Research Subject

Humanoid Robot Design for Mobility Evolution (Nakamura Group)

(1) Goal and summary

Development of mechatoronics technology produce integration of sensors, actuators and motor drivers, which generates success mechanical design of the humanod robots. For the higher mobility acquisition, the more degrees-of-freedom will be helpful. However, it requires further and harder challenge of integration, and it is not desirable from the lightweight and miniaturization points of view. In this paper, we focus on the driving mechanism for humanoid robots. The specific problems raised in this paper are

- Joint allocation design that maximizes the whole body mobility of humanoid robots.
- Joint transmission design that switches between the drive and free modes.

The conventional humanoid robots walk with bending knee joints. It is for the high controllability of the center of gravity (COG) and the avoidance of singularity. However, it causes high energy consumption and requires high power actuators in knee joints. The installation of the waist joints will get rid of this problem, and recent humanoid robots tend to have additional waist joint [1]. The importance of the waist joint is noticed for high mobility.

On the other hand, the current design of transmission of humanoid robots is not prepared to discuss dynamical coupling between the humanoid body and the environments. The natural human motion that we see in an elegant walk or in fine dancing is acquired through the coupling. Clearly, feeling the gravity and the environmental constraints not only with a specific sensor like vision but with the whole body dynamics suggests a design principle of sensory motor system of intelligent machines. Natural motions of humanoid robots may not be obtained from just imitating human motions. They would be acquired through the dynamics of their body and the environments including the gravitation. The passive walk of McGeer opened an interesting and suggestive approach to this problem[2]

In this paper, we develop two mechanisms that improving the humanoid robot motion. The double spherical joint is six DOF mechanisms whose axes intersect in one point. By using this mechanism for humanoid hip joints, the waist joint function is realized without increasing an actuator. We also propose a joint drive mechanism that can switch between drive and free modes. The backlash clutch solved the problem adopting a simple mechanism and a control algorithm. The backlash clutch is integrated in the knee mechanism of a humanoid robot.

The humanoid robot with the cybernetic shoulder[3], double spherical joint on the hip joint and the backlash clutch on the knee joints is developed. The preliminary results of experiments are to be shown in this paper to discuss the effectiveness of the body mobility.

On the other hand, many of the conventional humanoid robots lack of mobility at the current stage, so that they can hardly work against the severity of the real environment. We developed a miniature anthropomorphic robot which reduces the danger of experiments and has so high performance that one can feed the results of experiments back to as tall robots as humans.

Development of the humanoid robot UT-θ

Double spherical hip joint Figure 1 shows the conventional hip joint mechanism. It has six degrees-of-freedom that is realized two spherical joints. Roll, pitch and yaw rotation are independent and kinematics of the lower limb is easy calculation. Figure 2 shows the motion of the upper body using conventional hip joint. Though in the posture with the bending knee, the upper body has six degrees-of-freedom, the posture with the unbending knee reduces the degree-of-freedom of the upper body to four because of the singularity as shown in the right hand side of the figure. The motion of the center of the gravity along x axis is produced by the prismatic motion along x axis or rotation by ϕ of the upper body. On the other hand, the motion along y axis is produced only by the prismatic motion along y axis of the upper body. This motion is realized as shown in Figure 3 that requires the same size actuator as hip joint to the ankle joints.

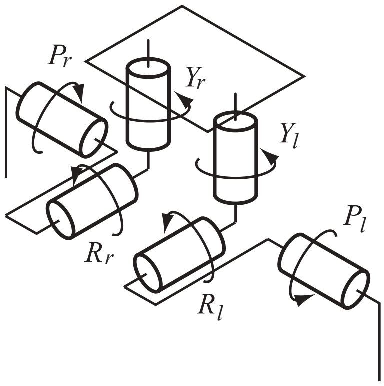


Figure 1: Conventional hip joints

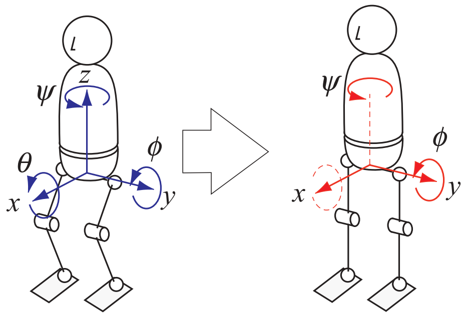


Figure 2: Motion of the upper body with conventional hip joint

On the other hand, Figure 4 shows the proposed double spherical hip joint. This mechanism has same number of degrees-of-freedom as conventional ones. $[\ \ ]_r$ and $[\ \ ]_l$ joints compose spherical joint respectively, and two centers of spherical joints coincide in one point. Figure 5 shows the upper body motion of a humanoid robot with double spherical hip joint. The number of degree-of-freedom is same as conventional one, whoever the configuration is different. The motion of the center of gravity along y axis is produced by the rotation by θ, which does not require the motion of the ankle joint. This mechanism does not realize only hip joint but also waist joints function. Figure 6 shows the design

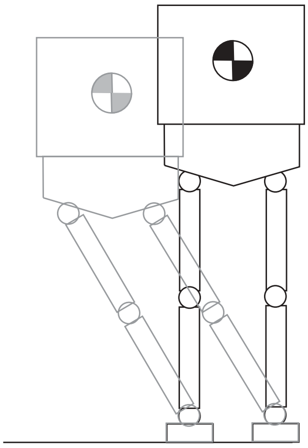


Figure 3: Motion of the center of gravity of the upper body along y axis

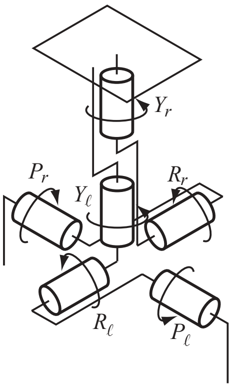


Figure 4: Hip joint using the double spherical joint

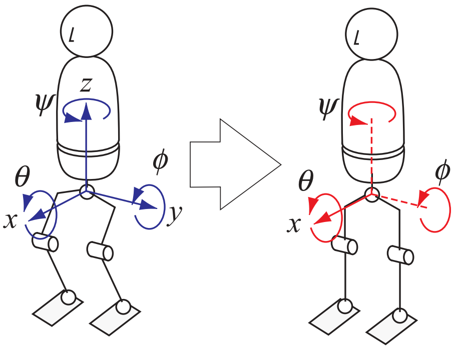


Figure 5: Configuration of the degree-of-freedom of the upper body with the double spherical joint

of the double spherical hip joint. Actuators are arranged so that the work space becomes large. Figure 7 shows photographs of developed joint. 90[W] DC servomotors and 1:100

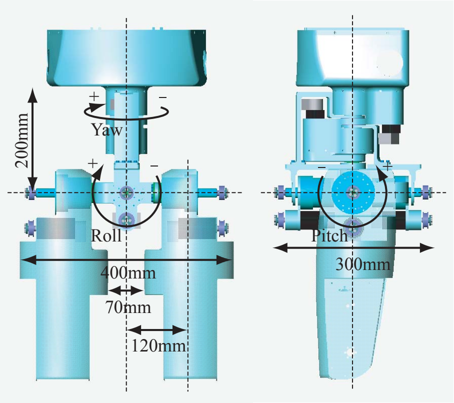


Figure 6: Design of the double spherical hip joint

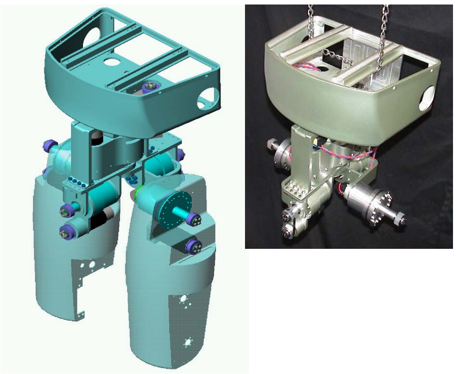


Figure 7: Designed double spherical hip joint

Harmonic drives gears are used to yaw and roll joints. In pitch joints, 150[W] DC servomotors and 1:100 Harmonic drives gears are used. The workspaces of the designed joints are shown in Table 1. For the comparison, the motion ranges of human joints are shown. The workspace of this mechanism is as large as human.

Design of knee joint Swing legs in walking motion take free swing motion after kicking the floor as shown in Figure 8. The lower leg follows gravity and the knee joint does not generate any torque. This motion is shown in passive walk[2] that is human-like motion without energy consumption of actuator torque. It is necessary for humanoid robots to implement some mechanisms that realize the free motion for lightweight and small battery. Because the high torque transmission is necessary for knee joints, the normal clutch mechanism that has low transmission power using disk friction is not sufficient.

Figure 9 shows the designed backlash clutch. This mechanism consists of three components. Part a is on the upper leg A and rotated by a motor. Part b is fixed to the lower leg B. When the gap d =0, the torque of motor is transmitted to B through a and b. By

Table 1: Workspace of double spherical hip joints

	Double spherical joint	Human
Yaw	-35∼35[degree]	-35∼35[degree]
Roll	-50∼50[degree]	-20∼35[degree]
Pitch	-120∼30[degree]	-135∼90[degree]

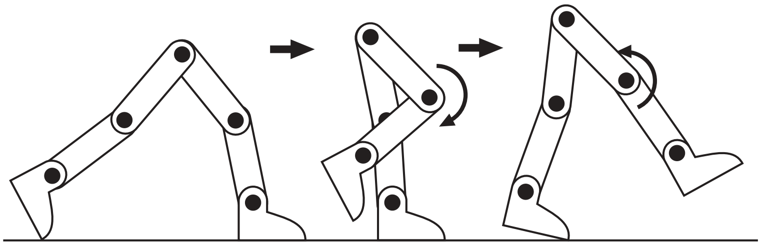


Figure 8: Free motion in walking

controlling the motor angle so that d=constant, the free motion is realized and when d=0, the high torque transmission is realized in one rotational way.

Figure 10 shows the components of backlash clutch. Each parts of a and b corresponds to that of figure 9. Hard rubber is implement as a shock absorber.

Figure 11 shows the designed knee joint using the backlash clutch. 150[W] DC servomotor and Harmonic drives gear (gear ratio is 1:100) are used. The rotational angle θ in Figure 9 is measured by an encoder attached to the motor and ϕ is measured by an additional encoder.

Development of humanoid robot We design the humanoid robot UT-θ using the double spherical hip joint and the knee joint with backlash clutch. Figure 12 shows the whole body of the humanoid robot. It is as tall as 150[cm] and has about 50[kg] weight. The head mechanism is shown in Figure 13. It has three degrees-of-freedom and two black

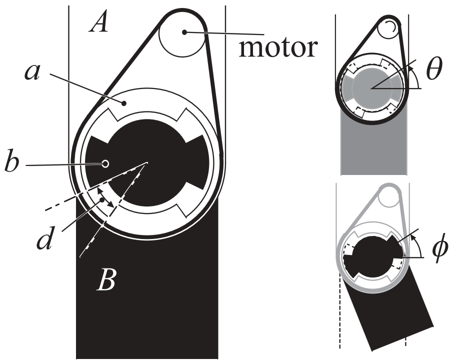


Figure 9: Backlash clutch

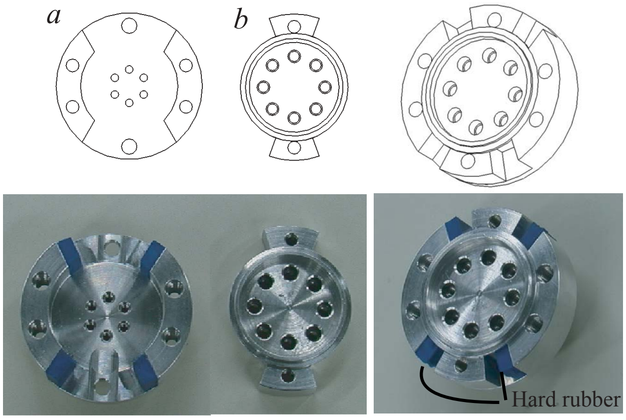


Figure 10: Components of backlash clutch

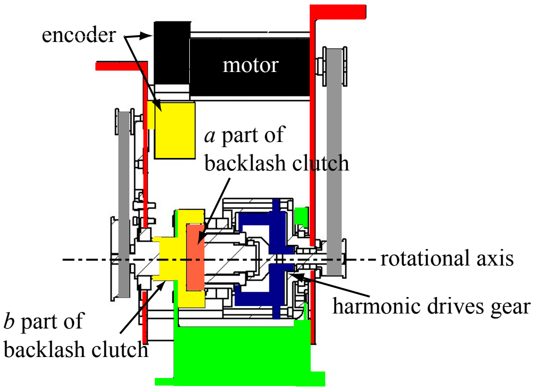


Figure 11: Design of knee joint

and white progressive CCD cameras and one NTSC CCD color camera. The chest mechanism is shown in figure 14. The cybernetic shoulder[3] is used for large mobile area and human-like motion. The body is made of magnesium alloy casting for lightweight and high rigidness.

Figure 15 shows the humanoid leg mechanism. There are one degree-of-freedom in knee and two degrees-of-freedom in ankles. The backlash clutch is implemented as figure 16.

Control algorithm of knee joint In this section, we propose a control algorithm of the backlash clutch. The backlash clutch needs the following three control modes.

Mode 1 Zero torque transmission (free)

Mode 1 High torque transmission

Mode 3 Transition from Mode 1 to Mode 2

To realize these three control modes, we adopt two degrees-of-freedom controller as shown in Figure 17. Wfere, P means the transfer function of the geared motor, K means

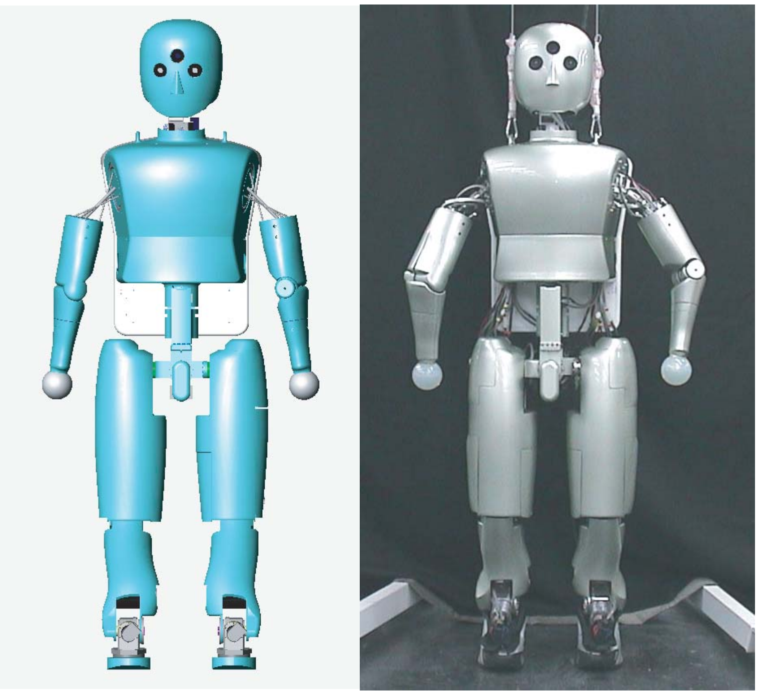


Figure 12: Whole body design of humanoid robot UT-θ

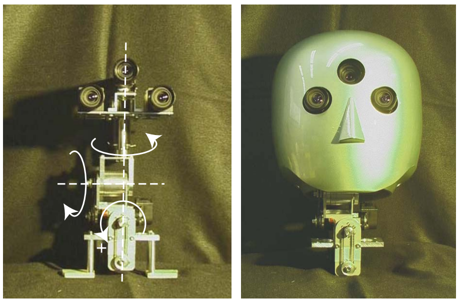


Figure 13: Head design

Figure 14: Shoulder design

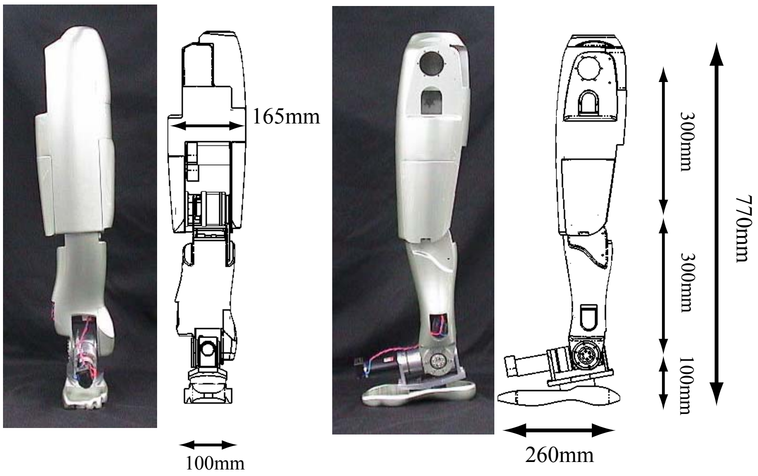


Figure 15: Design of humanoid leg

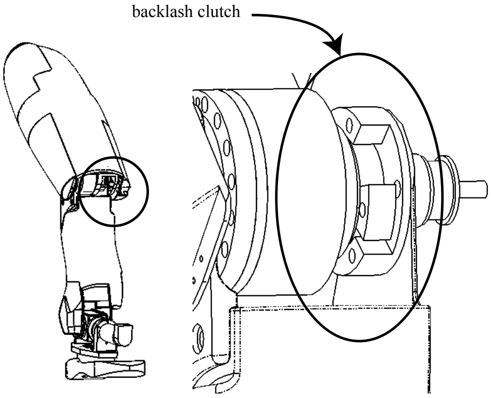


Figure 16: Location of backlash clutch

the feedback controller, G means the transfer function that describes the desirable response of θ, and r_1, r_2 are reference signals. G should be designed not to have zeros so that the response of θ does not have a over shoot with the high gain feedback controller K. r_1, r_2 are changed as follows according to the control mode.

Case 1 r_1 and r_2 are set as

$$r_1 = 0, \;\; r_2 = \phi \tag{1}$$

θ is controlled so that it follows ϕ and d is kept to be constant.

Case 2 r_1 and r_2 are set as

$$r_1 = \phi_{ref}(\text{reference angle of } \phi), \;\; r_2 = 0 \tag{2}$$

so that this control system works as normal feedback controlled system at $t \to \infty$.

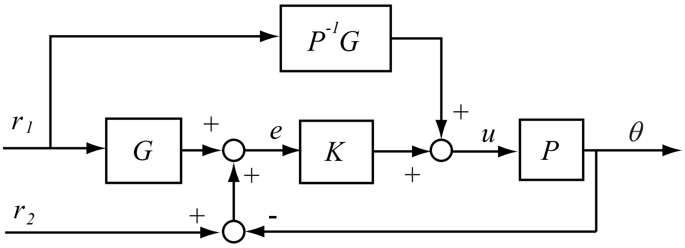


Figure 17: Two DOF control system

Case 3 r_1 and r_2 are set as

$$r_1 = \phi_{ref}, \;\; r_2 = \phi \tag{3}$$

> Because the two degrees-of-freedom control system is set so that the response of θ dose not have over shoot, part a bumps part b calmly.

By using the control law of mode 1, we realize the free motion of legs. Figure 18 shows the experimental results. The upper figure shows the responses of θ and ϕ in free swing of leg. The lower figure shows the gap $d(= \theta - \phi)$. Because opening of a and b is about 3[degree] and d is inside ±2[degree], free motion is realized.

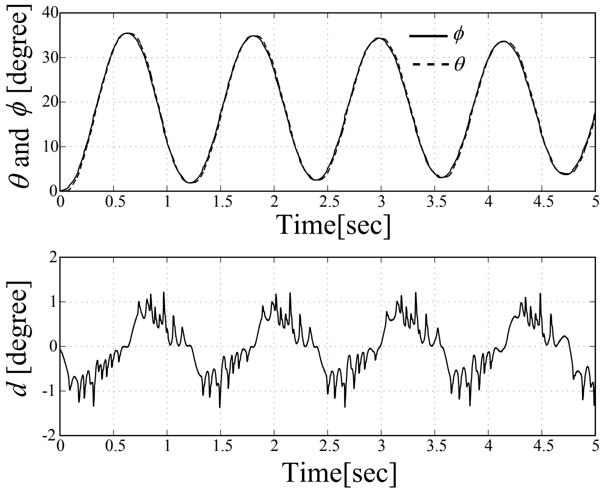


Figure 18: Experimental result of free motion

Figure 19 shows the experimental result according to the change of control mode. The control mode is changed as follows.

- 0∼0.8[sec] : mode 1
- 0.8∼1.6[sec] : mode 3
- 1.6∼5.6[sec] : mode 2 and bending the knee joint
- 5.6∼6.6[sec] : mode 2

- 6.6$\sim$: mode 1

The free motion, the high feedback control and the smooth transition of control mode are realized.

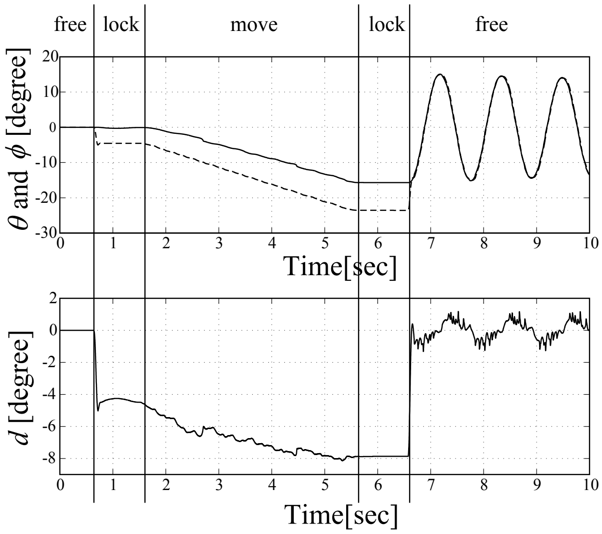
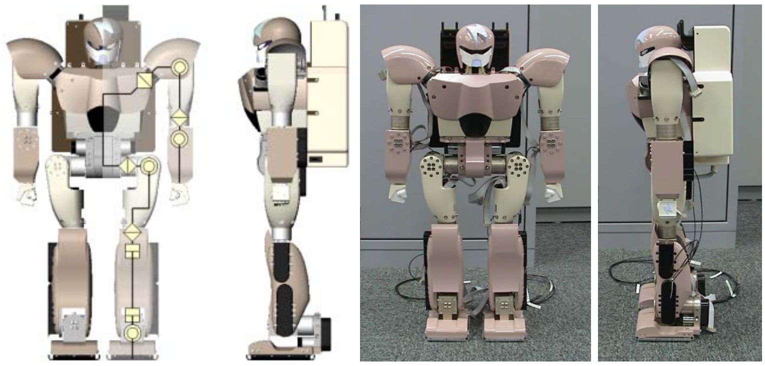


Figure 19: Experimental result for changing of control mode

Miniaturized humanoid robot UT-μ for the acquisition of the high mobility

Development of the minitualized humanoid robot for the experimental system We developed a miniature anthropomorphic robot which reduces the danger of experiments and has so high performance that one can feed the results of experiments back to as tall robots as humans.



Height	58cm
Weight	6.5kg
DOF:	20 (8 for arm) (12 for leg)

Figure 20: External view and specification of the robot

Figure 20 shows the external view, joint configuration and other specifications of the robot. Coreless DC motors (manufactured by MAXON) and Harmonic Drive gears are mounted on each joint, and the output power of motors at main joints is 11W. Thanks to them, precise control and sufficient torque output are realized. Although it causes the increase of weight of each joint component, we prevented the overweight of the robot by choosing magnesium alloy for the main structure which connects the joints. Stiffness of it is also ensured by casting thin cylindrical shells.

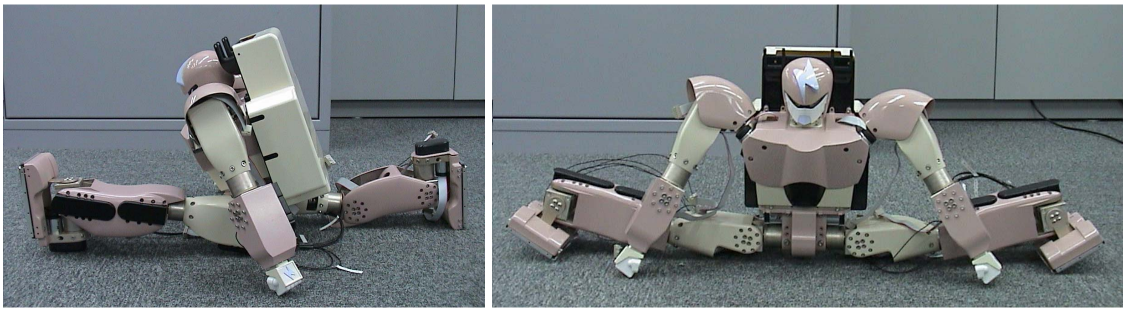
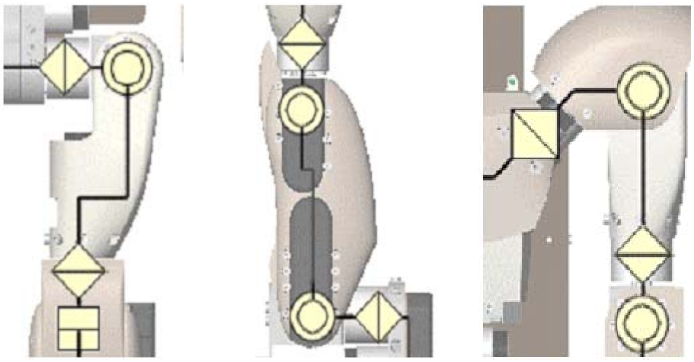


Figure 21: Hip joint movability



a. Hip joint b. Knee joint c. Shoulder joint

Figure 22: Joint configuration

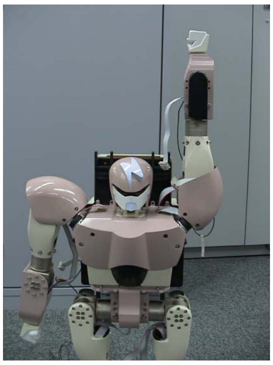


Figure 23: Hand-up posture

It has some features in joint configuration as follows.

i) Hip joint

is configured, aiming at the large movability in forward, backward and sideward direction as is shown in Figure 21. The distance between the left and right hip joints is offset, locating knee joints closer to each other(Figure 21.a). It has an effect of reducing the rolling motion in walking.

ii) Extension-flexion joints of legs

Ankle joint is located slightly behind the hip joint and the knee joint(Figure 21.b), The singularity in the standing posture is eluded.

iii) Shoulder joint

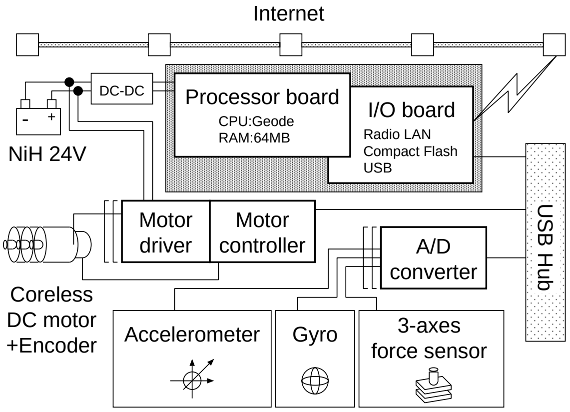


Figure 24: Hardware system of the robot

The root axis is slanted from a perpendicular axis to 45 degrees (Figure 21.c) in order to give a smoothness to the motion, mixing extensional and abductional motion(Figure 23).

Figure 24 shows the hardware system of the robot. It is an independent system in the sense that it has the processor board and battery within, excluding any cables from outer resources which disturbs robot's performance. The processor board is CARD-PCI/GX(EPSON) with a special I/O board (Fujitsu Japan Automation), featuring Geode GX1(National Semiconductor). It connects to the internet via wireless LAN card(Melco), so that one can remotely operate the robot. It also has the internal USB LAN which branches at small USB Hubs(Sanwa), and communicates with actuator drivers and A/D converters. The actuators, coreless DC motors, are controlled by the motor controller iMCs01 + motor driver iMDs01(iXs research corp.). The input signal from sensors, which includes the gyro sensor MG2(MicroStone), the accelerometer MA3(Microstone) and the 3-axes force sensor PicoForce(NITTA), are processed at A/D converter iMCs03(iXs research corp.). 3 axes force sensors are mounted on the soles and wrists. Those on the sole are located at four corners to calculate the resultant linear force and the moment of a couple.

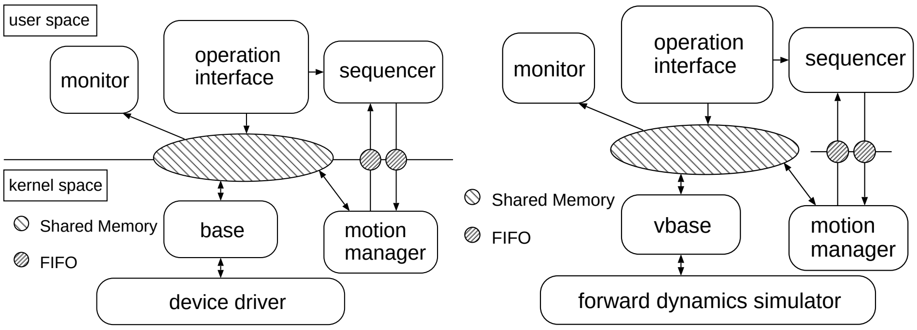


Figure 25: Software system Z-REVICHS

Concomitant use of computer simulations helps to decrease the cost and danger of experiments. In this case, it is desirable that the software developed through simulations can be ported to the real robot system with the minimum exertion, in order to encourage an efficient development and implementation of controlling methods. We developed the software system Z-REVICHS, which enables a compatible control of the real robot and the virtual robot in the simulator, on such a demand. Fig.25 shows the structure of the system. The compatibility is architecturally realized by switching base module, which directly manages device drivers, to virtual base module, which communicates with the simulator.

In this section, a small, light robot with high performance for preliminary experiments, its mechanism and software system architecture were introduced.

High Mobility Control of Humanoid Robotsthrough Reaction Force Manipulation based on Inverted Pendulum Model The humanoid as dynamical system has the following three features, namely,

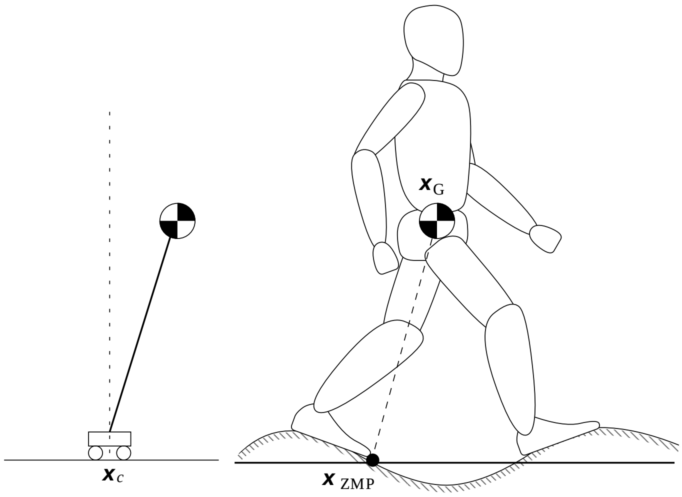
1. Large degrees of freedom system, consisting of from 20 to 50 joints.
2. Underactuated system because of the nonexistence of any fixed points in the inertia frame. It requires a conversion from internal joint forces to the external reaction forces through the interaction with the environment at each contact point.
3. Structure-varying system, collocating with the environment in accordance with the contact state transition during its motion.

This fact means that it is a strongly nonlinear system, so that there are no closed solution for the control of it basically. On the other hand, humanoid robots are expected to support our lives, working under various environment and meeting the various needs of us, since they have advantages of anthropomorphic forms. The real environment, however, is filled with much uncertainty. It increases the difficulty of control of them.

In order to overcome it, manipulation of reaction force is the key issue for the establishment of the fundamental mobility as is already stated above. This problem is decomposed into the following subproblems, namely, i) how the amount of reaction force should be decided to perform the objective motion, and ii) how the desired reaction force can be achieved. The idea described as follows is one to give a solution to it, and is the basis of this research.

Though the dynamics of humanoid is quite complicated, the essential characteristics of it can be abstracted when considering the relationship between the center of gravity (**COG**) and the center of reaction force. The relationship is explained by rather a simple model as is shown in Figure 26. One can note that the horizontal components of the moment around this point are zero (and because of this fact, this point is called Zero Moment Point, or ZMP), and that this model has a similar dynamics to that of the inverted pendulum. In this analogy, COG corresponds to the mass at the tip, while ZMP corresponds to the supporting point. Control of the inverted pendulum is a well known example, so that various applicable methods have been proposed. Thus, the subproblem i) how to decide the amount of reaction force is solved by application of them.

And the other subproblem ii) how to achieve the desired reaction force, namely, how to calculate the equivalent internal joint torques to the force, is translated to how to compensate the gap between the simple inverted pendulum model and the multibody humanoid



inverted pendulum

biped locomotion system

Figure 26: Biped model and Inverted Pendulum

model. Here, COG acceleration which would caused by the desired reaction force can be calculated explicitly. Therefore, the problem is solved if the equivalent joint angle accelerations of COG acceleration are calculated. However, another problem of computational cost lies on the implementation since the equation of motion of the multibody humanoid consists of large size matrices and vectors. Then, we integrate it and substitute the relationship between the impulse and the linear momentum of the whole system for the equation of motion. This is a solution to reduce the computational cost by ignoring the local dynamics of each link, and to comprehend the global dynamics of the system as the whole. Since the linear momentum is just the multiplication of COG velocity by the mass of the robot, manipulation of COG velocity is a fair approximation of manipulation of reaction force based on the equation of motion. We proposed a fast computation method of COG Jacobian which maps the joint angle velocities to COG velocity, and showed that COG velocity can be decomposed into the joint angle velocities using the Jacobian. Consequently, the remaining problem is solved by the local joint controllers.

We developed the following three controlling methods, based on the above strategy.

1. Dual Term Absorption of Disturbance

A pattern tracking approach – preparing a referential whole body motion trajectory in the known circumstance, computing the external force trajectory in the case the robot performs exactly according to the motion trajectory in advance, and letting the robot track those trajectories – helps the achievement of motion designed according to detailed path planning and dynamics analysis, or of a variety of motion. However, disturbance caused from model error of both the environment and the robot enlarges the gap from the prepared motion trajectory. A stabilization control which compensates this gap is needed. Stabilization for legged robots means the achievement of the two schemes, namely, conservation of the contact condition by modification of motion trajectory, and recovery of the posture by modification of force trajectory, which obviously conflict with each other. Here, we noted that the latter may be considered rather in a long term, while the former scheme should be considered in a short term. Then, we proposed Dual Term Absorption of Disturbance which make use of this difference of time span. Figure 27 is a snapshot of an example walking motion controlled by the method.

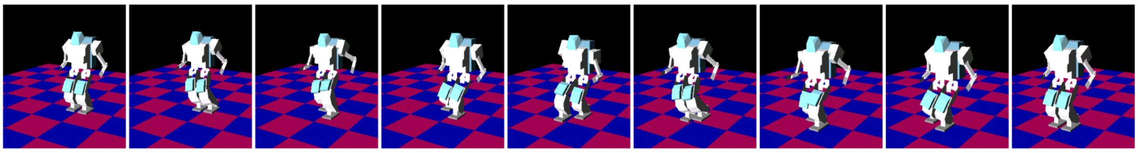


Figure 27: Walking motion with Dual Term Absorption of Disturbance

2. Inverted Pendulum Model based COG Control

Pattern tracking based method assumes that the circumstance is known and disturbance is small enough to be absorbed by a small modification of the trajectory. Since the real environment is filled with much uncertainty such as other moving objects or deformation of terrain, motion agility is required to avoid it or absorb it flexiblly. Then, we developed a whole body motion controlling method to realize the agile motion in real-time, by a combination of inverted pendulum control and the resolved motion rate control, which is frequently applied for manipulators. Figure 28 is a snapshot of a stepping motion. One can see that the robot flexiblly absorbs the sideward impact given during the motion.

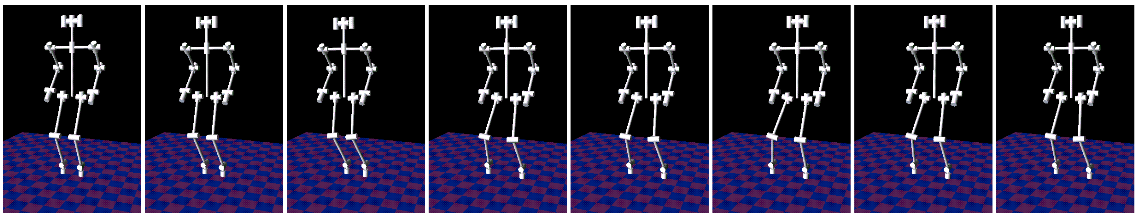


Figure 28: Absorption of impact during steping motion

3. Contact State Transition by Impedance Switching

Inverted pendulum is basically controlled through manipulation of supporting position in horizontal direction, and does not take the motion in vertical direction into account. And it also assumes a continuous contact of the supporting point with the ground. Further enhancement of mobility requires a control of motion in vertical direction, particularly a realization of motion through aerial phase, jumping and running for instance, for the purpose of robust performance against much larger impact, more improvement of a variety of motion, and expansion of the field of foot activity. Then, we augmented the inverted pendulum model, attaching a virtual impedance to the axis. Mechanical energy of the system in vertical direction is controlled by switching the impedance. Transition from contact phase to aerial phase is achieved by inputing sufficient potential energy, and the impact which occurs at the moment of touchdown in transition from aerial phase to contact phase is absorbed giving compliance characteristics. Figure 28 shows a snapshot of a jumping motion realized by the method.

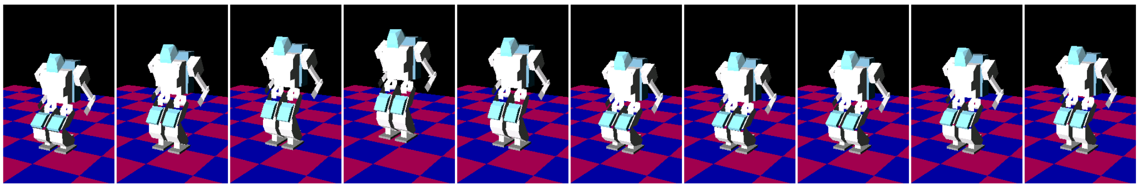


Figure 29: Jumping motion with impedance switching

(2) Results and their importance

In this research, we develop the double spherical hip joint and the backlash clutch knee joint, and develop the humanoid robot UT-θ and UT-μ. The results are as follows.

1. The double spherical hip joint has the same number of degree-of-freedom as the conventional mechanism. By the difference of the configuration of degree-of-freedom, the double spherical hip joint has the function of the waist joint. The humanoid robot with this mechanism walks without bending knee joint.
2. The knee joint with the backlash clutch realizes both the zero torque transmission (free) and high torque transmission. This mechanism realizes the dynamical interaction between the humanoid robot and its environment, which realizes the body dynamics specific motion.
3. By using the two degrees-of-freedom control, we propose the on/off control algorithm. By the change of the reference inputs, the control mode is changed.
4. We develop the humanoid robot UT-θ using the two proposed mechanisms and the cybernetic shoulder.
5. We develop the initialized humanoid robot UT-μ for the acquisition of the high mobility. And develop the control strategy based on the inverted pendulum model.

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