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Humanoid Robot Mechanisms for Responsive Mobility

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Abstract

In this paper, we developed two noble mechanisms for improving the motions of humanoid robots. The double spherical hip joint provides the equivalent function of waist joints without actually adding them. The backlush clutch is a new drive mechanism for knee joints of humanoid robots, which enables switching between drive and free modes. We developed a humanoid robot equipped with these two mechanisms.

1. Introduction

Research of humanoid robots extends from mechatronics integration, motion control, sensing and perception, toward experimental exploration of developmental theories of the communication, the symbol grounding, the sense of self, the binding problem of multimodal sensations, and the intention and mind. Such exploration is challenging not only from the engineering view point of building intelligent machines, but also from the scientific view point of understanding the human, and therefore it is open ended.

The body of humanoid robot is already a large scale system with, roughly speaking, motors, sensors and quite a few processors. The mechanical design of humanoid robots has focused on integrating all the mechatronic components in a limited space of human shaped body. The reported models of humanoid robot[1]∼[6] clearly show the success of the mechanical design. The issue of artistic design is illuminated more recently. However, the authors claim that ever developing research of humanoid robots also demands the evolution of body mechanisms.

The evolution of actuators, materials, and batteries will significantly change the mechanical design of humanoid robots in the future. In this paper, we rather focus ourselves and discuss the driving mechanisms of joints. The specific problems raised in this paper are:

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

The mobility is improved by simply introducing more joints and actuators, though it requires further and harder challenge of integration. Especially, for walking mobility, the recent design of humanoid robots tends to include waist joints, which are important both for human like mobility and for stability control of biped walk using the upper body. The humanoid robot without a waist roll-joint has to bend the knees to maintain the manipulability of the COG (center of gravity) in the horizontal direction in the frontal plane.

In this paper, we propose to have two hip joints at a point. A hip joint here is a virtual joint and indicates a point where the first three joints axes of a leg intersect like a spherical hip joint of the human. Therefore, we suggest having a point where six joint axes, namely first three of both legs, share a point of intersection. We designed and fabricated such a drive mechanism and named the double spherical joint. With the double spherical joint, a humanoid robot obtains an equivalent mobility that a waist roll joint and a waist yaw joint could provide without actually having them. Therefore, the double spherical joint guarantees full manipulability of the COG in the horizontal plane being independent to the leg configuration.

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. The rehabilitation of human sometimes starts from laying himself down on the floor to feel the gravitation or lean himself against the wall to remove the fear. Clearly, feeling the gravity and the environmental constraints not only with a specific sensor like vision but with the whole body 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[8, 9] opened an interesting and suggestive approach to this problem.

In this paper, we also propose a joint drive mechanism that can switch between drive and free modes. When the backlash clutch cuts mechanical transmission from the motor to the joint, the joint behaves like a free joint. The joint motion in the free mode is transparent and determined purely by the environmental forces and constraints. In the drive mode, on the other hand, the backlash clutch engages the motor with the joint and transmits large forces. Conventional clutch mechanisms either weigh heavy or transmit insufficient forces. 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.

A humanoid robot is under development adopting both the double spherical joint as the hip joints and the backlash clutch as the knee joints.

2. The Double Spherical Hip Joint

2.1. Mechanism of the double spherical hip joint

Figure 1 shows the conventional mechanical design of humanoid robot hip joint. In this figure, Y_l, R_l, P_l means yaw, roll, pitch joints of the left leg and Y_r, R_r, P_r means those of the right leg. The three joints have axes intersecting at a one point and compose the spherical joints. The total DOF of this mechanism is six DOF and the same as that of the human.

Figure 2 shows the motions to control the posture of the upper body. The pitch and roll inclinations of the upper body is used to control the COG(Center Of Gravity) of the whole body and this is effective to stabilize the biped walk. The pitch motion is always available even if the knee joints are stretched. However, the roll motion cannot be available when the knee joints are stretched. For this reason, the current humanoid robot has to bend the knees during biped walking and even standing still. The biped walking with bending the knees looks unnatural and leads up to waisting energy that could be saved if the knees are stretched. If the humanoid robot has a few degree of freedom as the waist joint, the manipulability of the COG could be improved, however, it would increase the total weight of the robot and the complexity of mechanism and control.

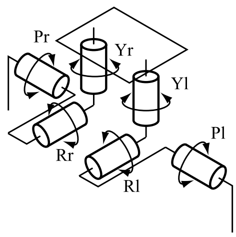

Figure 1: DOF arrangement of conventional hip joint

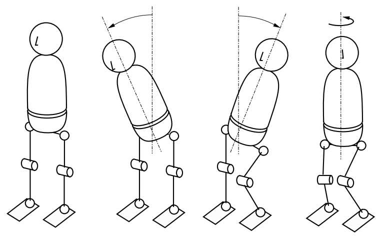

Figure 2: Bending motion of upper body with hip, knee and ankle joints

Figure 3 shows the mechanical design of the double spherical hip joint. The DOF of this mechanism is six DOF and the same as that of the conventional hip joint. All six axes of hip joint are intersecting at one common point. In other words, the distance between the center point of two spherical joints are set zero for the double spherical hip joint.

Figure 4 shows the same motions of Figure 2 with double spherical hip joint. The pitch, roll and even yaw motions are available independent to whether the knees are bent or not. This mechanical design implies that the mobility of three degrees of freedom of waist joints for rotating the upper body can be realized without actually adding waist mechanisms but adopting the double spherical joint as the hip joints.

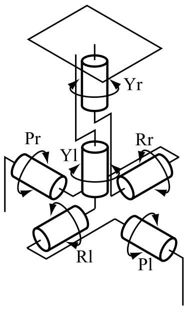

Figure 3: DOF arrangement of double spherical hip joint

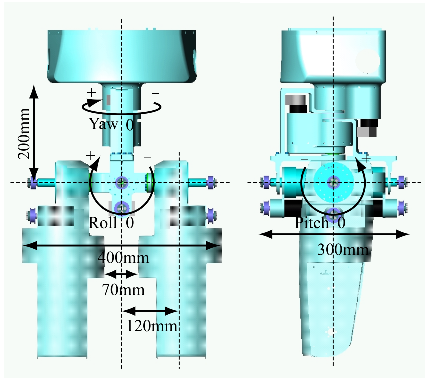

Figure 5: Demensions of the designed double spherical hip joint

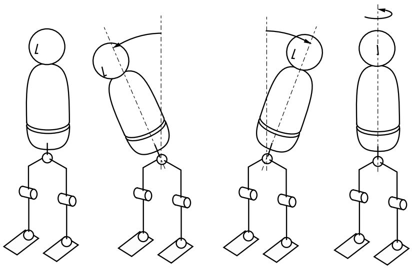

Figure 4: Bending motion of upper body with double spherical hip joints

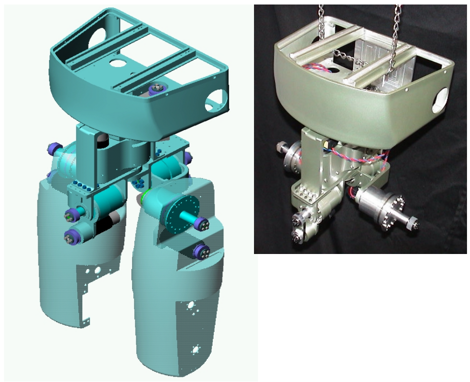

Figure 6: Photo of the double spherical hip joint

2.2. Designing the double spherical hip joint

The dimensions of the designed double spherical hip joint is illustrated in Figure 5. It has been the major design issue to accommodate a large workspace and to maintain high mechanical stiffness. Figure 6 shows a photograph of the developed. For yaw and roll joints 90[W] DC servomotors and 1:100 Harmonic drives gears are used. For pitch joints 150[W] DC servomotors and 1:100 Harmonic drives gears are adopted. Figure 7 shows the yaw, roll and pitch motions of the upper body with double spherical hip joint.

The workspace of the developed double spherical hip joint is shown in Table 1. For comparison, the motion ranges of typical human joints[7] are also included in the table. The double spherical hip joint has a smaller motion range for the roll and yaw direction than that of the human. The motion ranges of the double spherical joint would be enough for controlling balance with the upper body.

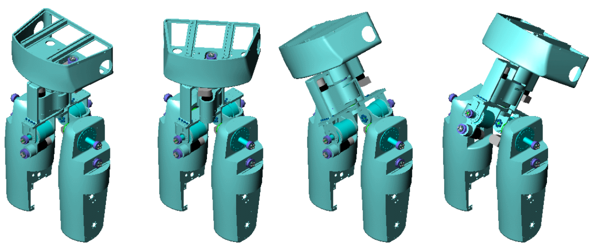

Figure 7: Trunk motion with the double spherical hip joint

Table 1: Workspace of double spherical hip joint

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

3. Knee Joints with the Backlush Clutch

3.1. Gravity compliant motions and mechanisms

An intelligence of machines would be seen if they could acquire by themselves appropriate motions that their body accepts. The passive walk proposed by McGeer[8, 9] showed that the passive dynamics of mechanism involves in itself the foundation of walking motion pattern. More surprisingly, the passive walk patterns in his video looked natural and even noble like those of animals. In our daily life, we learn sports and motion patterns by moving our body according to reference patterns and modifying them to fit ourselves. We may acquire such a motion by making the inertia and gravity force that is generated by the motion or generates the motion more comfortable to our body. To study the principle of intelligence for dynamic motion acquisition, a humanoid robot would need a body that is compliant to the inertia and gravity force.

It is also interesting why the passive walk looks natural to us. It would not be surprising that free joint motions are the most acceptable to our body, and that we feel them comfortable and therefore natural. If it explains the case, developing natural looking motions for humanoid robots should focus on utilizing passive motions.

Based upon the above motivations, we study the joint drive mechanism that can switch between drive and free modes.

3.2. Mechanism of the backlush clutch

Figure 8 shows the principle of the backlash clutch. The mechanism is composed of three components Part a is rotated by a motor and fixed neither to upper link A nor to lower link B. Part b is fixed to lower link B. There is a backlash between Part a and Part b. If the backlash is set zero, then the torque of motor is directly transmitted to B through a and b. We set the backlash an appropriate nonzero value. We measure the both rotations of Part a and Part b. If we control the motor and Part a so that Part a does not touch Part b, then free motion is actively realized. It is the free mode.

Switching to the drive mode, Part a is first controlled to make a surface contact with Part b, and then transmits an arbitrary driving force. Therefore, there is a slight time delay before actually transmitting driving force. The time delay should be minimized since it becomes critical when the driving force alternates its directions repeatedly and rapidly.

However, since the humanoid robot as well as the human lives in the gravity field, Part b usually pushes Part a in one direction due to the gravitation. Therefore, the motor can immediately transmit torques as much as the gravitation torque in the both directions. More precisely, it can transmit arbitrary torque in the pushing direction, and torque as much as or less than the gravitation torque in the pulling direction.

Mechanical components of the backlash clutch are shown in Figure 9. Parts a and b in the Figure 9 corresponds to those of Figure 8. Rubber material is used in the backlash to absorb excess collision forces.

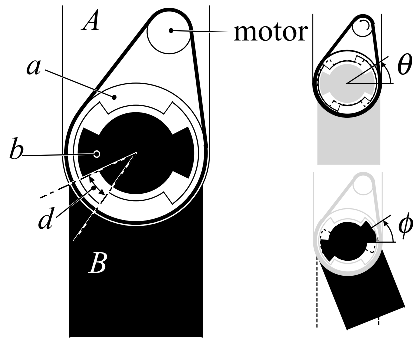

Figure 8: Principle of the backlush clutch

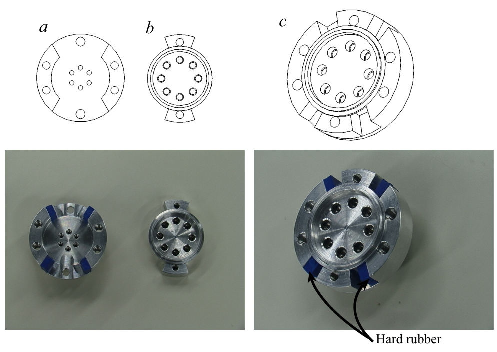

Figure 9: Components of the backlush clutch

3.3. Designing the backlush clutch in the knee joints

Figure 10 shows the design of the knee joints with the backlash clutch. The knee joint uses a 150[W]

DC servo motor and a 1:100 Harmonic drives gear. The rotation angle of Part a is θ in Figure 8. θ is measured by a motor encoder. The rotation angle of Part b is represented by ϕ. ϕ is measured by an additional encoder.

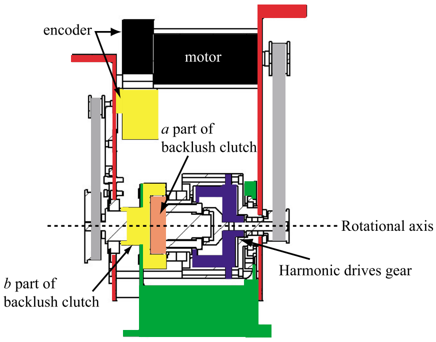

Figure 10: Design of the knee joint

3.4. Control algorithm of the backlush clutch

We propose a control algorithm of the backlash clutch. The backlash clutch needs the following three control modes: (1) free mode (2) drive mode, and (3)transition mode between free and drive modes.

To realize the above three control modes we adopted a two DOF control system as shown in Figure 11, where P denotes the transfer function of motor and gear, K means the feedback controller, G indicates the transfer function that describes the desirable response of θ, and finally r_1, r_2 are reference signals.

The transfer function G is designed not to have zeros, since the response of θ should have no over shoot with the high gain feedback K. The transfer function G must have an identity steady gain.

Reference signals r_1, r_2 are selected differently according to the control mode as follows:

1. Free mode: $r_1 = 0, r_2 = \phi$
   θ is controlled to follow ϕ maintaining the distance between Part a and Part b of Figure11.

2. Drive mode: $r_1 = 0, r_2 = \phi_{ref}$
   where ϕ_{ref} means the reference angle of ϕ. The control system works as normal feedback control at $t \to \infty$

3. Transition mode: $r_1 = \phi, r_2 = \phi_{ref}$
   The two DOF control system is designed so that θ should have no over shoot. Therefore Part a and Part b collides softly.

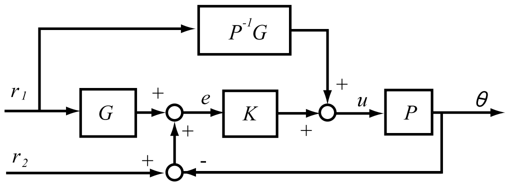

Figure 11: Two DOF control system

4. Development of the Humanoid Robot

4.1. Specification of the humanoid robot

We designed a humanoid robot adopting the double spherical hip joint and the knee joints with the backlash clutch. Figure 12 shows the photograph of the humanoid robot. It is 150[cm] in height and estimated to weigh approximately 45[kg].

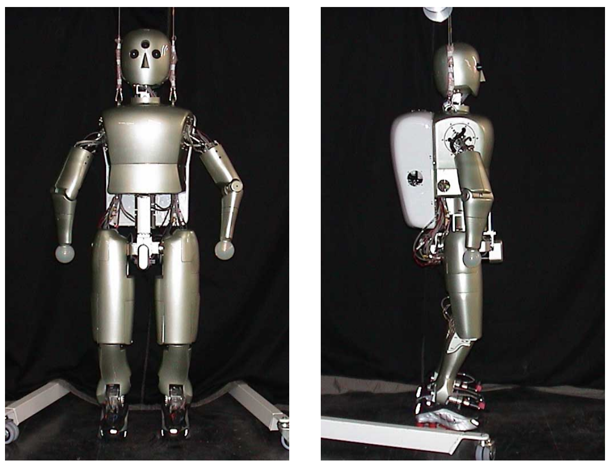

Figure 12: The humanoid robot UT-Θ

The neck has three degrees of freedom and the head is equipped with two monochrome progressive scan cameras and an NTSC color camera. The cybernetic shoulder[10] is adopted for the humanoid robot. This mechanism has advantages of the large workspace and the human like motion. The cybernetic shoulder is slightly modified to fit in the chest. It has three degrees of freedom each. The inertial sensors such as gyro sensors and accelerometers are also integrated in the chest. A six axes force sensor is equipped in the forearms. Each leg has six degrees of freedom, namely, one degree of freedom as a knee joint, two degrees of freedom as ankle joints and three degrees of freedom of a hip joint. The backlash clutch is implemented in the knee joint and the double spherical joint is implemented in the hip joint. A six axes force sensor is also equipped on the foot. The main structural parts of body made by magnesium alloy casting for pursuing both lightweight and high mechanical stiffness.

4.2. Motion experiment

We did some motion experiments with the humanoid robot. Figure 13 shows the leg stretching motion with hanging up in the air.

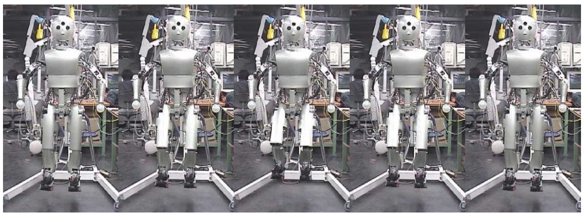

Figure 13: Leg stretching motion

5. Conclusions

In this paper, we discussed the mechanical design of humanoid robots. The driving mechanisms of joints are newly proposed in particular. The results of this paper are summarized as follows:

1. The double spherical joint was proposed as hip joints of humanoid robots. Replacing the conventional hip joints with the double spherical joint adds the mobility equivalent to the waist joints without actually adding them.

2. The backlash clutch was also proposed as a drive mechanism that can switch between drive and free modes. The backlash clutch can realize humanoid body compliant to the inertia and gravity force.

3. A humanoid robot was developed integrating both the double spherical hip joint and the knee joints with the backlash clutch.

4. The mode switching control of the backlash clutch was proposed based on the two DOF control system design.

Acknowledgments

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