Mechanical Design of Humanoid Robot Platform KHR-3 (KAIST Humanoid Robot - 3: HUBO)*

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Abstract **– KHR-1 has been developed on the purpose of research about biped walking. It has 21 DOF without hands and head, which has 12 DOF in legs, 1 DOF in torso, and 8 DOF in arms. The objective of KHR-2 (41 DOF) was to develop the humanoid which can walk on the living-floor with human-like appearance and movement. KHR-3 has the purpose that it has more human-like features, movements and human-friendly character.**

Mechanical design of KHR-3 is presented on this paper. The design concept, lower body design, upper body design and actuator selection of joints are included in this paper. We have developed and published KHR-1 and 2 in last three years. KHR-3 platform is based on KHR-2. It has 41 degree of freedom (DOF), 125cm height, and 55Kg weight. The differences from KHR-2 are mechanical stiffness and detailed design of the frame in the mechanical point of view. Stiffness of the frame is increased and detailed design about joints and link frame has been modified or redesigned. We introduced exterior art design concept on KHR-2 in beginning, and the concept has been implemented on KHR-3 in mechanical design stage.

Index Terms – KHR-3, HUBO, Humanoid, Biped walking

I. INTRODUCTION

The research in humanoid robots is now on its way of diverging into various categories. The research on such areas as artificial intelligence, hardware development, realization of biped locomotion, and interaction with the environment are gaining a rapid phase of development with the help of the rapid growth of technology. The research on humanoid robots has gained a particular interest in this new phase as humanoids tend to change the concept of the robot. In the past, robots were confined to the industry carrying out such jobs as welding, and parts-assembly (automobile and electronic devices) in that the objectives, specification and optimal design parameters were clearly defined with concern to the economic aspects, productivity and efficiency. As the economical paradigm is changing from mass production to small quantity batch production, people's concept of the robot has been gradually diverging. By today, it has come to a situation, where the robot should be able to perform a wide variety of functions that helps people in their daily life.

Recently, many researches have been focused on a development of humanoid biped robot. Honda R&D's humanoid robots[1], WABIAN series of Waseda University[2], ASIMO[3], Partner, QRIO, H6 & H7[4], HRP[5] and JOHNNIE[6][13] are well known humanoids. Since the humanoid is very complicated, expensive and unstable, it is difficult to construct the mechanical body itself, to integrate its hardware system, and to realize a real-time motion and stability control based on the sensory feedback similar to human behavior.

The objective of this project is to develop a reliable and nice looking humanoid platform which allows the implementation of various theories and algorithms such as dynamic walking, human interaction, AI (Artificial Intelligence), visual & image recognition, and navigation. Since this project is focused on developing the robot which has human-like and human-friendly appearance and movement, mechanical design and exterior art design should be closely related with each other.

The zero moment point (ZMP) equation of the humanoid can be simplified to find a useful relationship between robot's natural frequency and size, which says that if the size of the robot is small, the natural frequency is high, and vice versa. Finding the optimal size, weight, and mass distribution of the robot component is a different research problem. We predefined its height first and allocated the massive part in torso to make its centre of gravity (COG) be high.

The actuator specifications such as power, torque, and speed were investigated in KHR-0[7]. KHR-0 which was developed in 2001 has 2 legs without upper body. Based on KHR-1[8] and KHR-2[9] design, we designed KHR-3, the latest version of KHR series.

KHR-3 has some modifications. Its joint and link stiffness[10] of the robot have been improved. We retuned its actuator mechanism finely by experiment and its appearance has become more human-like and human friendly. Its design of hands, head and neck, eyes, and fingers are modified or retouched from that of KHR-2.

While developing the platform of KHR-3, walking control algorithm has been studied on the KHR-2 platform[11]. We got a lot of important information about the joint actuator behaviours, hardware problems, sensory data characteristics of the robot system, and etc. We present the details about mechanical design result and its deliberations of KHR-3, in the point of differences and improvements from KHR-2.

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II. KHR-3: Overall Description

KHR-3 is our latest humanoid robot. Its height and weight are 125cm and 55Kg. The robot has been upgraded from KHR-2. Its mechanical stiffness of links and reduction gear capacity of joints have been modified and improved. Increased stiffness makes the robot have low uncertainty in joint angle and link position, which can affect its stability. We positively considered its exterior art model shown in Fig.1 in mechanical design stage (wiring path, exterior case design and assembly, movable joint range and etc.). Joint and link shape are seriously designed to fit with its art design concept. The joint controller, motor drive, battery, sensors and main controller (PC) are designed to be installed in the robot itself. The specification of the robot is given in Table I.

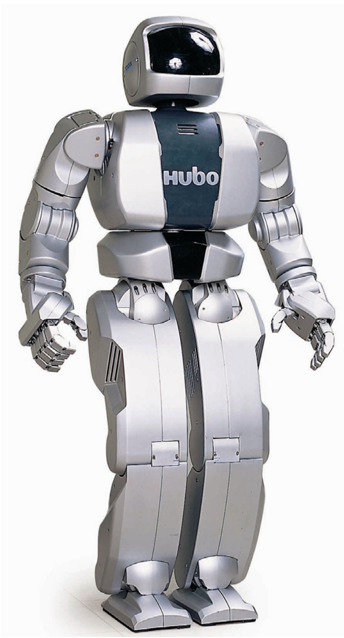

Fig. 1 Humanoid Robot KHR-3

TABLE I
Specification of KHR-3

Research term		2004.1 ~
Weight		55Kg
Height		1.25m
Walking Speed		1.25Km/h
Walking Cycle, Stride		0.95sec, 64cm
Grasping Force		0.5Kg/finger
Actuator		Servo motor + Harmonic Speed Reducer + Drive Unit
Control Unit		Walking Control Unit, Servo Control Unit, Sensor Communication Unit, Communication Unit
Sensors	Foot	3-Axis Force Torque Sensor, Inclinometer
	Torso	Rate Gyro & Inclination Sensor
Power Section	Battery	24V/3.3Ah – 2EA, 12V/6.6Ah -
	External Power	12V, 24V (Battery and External Power Supply Changeable)
Operation Section		Laptop computer with wireless LAN
Operating System (OS)		Windows XP and RTX
Degree of Freedom		41 DOF

III. Overview of Mechanical Design

A. *Degree of Freedom*

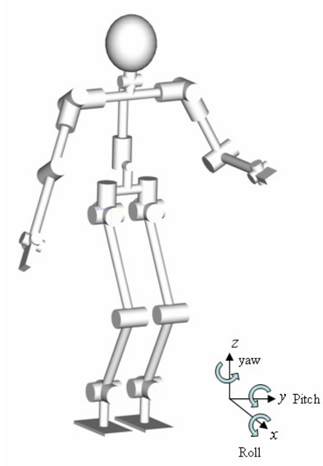

Fig. 2 Schematic of joint and link

DOF of KHR-3 is shown in Table II. We tried it to have enough DOF to imitate human motion such as walking, hand shaking, bowing, and etc. It has 12 DOF in legs and 8 DOF in arms. It can move its fingers and eye balls independently, because there are 2 DOF for each eye – camera pan and tilt, 1 DOF for torso yaw, and 7 DOF for each hand – 2 DOF for wrist and 1 DOF for each finger. The joint axes of shoulder (3/arm), hip (3/leg), wrist (2/wrist), neck (2) and ankle (2/ankle) are crossing each other as shown in Fig. 2 for simple kinematics and dynamic equation of motion[12].

B. *Actuator (Reduction Gear and DC Motor)*

We divided the reduction gears into 2 types as its application. First type is planetary gear. We use this gear for small error (e.g. backlash) allowable joints such as finger, wrist-pan, neck-pan and eyeball joints. Finger and wrist-pan joint error can not affect the whole body stability and overall motion of arms and legs. Second type is harmonic gear. We used it for the major joints such as leg and arm joints. It is used in neck-tilt, wrist-tilt also. Since the harmonic gear has little backlash on its output side, it is used in leg joints whose error can affect to the whole system stability and joint position repeatability. This second type of reduction gear has two types due to connection with motor (Direct connection type and indirect connection type). Indirect connection type needs some power transmission mechanisms (e.g. Pulley-Belt, Gear) between reduction gear and motor. We can adjust joint gear ratio and gear-motor design with disposition. This type is applied to KHR-3's neck-tilt, shoulder-pitch, hip, knee, and ankle joints.

TABLE II
Degree of Freedom of KHR-3

Head	Torso	Arm	Hand	Leg	Total
2 Neck 2/Eye (Pan-Tilt)	1/Torso (Yaw)	3/Shoulder 1/Elbow	5/Hand 2/Wrist	3/Hip 1/Knee 2/Ankle	
6 DOF	1 DOF	8 DOF	14 DOF	12 DOF	41 DOF

We choose gear types and harmonic drive types within given design conditions (e.g. space, shape, permissible power, weight and etc.).

Brushed 24V DC motors are used. It is relatively simple to develop motor drivers than the other type motors (e.g. brushless DC motor and AC motor), because we can design its size, shape and wiring. They also have suitable thermal property. When we drive them in harsh condition such as high speed and torque, generated heat is not so much compared to that of brushless DC motors. It reduces the probability of heat transfer problem from the motors to the other devices such as sensor and controller, even though DC motor characteristics are changed in themselves. The voltage of motor has trades off. The motor which has high voltage needs not to drive high current, and vice versa. This low current property has merits in developing driver, since it does not require high power transistor and high capacity cooling system. The voltage of motors is related on the battery size and weight. If we need high voltage source, we need more battery cells to be connected serially. The number of battery cell is directly related to the weight of battery system and weight distribution of the robot.

C. *Weight Distribution*

Main controller (PC), battery and servo controllers/drivers for upper body are located in torso. The mass except actuators is concentrated on torso, since we need to reduce the load which is inflicted to the actuators in frequently moving parts such as arms and legs and we want to have large inertia of upper body for small amplitude fluctuation of the trunk also.

IV. Joint Actuator and Mechanical Frame Design

A. *Joint actuator Selection*

The actuator selection of KHR-3 is based on the KHR-1[7][8] and KHR-2[9]. KHR-3 has almost same actuators of KHR-2. Joint design of hip-yaw, Hip-roll, wrist and neck is modified. We use unit type harmonic drive reduction gear on hip-yaw joint different from that of KHR-2. When the robot turns around, higher torque is applied to it than KHR-2, because we increase the turning speed of the robot by control algorithm. We use gears instead of pulley-belt mechanism on hip-roll joint. This joint needs to be hidden by the exterior case, which is wanted that those hip joints look like balls as shown in Fig.1. Since the massive parts except for the joint actuators are concentrated on the upper body, we need to increase its reduction ratio on the harmonic drive input side from 1.6:1 to 2.5:1. This joint may have low speed motion but when the robot supports on the ground with two feet, the robot's legs has closed kinematical configuration. If the feet have some position error on the situation, even though its value is comparatively small, the motor position error is larger than the other roll joint motors because of the length of legs. The motor consumes continuous current on that condition. This is why we do not increase the reduction ratio drastically.

All joint reduction ratios are finely tuned by experiments. We also tuned shoulder pitch joint reduction ratio. When we drive the robot arms, the joint frequently requires the highest speed and torque. We also tuned the optimal ratio by experiment.

Selected motors and reduction gears are shown in Table III, IV for all joints. Reduction gear type and input gear ratio means final output gear type and gear ratio between motor output and reduction gear input in the table.

TABLE III
Upper body actuators of KHR-3

		Joint	Reduction gear type	Input gear ratio	Motor power
Hand	Finger		Planetary gear (256:1)	1.5:1 (Pulley-Belt)	3 W
	Wrist	Pan	Planetary gear (104:1)	None	10W
		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	3W
		Tilt		1.5:1 (Pulley-Belt)	
Arm	Elbow	Pitch	Harmonic drive (100:1)	None	90W
	Shoulder	Roll			
		Pitch		1:1	
		Yaw		None	
Trunk		Yaw			

TABLE IV
Lower body actuators of KHR-3

	Joint	Harmonic drive reduction ratio	Input gear ratio	Motor power
Hip	Roll	120:1	Gear (2.5:1)	150W
	Pitch	160:1	Pulley-Belt (1.8:1)	90W
	Yaw	120:1	Pulley-Belt(2:1)	
Knee	Pitch	120:1	Pulley-Belt(1:1)	150W*2
Ankle	Roll	100:1	Pulley-Belt(2:1)	90W
	Pitch	100:1	Pulley-Belt(2:1)	

B. *Link and Joint Design*

KHR-3 has many joints which are actuated using the pulley-belt mechanism. This mechanism needs belt fastener, but we do not use it to reduce the number of mechanical components. We tuned the belt tension by adjusting motor position.

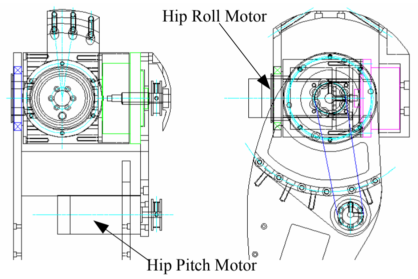

Fig. 3 Hip-roll and pitch joint design

Some joint designs are modified from KHR-2. Hip joint with intersecting 3-axis is designed as shown in Fig.3. The figure contains only 2-axis crossing joint, since the drawing of hip yaw actuator is omitted. We designed this joint with crossing tube type structure. The inner part of the tube is almost empty except for the reduction gear fixture. This design makes the frame be more rigid and have less weight. We increased its moment of inertia and decreased the weight of frame. This is one of the major factors to increase frame rigidity. Fig.4 shows hip yaw actuator output frame. This frame should sustain, with small deflection, various types of loads such as bending moment in X-Y direction and compression/tension in Z direction. Steel would be more suitable than aluminum for this component. The component is machined by numerical controlled (NC) machine, because the shape has 3D characteristics. All mechanical components of the robot have 2D shape except this one. We tried to design the frame have 2D shape, since machining and assembly time, cost and effort can be lower and retouching process can be simpler than those of 3D shape. Since this component functions not only as a mechanical frame but also as an art exterior, it has 3D shape exceptionally.

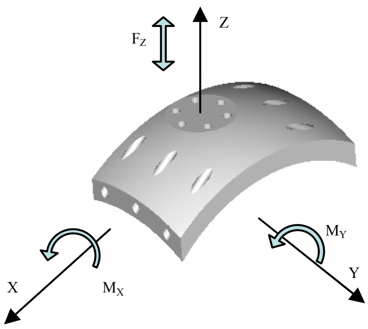

Fig. 4 Hip yaw actuator output frame

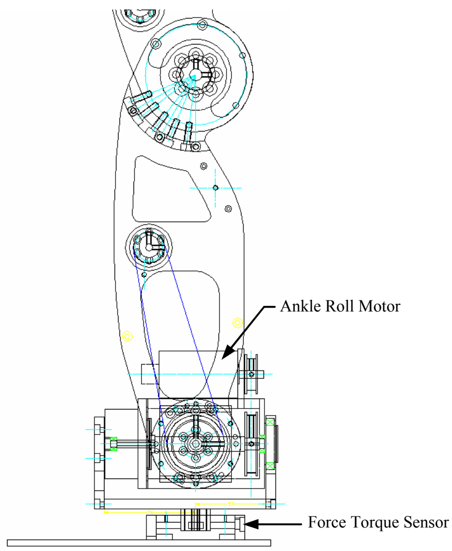

Fig. 5 Ankle joint design

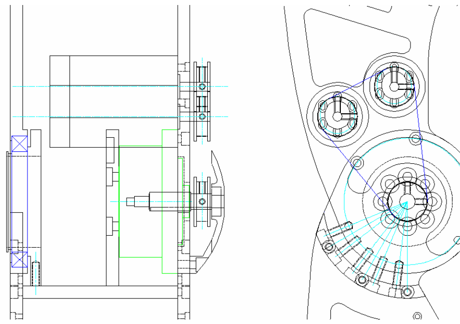
Fig. 6 Knee joint design

We placed the ankle joint motor and its driver far from the force torque (F/T) sensor located on the bottom. The motor and driver generate heat, which can be inflicted with high torque induced by landing shock from the ground. If they are located near to F/T sensor, they would transfer the heat to F/T sensor. The sensor is sensitive to temperature variance, because we used strain gages on it. The ankle pitch joint has $\pm 90^{\circ}$ movable range, since this joint need to have a wide movable range for long stride walk.

KHR-3 has 2 motors on the knee joint like KHR-2 and JOHNNIE[6][13], because knee joint actuator needs high speed and torque when it bent a leg. It can amplify the joint torque with conserving its speed. This means the joint actuator wattage is doubled and reduction ratio can be decreased. If the harmonic drive can sustain the load which is applied on it, we can increase the joint speed.

We designed the links and joints to avoid cantilever beam type in all KHR series. It is because clamped supporting type has more rigidity than cantilever support. We want the link itself to have small deflection and fluctuation. The joint always has double supported beam type link, which are assembled on the reduction gear output and on the other side by bearing support. We designed supporting beams between two beams of the link. KHR-1, 2 were designed to have flat plate type support, but KHR-3 has partial tube type support shown in Fig.3, 5 and 6. The link gets more rigidity by using this type support frame.

Head mechanism shown in Fig. 7 has 6 DOF. Eye balls can move independently since they have 2DOF/eye. We design it to be able to implement stereo vision algorithm in PC.

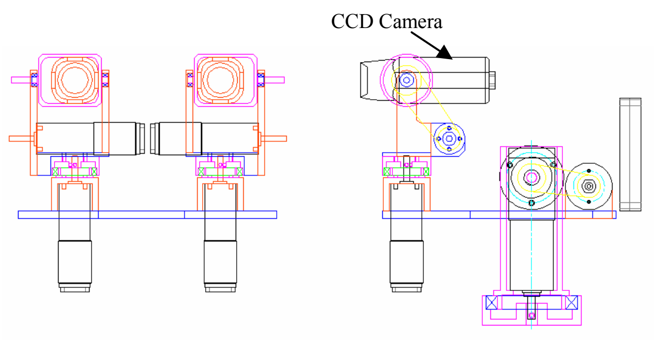

Fig. 7 Head mechanism

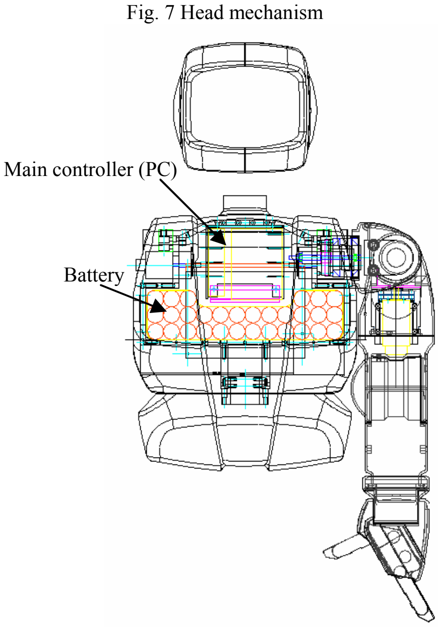

Fig. 8 Upper body design

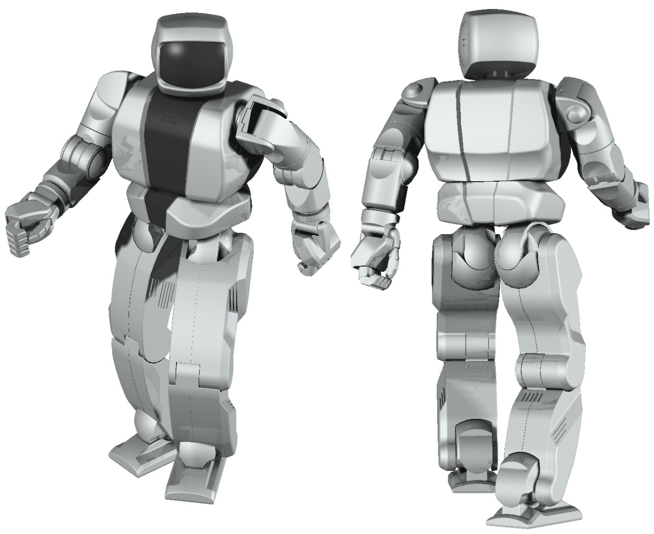

Fig. 9 Art design of KHR-3

Battery and PC are installed in the chest, as shown in Fig. 8 and 9 for exterior art design, since we want to remove backpack. KHR-3 becomes to have slim appearance. We have a convenience to change the battery (after disjointing the front chest case from torso frame, we can plug out or in the battery) with this design.

V. Mechanical Component of F/T Sensor

We have developed F/T sensors for detecting 1-force and 2-moment. Those are attached on wrist (ϕ 50) and ankle (80mm x 80mm) as shown in Fig. 10. Those sensors are used in KHR-2 also.

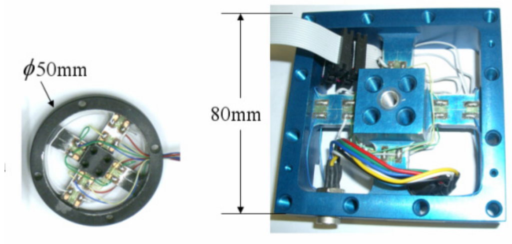

Fig. 10 3-Axis F/T Sensor

To sense the magnitude of beam deflection, we glued strain gages on the points of largest strain with respect to the loads stated above. The point is located at the ends of the beam, but we glued them with 5mm gap, since stress concentration and physical space of strain gage problem. The sensor for ankle is designed to measure normal force (F_Z: 100Kg Max.) and moments (M_X, M_Y: 50Nm Max.).

VI. Conclusion

We have presented the mechanical design, its deliberations and philosophy. KHR-3 design has an intention of human-like shape and movement. We constructed the robot on the design bases of KHR-1 and 2 by modifying, redesigning and retouching them. We implemented the knowledge, information and know-how gathered from these robots, and we wrote on this paper in mechanical design point of view.

Details of actuators composed of reduction gear and motor, mechanical frame design results of the joints and links, and the mechanical structure of F/T sensor are presented on this paper. We also proposed the concept of mass distribution briefly. It would be one of the ways of humanoid robot mechanical design.

VII. Acknowledgement

The art design of KHR-3 has done by Won-Sup Kim in Ewha Womans University in Seoul, Korea.

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