# Mechanical design of the humanoid robot platform, HUBO

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# Mechanical Design of the Humanoid Robot Platform, HUBO


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**Abstract**

The Korea Advanced Institute of Science and Technology (KAIST) humanoid robot - 1 (KHR-1) was developed for the purpose of researching the walking action of bipeds. KHR-1, which has no hands or head, has 21 degrees of freedom (DOF): 12 DOF in the legs, 1 DOF in the torso, and 8 DOF in the arms. The second version of this humanoid robot, KHR-2, (which has 41 DOF) can walk on a living-room floor; it also moves and looks like a human. The third version, KHR-3 (HUBO), has more human-like features, a greater variety of movements, and a more human-friendly character.

We present the mechanical design of HUBO, including the design concept, the lower body design, the upper body design, and the actuator selection of joints. Previously we developed and published details of KHR-1 and KHR-2. The HUBO platform, which is based on KHR-2, has 41 DOF, stands 125 cm tall, and weighs 55 kg. From a mechanical point of view, HUBO has greater mechanical stiffness and a more detailed frame design than KHR-2. The stiffness of the frame was increased and the detailed design around the joints and link frame were either modified or fully redesigned. We initially introduced an exterior art design concept for KHR-2, and that concept was implemented in HUBO at the mechanical design stage.



*Keywords: KHR-3, HUBO, humanoid, biped walking robot*


## 1. INTRODUCTION

Recently, many studies have focused on the development of humanoid biped robots. Some of the well-known humanoid robots are Honda's humanoid robots [1, 2], the WABIAN series of robots from Waseda University [3], Partner, QRIO, H6 and H7 [4], HRP [5] and JOHNNIE [6, 7]. Because humanoids are complex, expensive and unstable, designers face difficulties in constructing the mechanical body, integrating the hardware system, and realizing real-time motion and stability control on the basis of human-like sensory feedback. Among the robots, HRP, WABIAN and ASIMO are the most famous humanoid robots.

HRP-3P is a humanoid robot developed jointly in Japan by the National Institute of Advanced Industrial Science and Technology and Kawada Industries, Inc. It stands 1.6 m tall, weighs 65 kg, and has 36 degrees of freedom (DOF). Upgraded from HRP-2, the new platform is protected against dust and water [8].

The humanoid robot WABIAN-2, which was developed at Waseda University, has 7 DOF for each leg, 2 DOF for the waist, 2 DOF for the trunk, and 7 DOF for each arm [9]. This robot has more redundancy in the upper body, arms, and legs than a conventional biped humanoid robot, enabling it to move in various ways such as walking, hand shaking, and bowing.

Honda has unveiled a new type of ASIMO, named ASIMO Type-R, which stands 1.3 m tall, weighs 54 kg, and has 34 DOF. With the i-WALK technology, this robot has an impressive walking performance: it can walk at 3 km/h, and run at 6 km/h.

The objective of the HUBO project is to develop a reliable and handsome humanoid platform that enables the implementation of various theories and algorithms, such as dynamic walking, navigation, human interaction, and visual and image recognition. With the focus on developing a human-friendly robot that looks and moves like humans, we endeavored to closely align the mechanical design with exterior art design.

The zero moment point equation of a humanoid can be simplified to find a useful relation between the robot's natural frequency and size. In this relation the natural frequency is high for a small robot and low for a big robot. Finding the optimal size, weight, and mass distribution of the robot is a different research problem. We first predefined the height of the robot and then gave it a massive torso to ensure that it had a high center of gravity and low energy consumption for the frequently moving parts such as legs.

The actuator specifications, such as the power, torque, and speed, of the original Korea Advanced Institute of Science and Technology (KAIST) humanoid robot (KHR-0) were investigated in our previous study [10]. Developed in 2001, KHR-0 has 2 legs and no upper body. Our design of KHR-3 (HUBO) is also based on KHR-1 and KHR-2 [11, 12]. HUBO has several modifications. For instance, we improved the joints and the link stiffness [12]; we finely retuned the actuator mechanism by experiment; and we gave the robot a more human-like and human-friendly appearance. The design of the hands, head, neck, eyes, and fingers are based on modifications to KHR-2. We optimized the design considering the space, the heat transfer, the weight balance and etc.

While developing the HUBO platform, we studied the walking control algorithm of the KHR-2 platform [13] from which we gleaned important information about things such as the joint actuator behavior, hardware problems, and the sensory data characteristics of the robot system. We now present details of our mechanical design of HUBO and highlight the improvements to KHR-2.

## 2. HUBO: Overall Description

HUBO is our latest humanoid robot. Its stands 125 cm tall and weighs 55 kg. In this upgraded version of KHR-2, we modified and improved the mechanical stiffness of the links and we reduced the gear capacity of the joints. The increased stiffness improves the stability of the robot by minimizing the uncertainty of the joint positions and the link vibration control. In the mechanical design stage, we positively considered features of the exterior, such as the wiring path, the exterior case design and assembly, and the movable joint range, all of which are shown in Fig. 1. In particular, we seriously endeavored to match the shape of the joints and links with the art design concept, and we designed the joint controller, the motor drive, the battery, the sensors, and the main controller (PC) in such a way that they could be installed in the robot itself. Table I lists the specifications of the robot.


Fig. 1: Humanoid Robot, HUBO

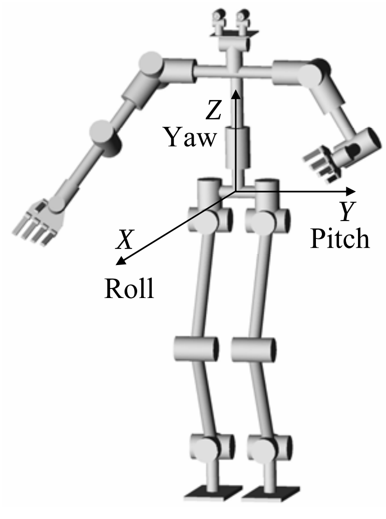


Fig. 2: Schematic of the joints and links

Table I: Specifications of HUBO

| | | |
|---|---|---|
| Research period | | January 2004 till the present |
| Weight | | 55 kg |
| Height | | 1.25 m |
| Walking speed | | 0 ~ 1.25 km/h |
| Walking cycle, stride | | 0.7 ~ 0.95 s, 0 ~ 64 cm |
| Grasping force | | 0.5 kg/finger |
| Actuator | | Servo motor + harmonic reduction gear + driver unit |
| Control unit | | Walking control unit, servo control unit, sensor communication unit, communication unit |
| Sensors | Foot | 3-axis force torque sensor; accelerometer |
| | Torso | Inertial sensor system |
| Power section | Battery | 24 V - 20 Ah (Lithium polymer) |
| | External power | 24 V (battery and external power supply changeable) |
| Operation section | | Laptop computer with wireless LAN |
| Operating system | | Windows XP and RTX |
| Degree of Freedom | | 41 DOF |

## 3. Design Concept and Strategy

i. Low development cost

- Rather than using custom-made mechanical parts, we used commercially available components such as motors and harmonic gears in the joints.

ii. Light weight and compact joints

- The power capacity of the motors and reduction gears enables short periods of overdrive because of the weight and size problem of the actuators.

iii. Simple kinematics

- For kinematic simplicity, we designed the joint axis to coincide at one point or at one axis.

iv. High rigidity

- To maintain rigidity, we avoided the cantilever-type joint design.

v. Slight uncertainty of the joints

- We used harmonic drive reduction gears at the output side of the joints because they don’t have backlash.

# 4. Overview of the Mechanical Design

## 4.1. Degrees of Freedom

Table II shows the degrees of freedom of HUBO. We tried to ensure that HUBO had enough degrees of freedom to imitate various forms of human motion, such as walking, hand shaking, and bowing. It has 12 DOF in the legs and 8 DOF in the arms. Furthermore, it can independently move its fingers and eyeballs because it has 2 DOF for each eye (for a camera pan and tilt), 1 DOF for the torso yaw, and 7 DOF for each hand (that is, 2 DOF for the wrist and 1 DOF for each finger). As shown in Fig. 2, the joint axis of the shoulder (3 DOF/arm), hip (3 DOF/leg), wrist (2 DOF/wrist), neck (2 DOF) and ankle (2 DOF/ankle) cross each other for kinematic simplicity and for a dynamic equation of motion [14].

Table II: Degrees of Freedom of HUBO

| Head | Torso | Arm | Hand | Leg | Total |
|---|---|---|---|---|---|
| 2 neck<br>2/eye (pan-tilt) | 1/torso (yaw) | 3/shoulder<br>1/elbow | 5/hand<br>2/wrist | 3/hip<br>1/knee<br>2/ankle | |
| 6 DOF | 1 DOF | 8 DOF | 14 DOF | 12 DOF | 41 DOF |

## 4.2. Actuator (Reduction Gear and DC Motor)

We used two types of reduction gears: a planetary gear and a harmonic gear. The planetary gear is used for small errors (such as backlash) allowable joints such as finger joints, wrist-pan joints, neck-pan joints and eyeball joints. Errors in the finger and wrist-pan joints don’t affect the stability of the entire body or the overall motion of the arms and legs. The harmonic gear is used for major joints, such as leg and arm joints, as well as for neck tilts and wrist tilts. Because the harmonic gear has little backlash on its output side and only a small amount of friction on its input side, it is particularly useful in leg joints, where errors can affect the stability of the entire system and the repeatability of the joint position. This harmonic type of reduction gear is connected to the motor in two ways: through a direct connection and through an indirect connection. The indirect connection has some power transmission mechanisms (such as a pulley belt or a gear mechanism) between the reduction gear and the motor. We adjusted the joint gear ratio and the gear-motor design on the basis of our experience with KHR-2. HUBO has this type of connection for the neck tilt, the shoulder pitch, the hip, the knee, and the ankle joints.

Our choice of gear types and harmonic drive types was limited by the given design conditions (such as space, shape, permissible power, and weight). We used brushed 24 V DC motors. With flexibility in designing the size, shape and wiring, we found it easier to develop the brushed DC motor drivers than other types of motors (such as brushless DC motors or AC motors). The brushed DC motors also have a suitable thermal property. When we drive them in harsh conditions, for example with high speed and severe torque, the generated heat is less than that of brushless DC motors. Hence, there is less chance of heat being transferred from the motors to other devices such as the sensors and controller.

The voltage of the motor has trade-offs. If the motor has a high voltage, it cannot drive a high current, and vice versa. The voltage of the motors is related to the size and weight of the battery. A high-voltage source requires more battery cells to be connected serially. The number of battery cells is directly related to the weight of the battery system and the weight distribution of the robot.

### 4.3. Weight Distribution

The main controller (PC), the battery, and the servo controller and drivers for the upper body are in the torso. We concentrated the mass, except for the actuators, in the torso because of the need to reduce the load that the actuators are afflicted with in the frequently moving parts such as the arms and legs; and also because we wanted the torso to have sufficiently large inertia for a small amplitude fluctuation. With this approach, the robot achieved low power consumption when swinging its arms and legs; moreover, the control input command ensured a zero moment point with a small positioning of the torso.

## 5. Joint Actuator and Mechanical Frame Design

### 5.1. Joint Actuator Selection

Our selection of actuators for HUBO was based on experience with KHR-0, KHR-1, and KHR-2 [10-12]. HUBO has almost the same actuators as KHR-2. We modified the joint design of the hip-yaw, the hip-roll, the wrist and the neck, and we used the unit-type harmonic drive reduction gear of the hip-yaw joint differently from the way it was used in KHR-2. When turning around, HUBO has a higher level of torque than KHR-2 because we increased the turning speed of the robot by means of a control algorithm and we increased the weight of the torso. As a result, the hip-yaw joint requires more rigidity in all directions of moment and vertical force.

We used gears instead of a pulley-belt mechanism for the hip-roll joint. This joint needs to be hidden in the exterior model. As shown in Fig. 1, we wanted the hip joints to look like balls. Because the massive parts, except for the joint actuators, are concentrated in the upper body of the robot, we increased the reduction ratio on the harmonic drive input side from 1.67:1 to 2.5:1. The hip-roll joint moves slowly. However, when the robot has both feet on the ground, the legs have a closed kinematical configuration. If the feet have a positional error in a particular situation, then, even though the error is comparatively small, the motor position error is larger than the other roll joint motors because of the length of the legs. Under those conditions, the motor consumes a continuous current, which is why we chose not to drastically increase the reduction ratio. All the joint reduction ratios were finely tuned on the basis of experiments, and we also tuned the shoulder pitch joint reduction ratio. When we drive the arms of the robot, the arm joint frequently requires the highest speed and torque.

Tables III and IV show the selected motors and reduction gears for all joints. In Table III, the reduction gear type and the input gear ratio refers to the final output gear type and the gear ratio between the motor output and the reduction gear input.

Table III: Upper body actuators of HUBO

| | Joint | | Reduction gear type | Input gear ratio | Motor power |
|---|---|---|---|---|---|
| Hand | Finger | | Planetary gear (256:1) | 14/9:1 (pulley belt) | 2.64 W |
| | Wrist | Pan | Planetary gear (104:1) | None | 11 W |
| | | Tilt | Harmonic drive (100:1) | 2:1 (pulley belt) | |
| Head | Neck | Pan | Planetary gear (104:1) | None | |
| | | Tilt | Harmonic drive (100:1) | 2:1 (pulley belt) | |
| | Eye | Pan | Planetary gear (256:1) | None | 2.64 W |
| | | Tilt | | 14/9:1 (pulley belt) | |
| Arm | Elbow | Pitch | Harmonic drive (100:1) | None | 90 W |
| | Shoulder | Roll | | | |
| | | Pitch | | 1:1 | |
| | | Yaw | | None | |
| Trunk | | Yaw | | | |

Table IV: Lower body actuators of HUBO

| Joint | | Harmonic drive reduction ratio | Input gear ratio | Motor power |
|---|---|---|---|---|
| Hip | Roll | 120:1 | Gear (2.5:1) | 150 W |
| | Pitch | 160:1 | Pulley belt (1.78:1) | 90 W |
| | Yaw | 120:1 | Pulley belt (2:1) | |

| | | | | |
|---|---|---|---|---|
| Knee | Pitch | 120:1 | Pulley belt (1:1) | 150 W*2 |
| Ankle | Roll | 100:1 | Pulley belt (2:1) | 90 W |
| | Pitch | 100:1 | Pulley belt (1.93:1) | |

### 5.2. Link and Joint Design

There are pulley-belt mechanisms in many joints of HUBO. This type of mechanism normally needs a belt fastener, but we omitted the fastener in order to reduce the number of mechanical components for simple maintenance. We tuned the belt tension by adjusting the motor fixture position.

Figure 3 shows the design of the hip joint, which features a 3-axis intersection. The figure contains only a 2-axis crossing joint because we omitted the drawing of the hip-yaw actuator. We designed this joint with a crossing tube-type structure. The inner part of the tube is almost empty, except for the reduction gear fixture. This design makes the frame lighter and more rigid, and gives it a higher moment of inertia. The crossing tube-type structure is one of the major factors of increased frame rigidity.

Figure 4 shows the hip-yaw actuator output frame. This frame should sustain, with minimal deflection, various types of loads such as the bending moment in the X-Y direction and the compression and tension in the Z direction. Steel is more suitable than aluminum for this component. The component was machined with a numerically controlled machine because of the 3-D characteristics. All the mechanical components of the robot except this one are two-dimensional. We originally intended to use a 2-D design for the frame because the 2-D design has several advantages over the 3-D design: for instance, it saves machining and assembly time; it is more economical and requires less effort; and the retouching process is simpler. However, because the frame has both a mechanical and artistic function, we made an exception in this case and designed a 3-D frame.

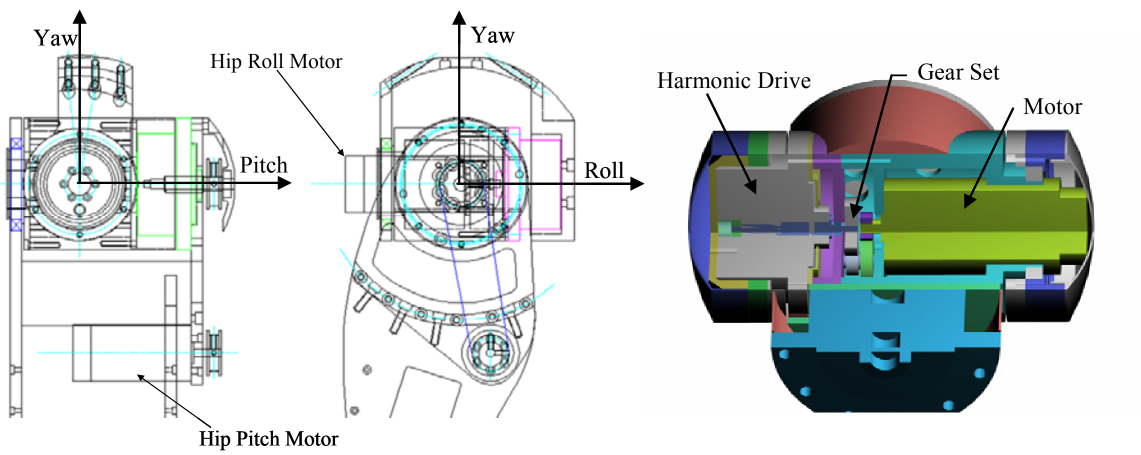


Fig. 3: Hip-roll and pitch joint design

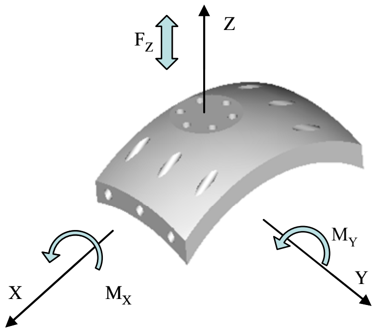


Fig. 4: Hip-yaw actuator output frame

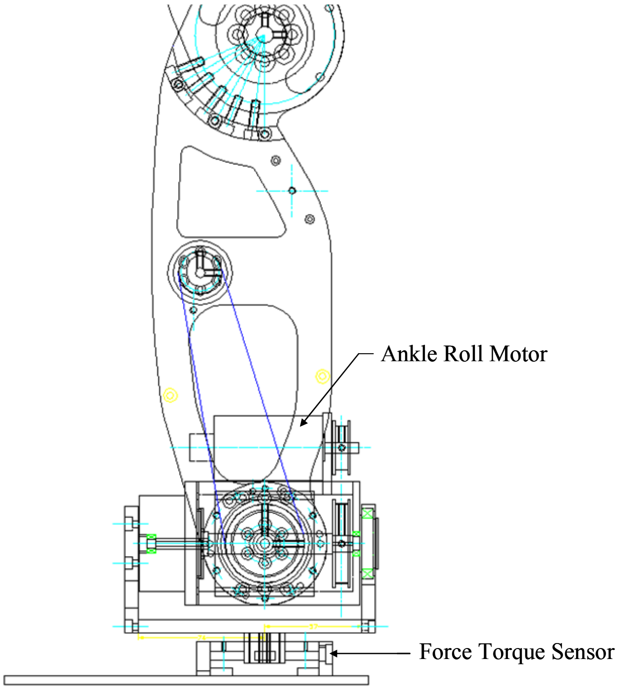


Fig. 5: Ankle joint design

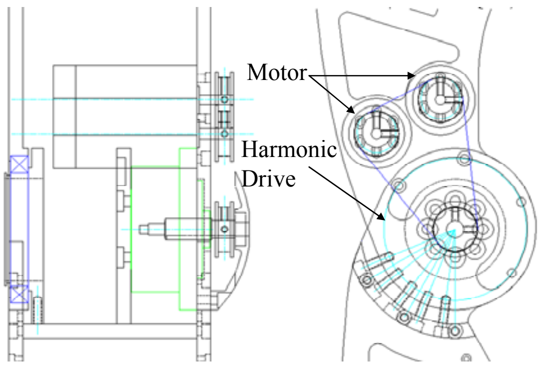


Fig. 6: Knee joint design

We placed the ankle joint motor and its driver far from the force/torque (F/T) sensor, which was located on the sole. The motor and driver may generate heat because they would be afflicted with high torque induced by landing shock from the ground. Hence, if the motor and driver are located near the

F/T sensor, they would transmit heat to the F/T sensor. The sensor is sensitive to temperature variance because we used strain gages in it. The ankle pitch joint has a wide movable range to enable the robot to take longer strides.

As with KHR-2 and JOHNNIE, HUBO has two motors on the knee joint [6, 9]. Two motors are used because the knee joint actuator needs high speed and torque for the bent leg posture, and they can amplify the joint torque while conserving speed. This two-motor joint enables that the joint actuator wattage is doubled and that the reduction ratio can be decreased. If the harmonic drive can sustain the load that is applied to it, we can increase the joint speed.

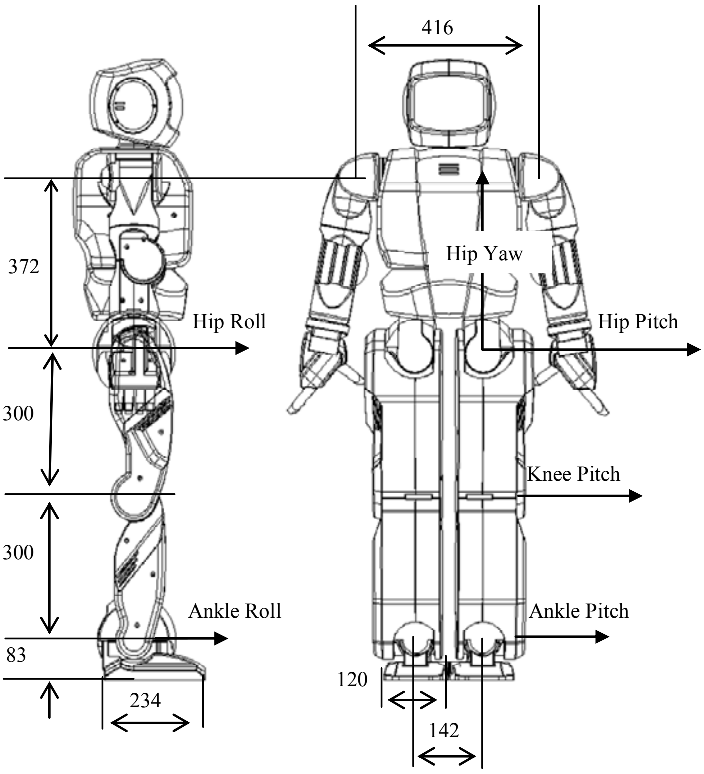

Fig. 7: Dimensions (unit: mm)

Table V: Movable angle range of lower body joints

| Joint | | Angle range |
|---|---|---|
| Hip | Yaw | 0 ~ +45° |
| | Roll | -31° ~ +28° |
| | Pitch | -90° ~ +90° |
| Knee | Pitch | -10° ~ +150° |
| Ankle | Pitch | -90° ~ +90° |
| | Roll | -23° ~ +23° |

For the entire KHR series, the design of the links and joints obviated the need for cantilever beams because a clamped supporting type of link has more rigidity than a cantilever support. We also wanted the link itself to be capable of a slight deflection and fluctuation. All the joints had a double supported beam-type link assembled on the reduction gear output and on the other side by the bearing support. We designed the supporting beams between two beams of the link. Although KHR-1 and KHR-2 were designed for flat plate-type support, HUBO has the partial tube-type support shown in Figs. 3, 5 and 6. This type support frame increases the rigidity of the link.

Figure 7 shows the overall dimensions of the robot. To give the robot a natural exterior, we based its proportions on standard human proportions [15]. However, there were frequent trade-offs between the robot's appearance and the appearance of a human. While keeping in mind the appearance of a human child, we determined the widths of the legs, arms, torso, and head on the basis of the components of the robot.

The head mechanism, which is shown in Fig. 8, has 6 DOF. The eyeballs can move independently because each eye has 2 DOF and their design enables a stereo vision algorithm to be implemented on a PC.

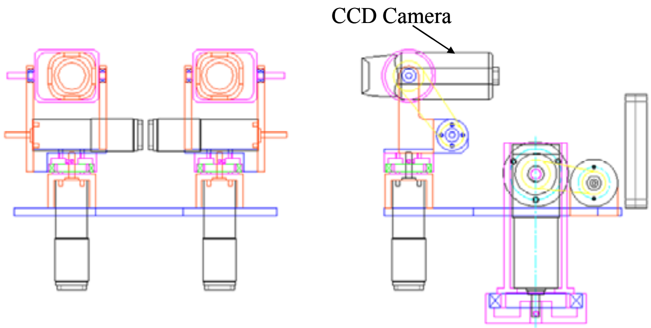


Fig. 8: Head mechanism

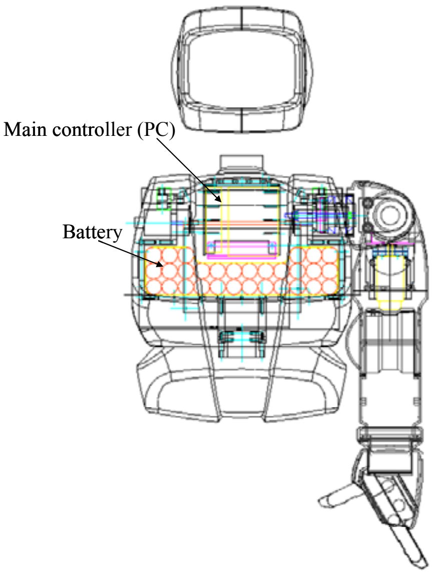


Fig. 9: Upper body design

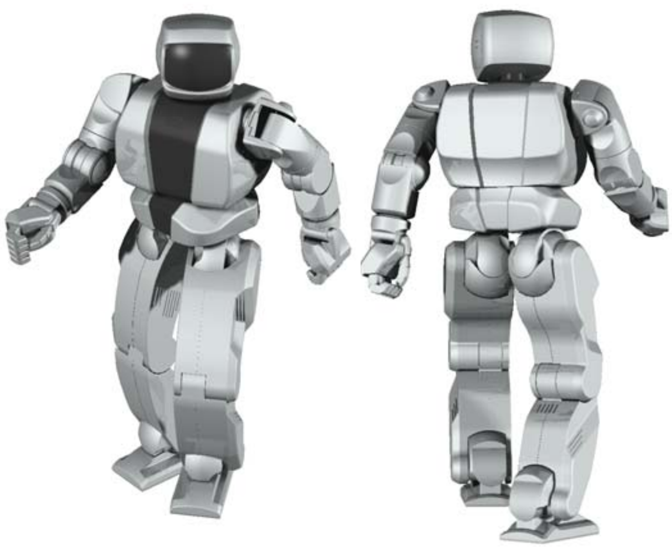

Fig. 10: Artistic design of HUBO

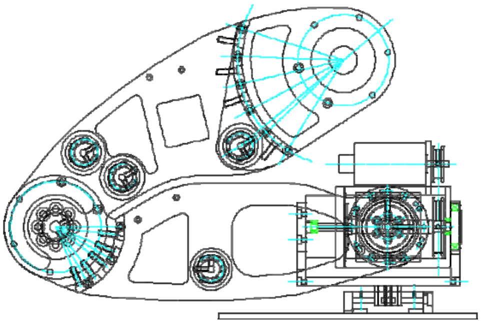

Fig. 11: Maximum pitch angle of knee and ankle joints

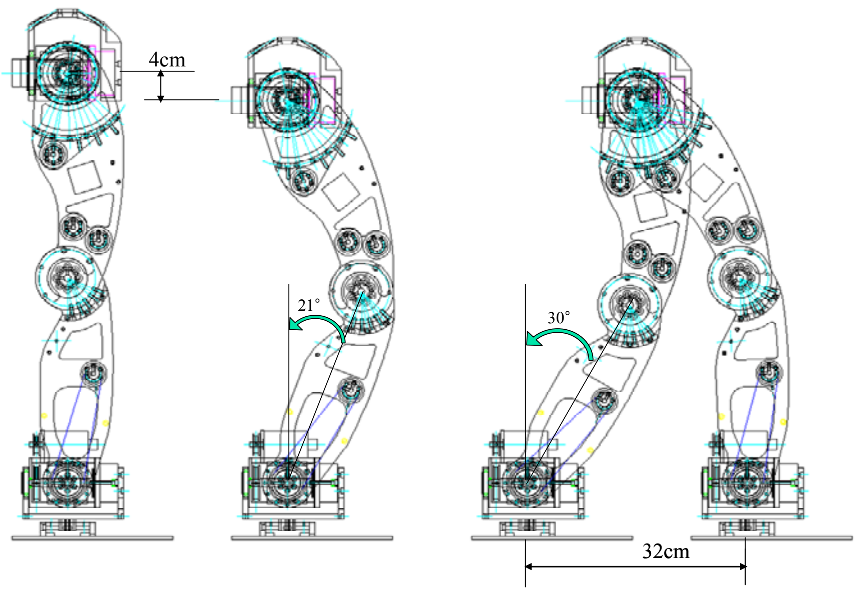


Fig. 12: Normal configuration of walking in sagittal view

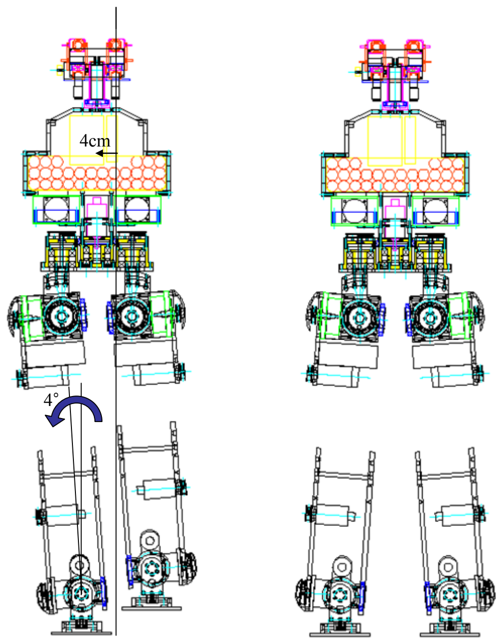


Fig. 13: Normal configuration of walking in coronal view

We installed the battery and the PC in the chest because, as shown in Figs. 9 and 10, we wanted to remove the backpack for the sake of artistic design. HUBO has a slim appearance. Moreover, the design of HUBO enables us to conveniently change the battery (that is, we can plug the battery in or out after opening the case in the front chest of the torso frame).

Table V shows the movable angle range of the lower body joints. The ranges are from the kinematic analysis as shown in Figs. 11, 12, 13. The maximum and normal moving angle ranges of the joints are related with the exterior artistic design in Fig. 10. In determining the ranges, we compromised the angle range and the appearance of the robot.

## 6. Mechanical Component of the F/T Sensor

Shaped like a Maltese cross, our F/T sensors can detect 1 force and 2 moments [16]. As shown in Fig. 14, we attached the sensors to the wrist (Φ50) and ankle (80 mm x 80 mm).

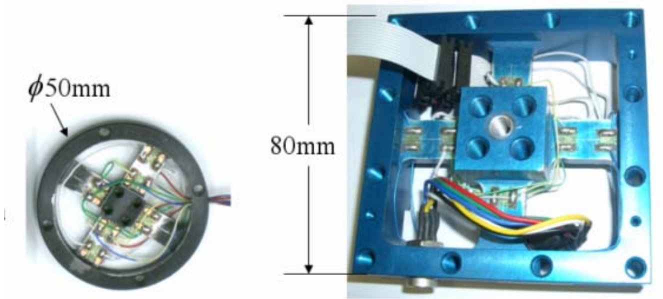


Fig. 14: Three-axis F/T sensor

To sense the magnitude of a beam deflection, we glued strain gages on the points where the load caused the largest strain. These points were located at the ends of the beam but we glued the gages 5 mm apart to minimize the problems of stress concentration and physical space. The ankle sensor was designed for a maximum normal force ($F_Z$) of 100 kg and maximum moments ($M_X$, $M_Y$) of 50 Nm.

## 7. Conclusion

We have presented our mechanical design, deliberations and philosophy with respect to the humanoid robot HUBO, which looks and moves like a human. Our mechanical design perspective is based on the knowledge, information and know-how derived from the KHR series (KHR-0, 1, and 2).

Our presentation explains the actuators, which are composed of the reduction gear and the motor, as well as the mechanical frame design of the joints and links, movable ranges of the lower body joint angles, and the mechanical structure of the F/T sensor. We also briefly proposed the concept of mass distribution, which represents one type of mechanical design for the humanoid robot.

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