. Also, the three online controllers (the posture balance controller in the sagittal plane, transient balance controller in the frontal plane, and the swing ankle compensator in the sagittal plane), which help to maintain stable running, are located in this loop.

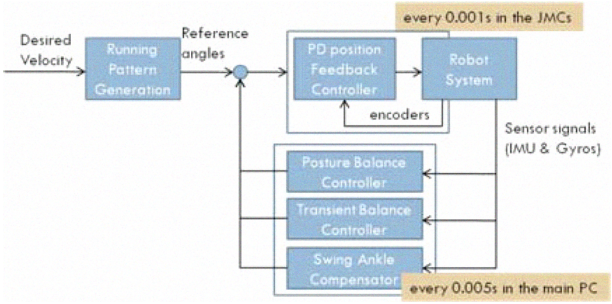

Figure 2. On-line control structure

### A. *Posture Balance Controller in the Sagittal Plane*

Due to the geometrical structure of the humanoid robot, reducer, the rubber bush of the sole, and so on, the humanoid robot has compliance. This compliance causes vibration when the robot stands on the ground and the vibration causes instability. Therefore, a posture balance controller in the sagittal plane is proposed to reduce the vibration and maintain balance. It is applied only in the sagittal plane, and it makes the robot maintain its posture.

#### 1) *System Identification*

To design the posture balance controller in the sagittal plane, the humanoid robot in the sagittal plane is simplified as shown in Figure 3. $m$ is the total mass of the robot, $u$ is the position command of a motor, g is the gravity, and $L$ is the distance from the ankle joint to the center of mass (COM). Also, the compliance of the robot is composed of a spring $(K)$ and a damper $(C)$. $\theta$ is the real angle of the robot and is measured by the IMU sensor attached to the upper body.

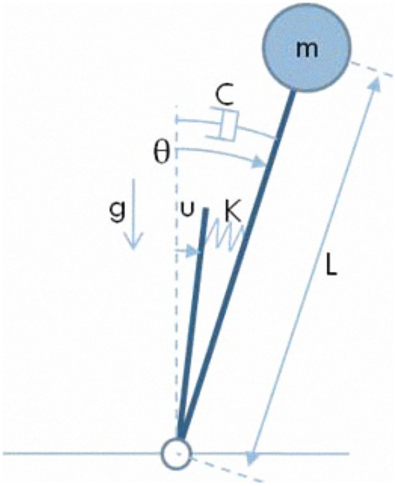

Figure 3. Simple model in the sagittal plane

The dynamic equation of the simple model is as follows.

$$mL^2\ddot{\theta} + C\dot{\theta} + K\theta - mgLsin\,\theta = Ku \qquad (1)$$

Equation (1) is linearized as follows.

$$mL^2\ddot{\theta} + C\dot{\theta} + K\theta - mgL\theta = Ku \qquad (2)$$

The transfer function between $\theta$ and $u$ is as follows.

$$\begin{aligned} TF \equiv G(s) &= \frac{\Theta(s)}{U(s)} = \frac{K}{mL^2s^2 + Cs + (K - mgL)} \\ &= \frac{\frac{K}{mL^2}}{s^2 + \frac{C}{mL^2}s + \frac{K - mgL}{mL^2}} = \frac{\frac{K}{mL^2}}{s^2 + 2\varsigma\omega_n s + \omega_n^2} \qquad (3) \end{aligned}$$

The unknown values of the transfer function are $K$ and $C$. They are calculated through the analysis of the free vibration response of the robot. The vibration frequency ($f_d$) and real pole ($\sigma$) of the free vibration response are easily estimated. With $f_d$ and $\sigma$, the undamped natural frequency ($\omega_n$) and the damping ratio ($\varsigma$) are calculated as follows.

$$\begin{gathered} \sigma = \varsigma\omega_n \\ f_d = \frac{\omega_d}{2\pi} \\ \omega_d = \omega_n\sqrt{1 - \varsigma^2} = \sqrt{\omega_n^2 - \sigma^2} \\ \therefore \omega_n = \sqrt{\omega_d^2 + \sigma^2} = \sqrt{(2\pi f_d)^2 + \sigma^2}\ and\ \varsigma = \frac{\sigma}{\omega_n} \qquad (4) \end{gathered}$$

Therefore, $K$ and $C$ are calculated as follows.

$$\begin{aligned} K &= mL^2\omega_n^2 + mgL \\ &= mL^2((2\pi f_d)^2 + \sigma^2) + mgL \quad (5) \\ C &= 2\varsigma\omega_n mL^2 = 2\left(\frac{\sigma}{\omega_n}\right)\omega_n m = 2\sigma mL^2 \quad (6) \end{aligned}$$

Figure 4 shows the free vibration response of HUBO in the sagittal plane. Therefore, $f_d$ and $\sigma$ were estimated as follows.

$$\begin{gathered} \sigma \approx 0.9 \\ f_d \approx 1.17Hz \end{gathered}$$

With Equation (4), $\omega_n$ and $\varsigma$ were calculated.

$$\begin{gathered} \omega_n = 7.4\,rad/sec \\ \varsigma = 0.12 \end{gathered}$$

With Equation (5) and (6), $K$ and $C$ were calculated.

$$\begin{gathered} K = 753Nm/rad \\ C = 18Nm/(rad/sec) \end{gathered}$$

Therefore, the transfer function of HUBO is as follows.

$$TF \equiv G(s) = \frac{75.3}{s^2 + 1.8s + 54.9} \qquad (7)$$

*2) Design the posture balance controller in the sagittal plane*

The control law is as follows.

$$\begin{aligned} u_{AnkleRoll} &= \theta_{Ankle}^{Ref} + \theta_{Ankle}^{control} \\ &= \theta_{Ankle}^{Ref} + C_f K_P\left(\theta_{Ankle}^{Ref} - \theta_{IMU}\right) \quad (8) \end{aligned}$$

$\theta_{Ankle}^{Ref}$ means the pre-scheduled ankle trajectory in the running pattern generation, and $\theta_{Ankle}^{control}$ means the control input created by the posture balance controller. The posture balance controller uses the P-controller. The structure of the posture balance controller in the sagittal plane is shown in Figure 5.

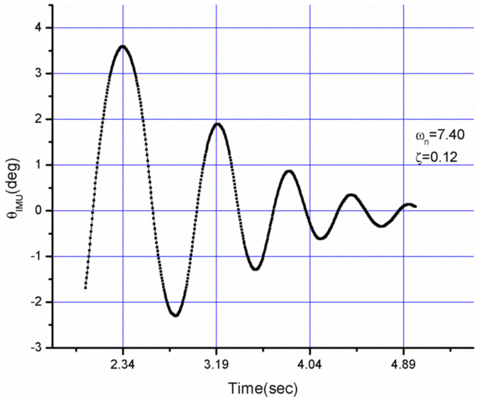

Figure 4. Free vibration response of HUBO in the sagittal plane

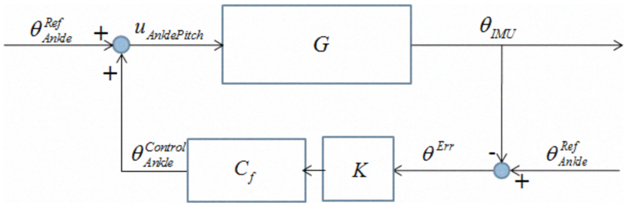

Figure 5. Posture balance controller in the sagittal plane

The transfer function of the simple model with the posture balance controller is as follow.

$$\begin{gathered} U = R + C_f KE \\ E = R - \Theta \\ \Theta = GU = G\left(R + C_f K(R - \Theta)\right) \\ \left(1 + C_f KG\right)\Theta = \left(\mathrm{G} + C_f KG\right)R \end{gathered}$$

$$\therefore \frac{\Theta(s)}{R(s)} = \frac{G + C_f K G}{1 + C_f K G} \tag{9}$$

U, R, E, and Θ mean the Laplace transforms of $u_{AnkleRoll}$, $\theta_{Ankle}^{Ref}$, $\theta_{Ankle}^{Err}$, and $\theta_{IMU}$. G is the transfer function of the simple model, and K is the transfer function of the posture balance controller. $C_f$ is the transfer function of the spill-over filter. The spill-over filter prevents an unpredicted response caused by the difference between the real humanoid robot and the simple model. The gain of K is calculated by the root locus design method.

As part of this procedure, the posture balance controller in the sagittal plane of HUBO is designed. The characteristic equation of the system applied controller is as follows.

$$1 + K C_f G(s) = 0 \tag{10}$$

Here,

$$C_f(s) = \frac{10}{s + 10} \tag{11}$$

$$G(s) = \frac{75.3}{s^2 + 1.8s + 54.9} \tag{12}$$

The root locus of the characteristic Equation (10) is shown in Figures 6 and 7. Figure 6 shows the root locus when $K_P$ is larger than zero, and Figure 7 shows the root locus when $K_P$ is smaller than zero. If $K_P$ is set to a positive value, the system diverges. Therefore, $K_P$ is set to a negative value.

$K_P$ is set to -0.5 in this research. When $K_P$ is -0.5, the damping ratio (ς) becomes 0.59. It is 4.9 times larger than the damping ratio when the posture balance controller is not applied. Since $K_P$ is a negative value, the posture balance controller is the positive feedback controller.

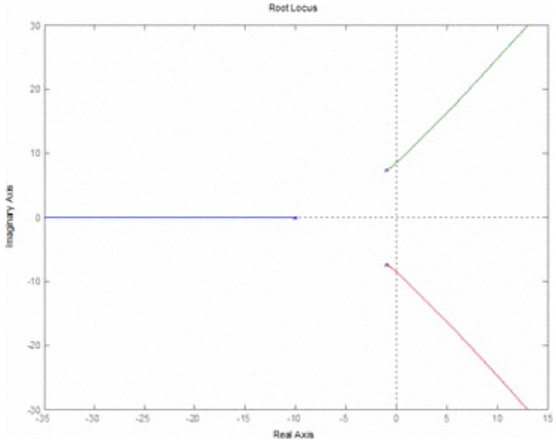

Figure 6. Root locus when $K_P>0$ (negative feedback)

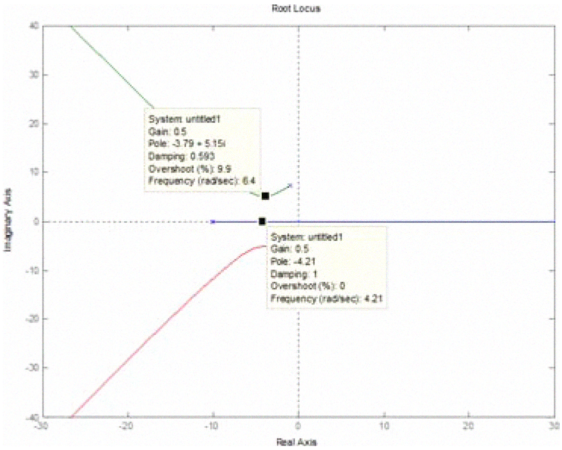

Figure 7. Root locus when $K_P<0$ (positive feedback)

### A. Transient Balance Controller in the Frontal Plane

When the humanoid robot runs forward, it moves in the same direction, regardless of the stance foot in the sagittal plane point of view. However, since the humanoid robot can shifts weight itself to the left and right in this plane, the direction of the motion changes every step. Therefore, since the previous posture balance controller does not work in the frontal plane, the transient balance controller in the frontal plane is addressed.

The simple model of the humanoid robot in the frontal plane is shown in Figure 8. When the robot stands on a single leg, it is assumed to be a single mass inverted pendulum, like a simple model in the sagittal plane. Furthermore, rate gyros are attached to both thigh parts, and they measure the inclination rate of the stance leg. When the robot stands on its right leg, the rate gyro attached to the right thigh is used. When the robot stands on its left leg, the rate gyro attached at the left thigh is used. $\theta_{AnkleRoll}^{Ref}$ means the pre-scheduled ankle roll trajectory in the running pattern generation, $\dot{\theta}_{AnkleRoll}^{Gyro}$ is the angular velocity of the stance leg measured by the rate gyro, and $u_{AnkleRoll}$ means the control input created by the transient balance controller.

Figure 9 shows the control structure of the transient balance controller in the frontal plane. The role of the transient balance controller is to recover the inclination with the ankle-roll joint when the humanoid robot inclines in the frontal plane. Similar to a PD feedback controller, the angle and angular velocity of the stance leg are used to calculate the control input. Since the rate gyro measures only the angular velocity, the angle is estimated by the integration of the rate gyro. However, since the signal of the rate gyro drifts, the real angle and the estimated angle are different. Therefore, the drift of the rate gyro is eliminated by the high pass filter and the integrator. Also, the spill-over filter is used to prevent the unpredicted response caused by the difference between the real humanoid robot and the simple model.

The control law is as follows.

$$
\begin{aligned}
u_{AnkleRoll} &= \theta^{Ref}_{AnkleRoll} + \theta_{Comp} \\
&= \theta^{Ref}_{AnkleRoll} + \frac{a_1}{s+a_1}\left(\frac{K_P}{s+a_2} + K_D\right)\left(\dot{\theta}^{Ref}_{AnkleRoll} - \dot{\theta}^{Gyro}_{AnkleRoll}\right) \qquad (13)
\end{aligned}
$$

The structure of the transient balance controller in Figure 9 is somewhat similar to the posture balance controller in Figure 5, but the performance is different. Since the transient balance controller uses a negative feedback controller, the values of $K_P$ and $K_D$ applied to HUBO are positive. Furthermore, the controller is reset when the stance leg is changed from the one leg to the other leg since the direction of motion is also changed.

Through the transient balance controller, the humanoid robot runs stably in the frontal plane.

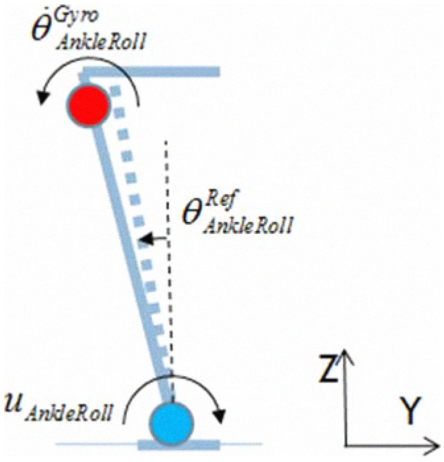

Figure 8. A simple model in the frontal plane

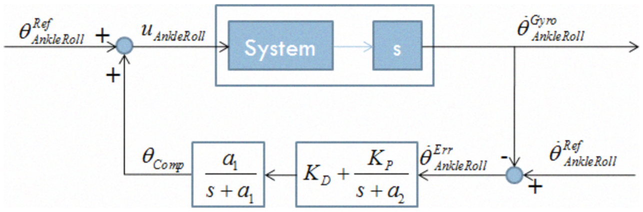

Figure 9. The structure of the transient balance controller in the frontal plane

## B. *Swing Ankle Compensator in the Sagittal Plane*

When the humanoid robot runs forward, it can be inclined forward or backward due to the environmental factors. When it is inclined forward, the toe of the swing foot is able to touch the ground, and this causes the unstable running. Therefore, the toe of the swing foot is lifted up according to the upper body's inclination, as shown in Figure 10. The inclination of the upper body is measured by the IMU sensor.

The control law is as follows.

$$
\begin{aligned}
u_{AnkleRoll} &= \theta^{Ref}_{Swing} + \theta^{Comp}_{Swing} \\
&= \theta^{Ref}_{Swing} + (K_P + sK_D)\left(\theta^{Ref}_{Swing} - \theta^{IMU}_{Swing}\right) \qquad (14)
\end{aligned}
$$

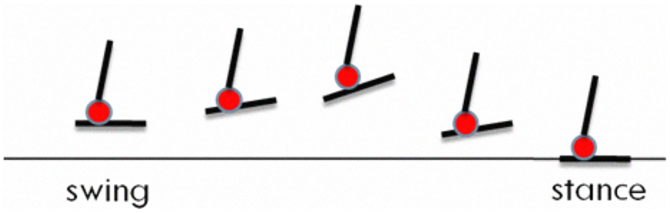

Figure 10. Lifting of the toe of the swing foot

## IV. EXPERIMENT

The proposed controllers were applied to the humanoid robot, HUBO. In the experiment, HUBO ran stably. Figure 11 shows a series of pictures in which HUBO ran.

Figure 11. Un-cased HUBO running

Table 1 shows the experimental result. HUBO can run at a maximum speed of 3.24km/h. The step time, a cycle of running is 0.33seconds, and the length of each step is 0.30m. In addition, the flight time is 0.04sec, and the flight length is 0.036m.

Table 1. Experimental Results

| | |
|---|---|
| Max. Running Speed | 3.24km/h(0.9m/sec) |

| | |
|---|---|
| Running Cycle | 0.33sec/step |
| Max. Running Step Length | 0.30m/step |
| Flight Time | 0.04sec/step |
| Max. Flight Length | 0.036m/step |

## V. CONCLUSIONS

In this paper, the on-line controller is proposed to stabilize running in the humanoid robot. The on-line controller is composed of the posture balance controller in the sagittal plane, the transient balance controller in the frontal plane, and the swing ankle pitch compensator in the sagittal plane. They are verified via experimentation. In the experiment, the humanoid robot, HUBO ran stably at speeds from 0 to 3.24km/h.

In the future, with improvement, humanoid robots will be redeveloped so that they can move faster and more stably. Also, the controller will be developed to maintain the stability of the robot according to the large disturbance.

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