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Design and Experiments of Advanced Leg Module (HRP-2L) for Humanoid Robot (HRP-2) Development

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Abstract

This paper presents an advanced leg module developed for, HRP-2, a new humanoid robotics platform, which has been developed in the phase two of the Humanoid Robotics Project(HRP), a five year program sponsored by the Ministry of Economy, Trade and Industry of Japan (METI) from 1998FY to 2002FY. The biped locomotion ability of HRP-1, the humanoid robotics platform developed in the phase 1 of HRP, is to be improved so that HRP-2 can cope with rough terrains and can prevent possible damage to the robot's body caused by tipping over. In this paper, the mechanisms and specifications of the leg module, the electrical system, the simulation results utilized for deciding specifications, and some experiment results are presented.

1. Introduction

As the number of humanoid robots that can walk and can go up/down stairs increases, such robots will be expected to have more sophistication in their ability to handle several application tasks in an actual human living environment.

To encourage research and development of humanoid robots which have the capability of handling several application tasks, METI has launched HRP [1]. The project term is five years from 1998FY to 2002FY, consisting of the phase one for the first two years and phase two for the last three years. In the phase one (FY 1998-1999), a humanoid robotics platform (HRP-1), a tele-existence cockpit to control the humanoid, and an equivalent virtual robot including dynamic simulator [2] were developed. In the phase two (FY 2000-2002), research and development have been carried out on the application tasks of humanoid robots (maintenance tasks for industrial plants, human care, tele-operations of construction machines, security services of home and office, and cooperative works outdoors) using HRP-1.

This paper presents an advanced leg module (HRP-2L) developed for HRP-2. HRP-2 is a new humanoid robotics platform, whose manufacturing process is currently in progress in the phase two of HRP. HRP-2 has two important features, which are especially necessary for cooperative works outside. The first is that the ability of the biped locomotion of HRP-1 has improved so that HRP-2 can cope with rough terrains outdoors as shown Figure 1 [3]. The second is that special attention was paid in designing HRP-2L in order to avoid easily tipping over. The improved HRP-2 is feminine in size and is expected to be 1500 [mm] tall and weigh 60 [kg].

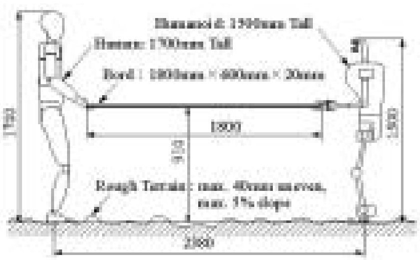


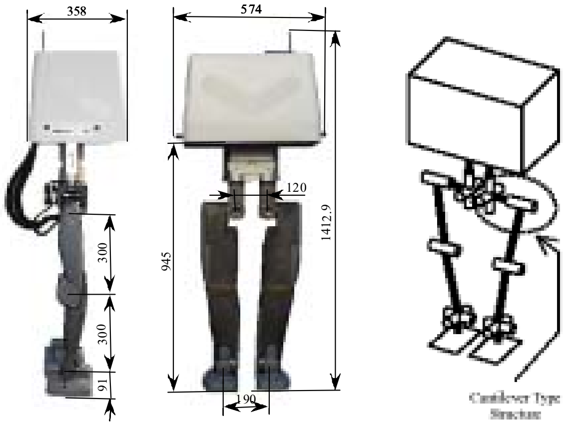
Figure 1: *Outdoor Cooperation Work*

In this paper, the mechanisms and specifications of the leg module, the simulation results utilized for deciding specifications, and the experiment results are explained.

2. Specifications of HRP-2L

Figure 2(a) presents an overview of the developed leg module for HRP-2 and (b) its kinematical design, respectively.

Table 1 details the dimensional specifications and Table 2 illustrates the working angle of leg module [9].



(a) Developed HRP-2L *(b) Configuration*

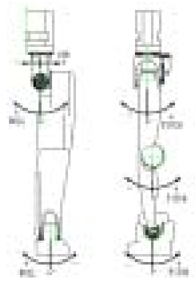
Figure 2: *Leg Module for HRP-2*

Table 1: *Dimensional Specifications of Leg Module*

Legs	6 D.O.F. / Leg (Hip: 3 Knee: 1 Ankle: 2)	
	Upper leg length:	300 [mm]
	Lower leg length:	300 [mm]
	Ankle length:	91 [mm]
	Length between hip joints:	120 [mm]
Weight	Legs: 8.6 [kg/leg] × 2 [legs] =	17.2 [kg]
	Batteries:	11.4 [kg]
	Controller Box:	7.0 [kg]
	Dummy Weights:	22.6 [kg]

Table 2: *Working Angle of Leg Module*

Hip	Yaw	-45 deg. to 45 deg.
	Roll	-45 deg. to 20 deg.
	Pitch	-135 deg. to 42 deg.
Knee	Pitch	-0 deg. to 150 deg.
Ankle	Pitch	-100 deg. to 42 deg.
	Roll	-20 deg. to 35 deg.



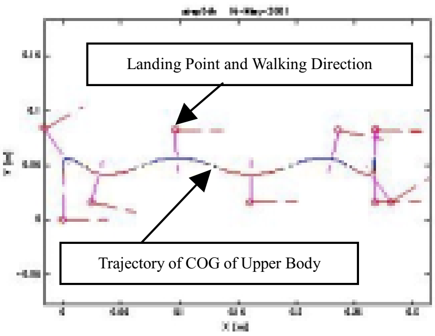
3. Design and Construction

As mentioned previously, the design concepts of HRP-2 are light and compact, while having the capability of performing some application tasks like cooperative works outside. In this section, the details of mechanical design are explained.

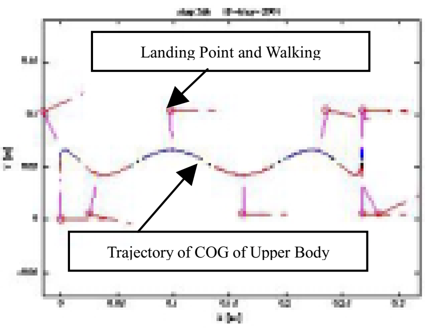
3.1. Mechanism for Prevention of Tipping Over

The humanoid robot tends to tip over easily, since the area of foot sole that supports the whole body is so small. The mechanism for preventing the robot from tipping over is very important to successfully develop a humanoid robot.

The tipping over easily occurs when the target zero moment point (ZMP) is outside of the support polygon made by the supporting leg(s). The stable walk is achieved by constructing the mechanism that enables to have a wide sphere of landing point for swinging leg. By changing the support polygon immediately, the tipping over would be prevented even if the humanoid robot begins to tip over. The other factor throwing the humanoid robot off balance is caused by rolling motion of gait. The mechanism to make the trajectory of the center of gravity (COG) of the upper body smoother is effective in the prevention of tipping over.



(a) Length between Landing Points of Pitch Axis: 65 [mm]



(b) Length between Landing Points of Pitch Axis: 100 [mm]

Figure 3: *Analytical Results on Trajectory of COG of Upper Body in the Horizontal Plane*

Based on the above analysis, the mechanism for preventing the robot from tipping over was designed as follows. To realize a wide sphere of landing point for the swinging leg, the hip joint was designed to be a cantilever type structure as shown in Figure 2. Figure 3 also illustrates that a smoother movement with less rolling motion is achieved by the shorter length between both landing points of pitch axis.

3.2. Mechanism to Balance on Rough Terrains

For practical use, the humanoid robot should be able to walk not only on flat floors but also on rough terrains. To design the mechanism for walking on rough terrains, we set our goals to enable the humanoid robot to cope with a rough terrain whose irregular is within 40 [mm] per one step and whose slope is less than 5 %.

To realize our goals, the torque control of foot sole is very important. HRP-2L has a mechanism shown in Figure 4 at each foot part. The mechanism consists of a six-axis force sensor and rubber bushes. Since the rubber bushes implement compliance elements along the roll and pitch axes, the control system of torque imposed on foot sole can be achieved by controlling its rotational deformations using a six-axis force sensor [10].

This mechanism also has a compliance element in the vertical direction, and these compliance elements are effective in also reducing the landing impact force and torque.

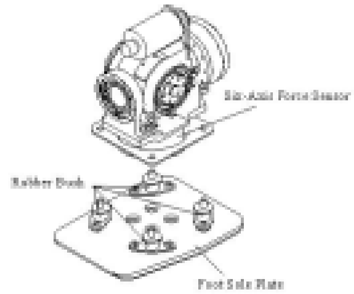


Figure 4: *Mechanism for Rough Terrain*

3.3. Structural Design for Light Weight

The weight of the structural parts is quite significant. As stated in Ref. [4], the proportion of structural weight to total weight of the humanoid robot is more than 60 %. The weight of screws is also significant, since 20 % of the overall weight is due to screws [5].

The first approach to realizing a lightweight structure was carried out by casting several links. Figure 5 shows the cast links for HRP-2. The material used is magnesium alloy, since the specific gravity of magnesium alloy is 68 % of that of aluminum alloy.

Figure 5: *Magnesium Cast Links*

3.4. Selection of Actuator and Reduction Ratio

The selection of actuator and reduction ratio is an important issue in the design of a humanoid robot. To optimize the selection of actuators and reduction ratios, iterations of the mechanical design, simulation analysis of the control system, and application of the real system are necessary [6].

Several simulation analyses on humanoid robot motions were carried out. One example of simulation analyses is shown in Figure 6. These analytical results were obtained from simulating dynamically a humanoid robot going up stairs with 200 [mm] height per step and 1.5 [sec/step] in speed. Figure 6(a) shows the time response of angular velocity of pitch axis, (b) joint torque of pitch axis, and (c) consumed power of pitch axis. These results provide the guidelines to decide hardware specifications such as actuators and reduction ratio. Based on several dynamic simulations, we finally decided on the hardware specifications for actuators and Harmonic Drive gears as shown in Table 3.

Table 3: *Actuators and Harmonic Drive gears used in HRP-2L*

Joint		Actuator.	Ratio of Harmonic.
Hip	Yaw	DC 20 [W]	1/160
	Roll	DC 90 [W]	1/160
	Pitch	DC 90 [W]	1/120
Knee	Pitch	DC 150 [W]	1/160
Ankle	Pitch	DC 90 [W]	1/160
	Roll	DC 70 [W]	1/160

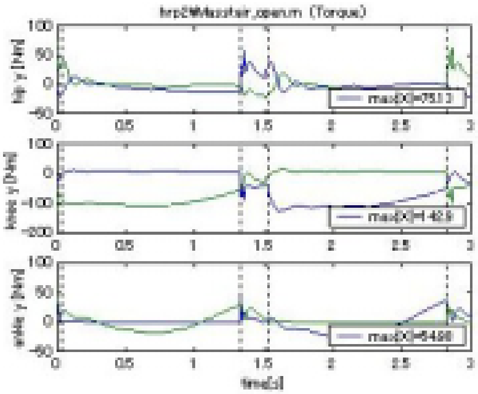
3.5. Electrical Design

In planning the electrical design for HRP-2L, several efforts to realize a lightweight and compact body were made. In this section, the details of electrical design are explained.

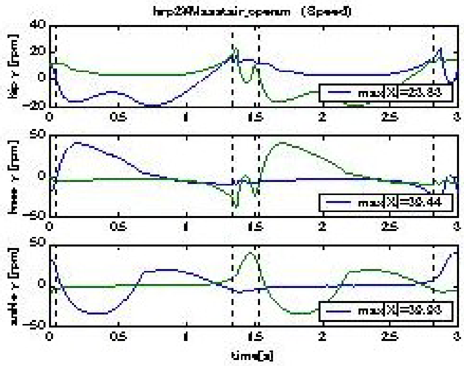
3.5.1.Servo Driver Module

Since the humanoid robot has over 30 D.O.F.'s, the volume of the servo drivers is a significant issue in the construction of a compact humanoid. To address this issue, a compact servo driver module was developed for HRP-2L.

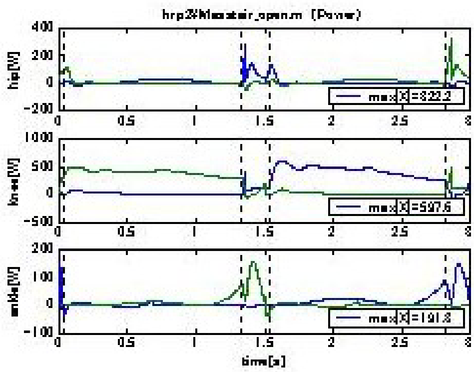
Figure 7 is a photograph of the developed DC motor driver module. This module controls two DC motors independently. It is compact enough to enable several modules to be installed inside the body of a humanoid, even if high D.O.F.'s are required. Table 4 demonstrates that the module has a powerful output for controlling motors for HRP-2L.



(a) Joint Torque of Pitch Axis



(b) Angular Velocity of Pitch Axis



(c) Consumed Power of Pitch Axis

Figure 6: *Analytical Results when going up Stairs with 200[mm] Height per Step and 1.5[sec/step] in speed*

Figure 7: *DC Motor Driver Module for 2-Axes*

Table 4: *Specifications of DC Motor Driver Module*

Controllable Axes	2-Axes independently
Supply Voltage	48 [V]
Maximum Output Voltage	± 48 [V]
Maximum Output Current	± 20 [A]
Input Command Voltage	± 10 [V]
Control Mode	Current Control
Size (L × W × H) [mm]	95 × 65 × 15
Weight [g] (Including plate of)	120

3.6.2. Batteries and Sensors

HRP-2L has Ni-MH batteries (total 48.0 [V], 18 [Ah]) inside of its body. The total weight of the batteries is 11.4 [kg]. This power supply system is designed so that HRP-2 can be operated for about 60 minutes.

A 6-axes digital force sensor is mounted on each foot sole to calculate ZMP as shown in Figure 4.

A 3-axes acceleration sensor and three angular velocity sensors are mounted inside of HRP-2L's body. These sensors are used for stabilizing the motion of the robot.

3.6.3. Computer System

The real-time controller runs on a CPU board (Pentium III, 933 [MHz]) in the body of HRP-2L. The operating system is ART-Linux [7]. ART-Linux enables the execution of real-time processes at the user level so that users can implement real-time applications as if they are non-real-time ones. This feature of ART-Linux is essential for operating the identical controller for the simulation and the real robot [8].

4. Experiments and Analysis

4.1. Experiment Procedure

After HRP-2L was manufactured, basic experiments were carried out to obtain the fundamental performance data. In order to measure motor current, 6 sets of current sensors were inserted into all the output lines of left leg servo drivers, and the data obtained from the sensors were recorded in a personal computer through an A/D board. The data of all the 12 joint angles, 6-axes forces detected at both ankles and transverse and angular accelerations of the body were also recorded simultaneously so that the current variation in time could be compared with the robot behavior.

The measurements were taken for three operation modes of the robot, those are, (1) stepping at a position, (2) forward walk, and (3) squat.

4.2. Experiment Results

Figure 8 shows the variations of the motor current and power consumption of the three selected joints. The leg module was operated at a forward walking mode with the speed of one step in 1.5 [s]. From the current plot of the knee in Figure 8, it is known that the current exceeds its rating (3.3[A]) when the leg is supporting the body while the motor operates within its rating range when the leg is raised from the ground. Looking at the leg pattern, it is understood that the current spike occurs by kick motion. The power of all the joints stays at a low level throughout almost all the range of the motion, indicating that these motors rotate with relatively low speed during the motion.

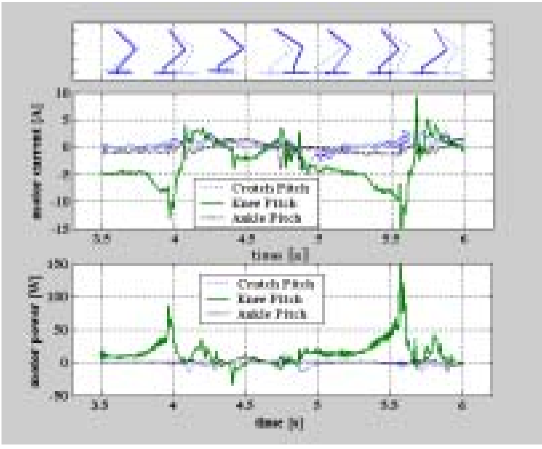


Figure 8: *Current and Torque at Forward Walk*

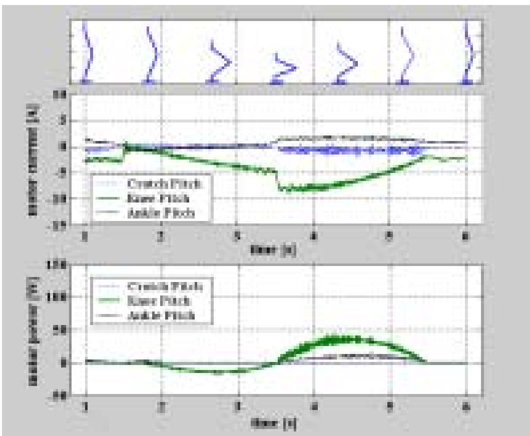


Figure 9: *Current and Torque at Squat*

Figure 9 shows the same motor current and power consumption variations as Figure 8 but in this case the leg was in a squat operation. Two current discontinuities are observed in the knee joint, which is due to a low inverse transmission efficiency of harmonic drive. From the power plot of the knee joint, it is observed that work is done to the motor in the phase of retraction. Because of low inverse efficiency of the reduction drive, this negative area is relatively small. However if this mechanical transmission efficiency is improved, it is expected that the energy is utilized as recovery energy during this motion.

Figure 10 plots the net knee joint torque at forward walk with the simulation results. The net output torque was calculated from the motor current considering the gear efficiency that was previously obtained from test bench experiment as a function of input RPM and input torque. High correlation between the simulation and experimental results can be seen. This means that the leg module follows almost exactly the pattern generated by the simulator.

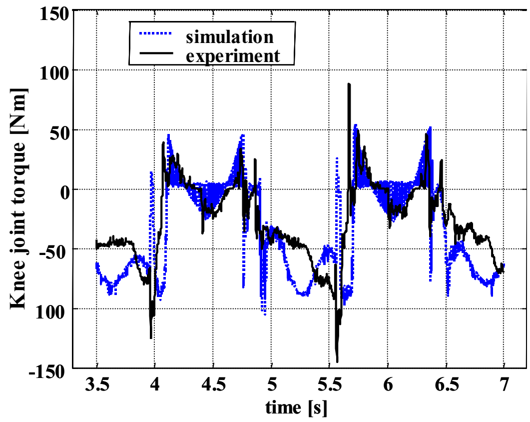


Figure 10: *Output Torque at Walk*

To achieve a comprehensive evaluation of the performance of HRP-2L, the effective motor current was calculated and compared with the motor specifications. To obtain these values, RMS (root-mean-squared) of current data was calculated for the time interval of 3 steps at forward walk operation and for the whole period at squat operation. Figure 11 is the calculated results. Except for the knee joint, the motors operate under their continuous current rating. For the knee joint, careful attention must be paid to the motor so that it is not overheated during the operation.

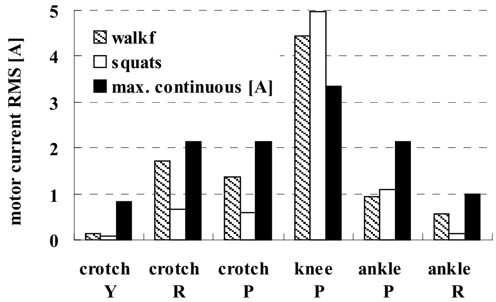


Figure 11: *Motor Effective Current*

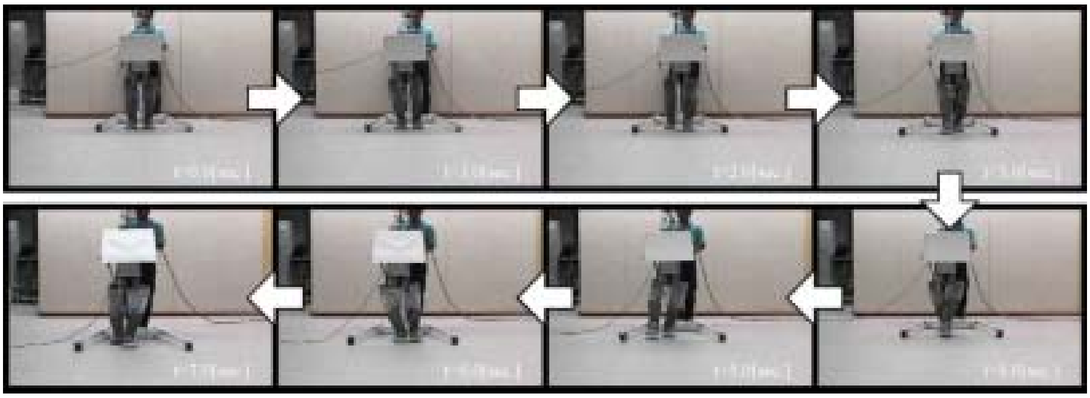


Figure 12: *Cross-Step Walk achieved by HRP-2L*

The total energy necessary for each motion was calculated, by integrating the power plot. Table 5 is the total energy consumption of all the motor implemented in the left leg. Net energy consumption used for leg motion was calculated and put in the table also. From this table it appears that the loss of energy due to harmonic drives is from 20 to 30% of the energy exerted by the motors.

Table 5: *Total Energy Consumption*

per leg		walk for 3 steps	squat
motor work	[J]	54	56
net output work		39	45
total efficiency	[%]	72	81

As mentioned before, the cantilever structure was employed in the hip joint for the purpose of improvement of the ability of prevention from tipping over. To demonstrate the effect of the cantilever structure, HRP-2L was operated with the cross-step walking pattern. Figure 12 is the sequence of this operation. As seen in the figure, the swinging leg lands right in front of the supporting leg, which was realized by the cantilever structure in the hip joint.

5. Conclusions

This paper presented how we developed the advanced leg module for HRP-2, which copes with rough terrains outdoors. Several distinctive mechanisms such as a mechanism to prevent tipping over and a mechanism for walking on rough terrains were employed for HRP-2L.

We are planning to perform more walking experiments outdoors using HRP-2L to develop a brand new humanoid robotics platform named HRP-2.

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