Development of Humanoid Robot Platform KHR-2 (KAIST Humanoid Robot - 2)

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We are presenting the mechanical and electrical system design and system integration of controllers including sensory devices of the humanoid, KHR-2 in this paper. The concept and the objective of the design will be described. We have developed KHR-2 since 2003 which has 41 DOF (Degree Of Freedom). Each arm including a hand and a wrist has 11 DOF (5+2 DOF/hand (finger + wrist), 4 DOF/arm) and each leg has 6 DOF. Head and trunk have 6 DOF (2 DOF/eye and 2 DOF/neck) and 1 DOF respectively. The mechanical part of the robot is designed to have human friendly appearance and wide movable angle range. Joint actuators are designed to have negligible uncertainties such as backlash. To control all axes, distributed control architecture is adopted to reduce the computation burden of the main controller (PC) and to expand the devices easily. We developed a sub-controller which is a servo motor controller and sensor interfacing devices using microprocessor. The main controller (PC) attached on the back of the robot communicates with sub-controllers in real-time by using CAN (Controller Area Network). Windows XP is used for OS (Operating System) for fast development of main control program. RTX (Real Time eXtension) HAL extension software is

used to realize the real-time control in Windows XP environment.

KHR-2 has several sensor types, which are 3-axis F/T (Force/Torque) sensors at foot and wrist, inertia sensor system (accelerometer and rate gyro) and CCD camera. The F/T sensor at the foot is the most fundamental sensor for stable walking. The inertia sensor system is essential for determining the inclination between the ground and the robot. Finally, we will use the CCD camera for navigation and stabilization of the robot in the future. We will describe details of the KHR-2 in this paper.

Keywords: Humanoid robot; KHR-2; Biped Locomotion.

1. Introduction

Nowadays the research in humanoids is diverging into various categories. Research in artificial intelligence, robot hardware development, realization of biped locomotion, interface with environment and others existed in the past. With the help of rapid growth of technology, these researches are getting accelerated, but they start to make their focus on the humanoid because of the concept change of robot. In the past, ordinary robot was an industrial robot. Equipped in the factory, it was welding or assembling parts of cars or electronic devices. The objectives, specification and optimal design parameters are well defined and clear in the point of economics, productivity and efficiency. As the economical paradigm is changing from mass production to small quantity batch production, people's concept of the robot is diverging. So, the desired function of robot is now changing. Nowadays, people want the robot to have various functions.

Recently, many researches have been focused on a development of humanoid biped robot which is similar to human being. Honda R&D's humanoid robots[1], WABIAN series of Waseda University[2], ASIMO[3], H6 & H7[4], HRP[5] and JOHNNIE[6] are well known human size humanoid biped robots. Since the humanoid biped robot is very complicated, expensive and unstable, it is very difficult to realize a real-time motion control based on the sensory feedback like real humans.

The objective of this project is to develop a reliable humanoid platform which can be implemented various theory and algorithm such as dynamic walking, human interaction, AI (Artificial Intelligence), visual & image recognition, navigation and etc. We used a familiar OS to implement those theories easily and designed the platform be easy to maintain. For example, the mechanical parts have simple shape which can be machined by 2-D process and electrical parts are easy to upgrade, replace and reprogram.

When we simplify the ZMP equation to find the relation between robot's natural frequency and size, we can get a reasonable result. If the size of the robot is small, the natural frequency is high, and vice versa. Finding the optimal size of the robot may be another interesting problem. The actuator requirements including power, torque, speed, and etc. are studied in KHR-0[7]. KHR-0 which was developed in 2001 has 2 legs without upper body. We studied the actuator requirements using the robot. Based on KHR-1[8] design, we designed, including the size change, a new version of KHR series robot. In detail, KHR-2 has updated design in the mechanical and electrical point of view. In mechanical design, the joint stiffness and the movable joint angle range are improved, and its appearance becomes more human-like and human friendly. As an example, it has hands and a head including neck, eyes and fingers. While developing the platform of KHR-2, walking control algorithm is studied with the platform KHR-1. When the development of KHR-2 hardware is completed, we can use the same control algorithm of KHR-1. Now we are developing the control algorithm using the inertia sensor system for robust walking in uneven terrain and the hardware of KHR-3 including mechanical and electrical design simultaneously which will be the new version of KHR series.

2. KHR-2: KAIST Humanoid Robot – 2

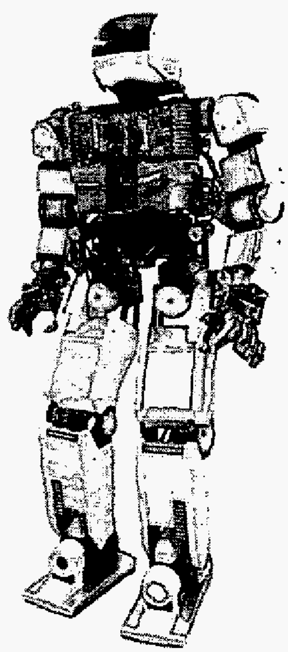


Fig. 1. Humanoid Robot KHR-2

KHR-2 is a new humanoid robot platform. Fig. 1. shows the outline of our humanoid robot KHR-2. The height is 1.2m and the weight is 56Kg. Its design concepts are human like shape, stiff & backlash free joint, self-contained controller system and simple kinematics. We want to make it to have human like appearance, work space, and degree of freedom (DOF) which is enough to imitate human motion. Using harmonic drive reduction gear, we designed backlash free joints. Its joint controller, motor drive, battery and main controller (PC) are fully installed in the robot. KHR-2 has simple kinematics by crossing the joint axis in the shoulder, wrist, hip and ankle joint. Its OS is Windows XP and RTX. The OS can make the controller programming environment to be comfortable for the developer and it has many references in developing the hardware and software.

Table 1. Overall spec. of KHR-2

Research term		2003~
Weight		56Kg
Height		1.2m
Walking Speed		1.0Km/h
Walking Cycle		0.95sec Fixed Cycle, 52cm Fixed Stride
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
	Torso	Rate Gyro & Inclination Sensor
Power Section	Battery (Ni-H)	24V/8AH (192Wh), 12V/12AH (144Wh)
	External Power	12V, 24V (Battery and External Power Supply Changeable)
Operation Section		Keyboard, Mouse, Wireless LAN
Operating System (OS)		Windows XP and RTX
Total Degree of Freedom		41 DOF

In this section, overall specification of KHR-2 is introduced in Table 1. The details of the design will be explained later.

3. Design Concepts and Objectives of KHR-2

In this section, we will introduce the design concepts and objectives of KHR-2. As briefly mentioned above, the design concepts are divided into 4 categories as follows.

(1) Human like shape and movement

(2) Negligible uncertainty of actuators – Stiff & backlash free
(3) Self-contained system
(4) Simple kinematics

3.1 Human like shape and movement

Human likeness has two points of view. One is human like appearance and the other is human like movement. Regarding the first, the appearance of the robot has the characteristics of human and robot simultaneously. The second, the robot should be able to imitate the movement of human. It should have enough DOF, power, and movable range of joint.

3.2 Negligible uncertainty of actuators

The major joints such as all the joints of both legs should be robust. In other words, the output side of the major joint has negligible uncertainty such as backlash and noise. That is why harmonic drive reduction gears are used in the major joints such as legs, arms and trunk and motor drive units such as servo controller and amplifiers are placed near the side of the actuators because of the cable noise. It is important to design the actuators to be reliable, because the uncertainty of the actuator can make the robot system unstable.

3.3 Self-contained system

The main controller, servo controller units, sensor units and batteries are stored inside the robot for the autonomous movement and human like appearance, and the robot doesn't need backpack. The robot should be able to be operated remotely. For example, we can operate it by PC like a note book PC through wireless LAN. By using this protocol, we may operate it with various kinds of devices which has wireless LAN module in the near future.

3.4 Simple kinematics

The robot joint is designed to have simple kinematics. By intersecting the joint axis such as hip (3-axis), ankle (2-axis), shoulder (3-axis), wrist (2-axis), we have a simple closed form inverse kinematics solution[10]. This can make the path generation and controller design to be simple, because if the control hardware can calculate the floating point such as sine and cosine with enough speed, we don't need to solve the Jacobian to get the numerical inverse kinematics solution.

4. Mechanical Design

Cost and development time problem, wiring and movable joint angle range are considered when we design the mechanical part.

Mechanical part of the robot is designed to be easy to manufacture. 3-D manufacturing process such as die casting, CNC machining is excluded to save development time, maintenance and cost problem. Only 2-D machining process such as turning, milling, wire cutting and drilling process is used.

There is a lot of wiring in the robot. Communication cables, power supply cables (which are used in controllers and actuators), sensor signal cables should have organized path with proper tradeoffs between moving joint paths, nice looking appearance, line length, etc. To make the wiring as simple as possible, cable paths are designed to go through the center of the joint axis, and we can minimize the cable length and simplify the cable paths with small slack.

Table 2 shows the DOF of KHR-2. It has totally 41 DOF, 12 DOF in the leg for walking and 19 DOF in the upper body. Hand mechanism has 7 DOF/hand, 1 DOF/finger and 2 DOF/wrist. It has 5 fingers in hand. Head mechanism has 6 DOF, 2 DOF/eye and 2 DOF for neck. The eyes are designed to move independently for visual image tracking and stereo vision. Torso has 1 DOF in yaw axis for compensation of yaw moment when the robot walks.

Table 3 shows the joint angle movable range of the robot. As shown in the table, the movable joint angles are wide. This platform is designed not only for walking and running but for more various movement imitation of human such as sitting down on a chair and floor, crawling on the ground. For example, sitting on a chair may be useful to carry the robot in the car. So, if a robot platform has a wide range of movable joint angle, its application area can be expanded.

Table 2. Degree of Freedom (DOF) of KHR-2

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

Table 3. Movable Angle Range of Lower Body Joint

	Joint	Movable angle range
Hip	Roll	-90 to +38°
	Pitch	-90° to +90°

	Yaw	-77° to +60°
Knee	Pitch	0° to +150°
Ankle	Roll	-40° to +23°
	Pitch	-90° to +90°

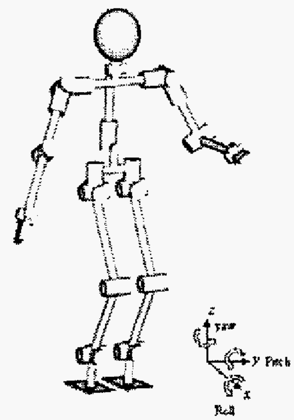


Fig.2 Schematic of KHR-2

4.1 Upper Body Design

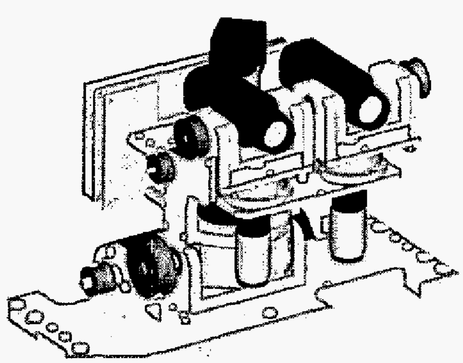


Fig. 3 Head mechanism design

As shown in Table 1, Table 2 and Fig. 2, the robot has 41 DOF. For eye vision system, pan and tilt mechanism is used in the neck and eye as shown in Fig. 3 and Table 4. DC motor and planetary gear is used as pan actuators in the neck and eye. DC motor, planetary gear and pulley-belt mechanism is used as tilt actuators. There is space for a PC which could be used for vision processing as shown in fig. 3. Now the robot has one PC as main controller which is used for walking schedule and control, but may need more PC to realize the vision processing algorithm such as recognition and tracking.

The objective of the finger design is to imitate the human hand. The important factor when designing the hand is not manipulation but dexterity. To realize it, we designed the fingers to have 5 DOF/hand. One DOF/finger is designed using pulley-belt series as shown in Fig. 4. The thumb of human is a little bit inclined with the other fingers, but it is parallel with the other fingers in the robot hand, because of design simplicity.

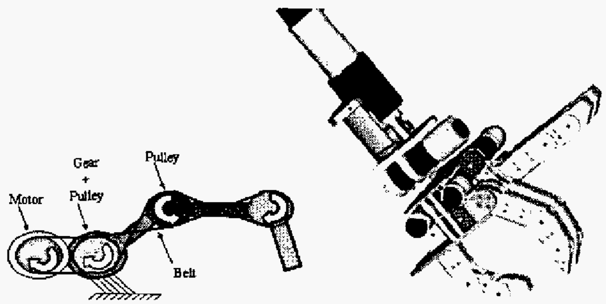


Fig. 4 Schematic of finger mechanism

Table 4. Actuators in upper body

		Joint	Reduction Gear type	Pulley-Belt Ratio	Motor Power
Hand	Finger		Planetary gear head	14/9:1	2.64W
	Wrist	Yaw		No pulley-belt	11W
		Pitch		1.6:1	3.46W
Head	Neck	Pan		No pulley-belt	11W
		Tilt		2:1	
	Eye	Pan		No pulley-belt	2.64W
		Tilt		1.5:1	
Arm	Elbow	Pitch	Harmonic Drive, FB series	No pulley-belt	90W
	Shoulder	Roll		No pulley-belt	
		Pitch		2:1	
		Yaw		No pulley-belt	
Trunk		Yaw		No pulley-belt	

Harmonic drive reduction gear is not used in the head and hands because of the compactness and cost problem. So backlash problem may exist, but that is considered as minor factor in the stability point of view. When backlash free smooth motion is required, design of these parts can be redesigned easily.

There is only one joint in the trunk because if we add pitch and roll joint, the joints may be regarded as redundant. The pitch joints are in the shoulder, hip, knee, and ankle, and the roll joints are in the shoulder, hip and ankle. The DOF and the length and mass of the link for moment compensation may be enough in lateral and frontal view, but the yaw joints which are for the direction change of walking are only in the hip. Using the hip yaw joint, it may be difficult to compensate of yaw moment in top view. Trunk yaw joint is needed for yaw moment compensation in walking.

Other platform such as HRP[5] series and WABIAN[9] series have trunk joints pitch and yaw or pitch and roll. In KHR-2 case, there are servo controllers and amplifiers, inertia senor system module, main controller PC, and batteries in the trunk. As shown in Fig. 2, all the upper body components stated including the head and arms have an effect as inertia on the trunk joint. If the trunk joints (Roll, Pitch & Yaw) are not controlled actively for the purpose of stabilization or some other purpose, they may generate problems such as oscillation and instability. In other words, all the upper body inertia which is fixed on the trunk joint may cause the problems because of backlash or compliance of the actuator. If the algorithm which is using the roll and pitch joint of the trunk is needed, we can redesign those joints in the future. Now, KHR-2 walking control algorithm which was made in KHR-1 does not actively use the joints stated above.

4.2 Lower Body Design

As shown in Table 5, pulley-belt, DC motor and harmonic drive reduction gear system are used as leg joint actuator. Pulley-belt is used for compact design and reduction ratio adjustment. Except for the hip yaw joint, unit type harmonic drive is used. Since those joints are important the leg joints should be stiff against the load such as moments and force. Because the unit type harmonic drive is a commercially assembled unit of harmonic gear tooth, wave generator, cross roller bearing, housing fixture and coupling at input side, its performance is guaranteed. This type of harmonic drive is assumed to be stiff and robust enough.

As shown in Table 5, FB series harmonic drive is used in hip yaw actuator. High power actuator is not needed in this joint. This joint is for turning the direction of walking and only requires resisting leg's rotational inertia. However we should be careful about the joint bearing design. The loads exerted on this joint are a little bit complicated. When the robot walks, compression from the upper body and tension of the non-supporting leg are exerted along the axis, and pitch & roll moments are exerted perpendicular to the axis simultaneously. On the other hand, its size should be compact because of the space for the components of the upper body.

It is known that the highest torque and angular velocity is needed in the knee joint. To achieve these two conditions simultaneously, as shown in Fig. 5, two DC motors and one harmonic drive reduction gear are used like the hip joint of JOHNNIE[6]. By designing like this, the actuator power can be doubled in the ideal case. So, increasing the angular velocity without loss of torque performance or increasing the torque and the angular velocity of the joint is possible. The servo controller of this joint will be explained later.

Table 5. Actuators in lower body

	Joint	Harmonic Drive Type	Pulley Belt Ratio	Motor Power
Hip	Roll	Harmonic Drive, CSF Unit type	5/3:1	150W
	Pitch		19/16:1	
	Yaw	Harmonic Drive, FB series	2:1	90W
Knee	Pitch	Harmonic Drive, CSF Unit type	1:1	2-150W
Ankle	Roll		2:1	90W
	Pitch		29/15:1	

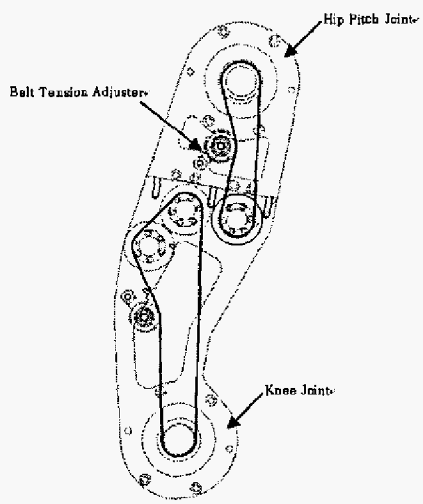


Fig. 5 Thigh Design (Hip Pitch Joint & Knee Pitch Joint)

When we designed the ankle joint, we considered control algorithm which is used in KHR-1 such as damping and landing controller. The algorithm controls the ankle joint actuator based on the F/T sensor signal in the ankle. Because it may have the possibility of harmonic drive latching in developing stage, we used unit type harmonic drive instead of compact FB type harmonic drive as stated above. To make the joint compact and to have wide movable angle range as stated above, reengineering process of unit type one is done. On the other hand, the importance of the ankle actuator design is more critical than the other joint, because the robot has F/T sensors in the ankles. The actuators are connected directly and closely to the sensor. They may introduce other problems such as ripple noise and discontinuity of the sensor signal if they are not controlled or actuated smoothly. They can affect the sensor more directly than the other actuators placed at a distance and compliance between the sensors and the actuators points of view. When the robot walks in rough terrain, this joint actuator performance can be more critical.

5. Electrical Design

We designed the electrical system for the robot. The electrical parts which we designed are JMC (Joint Motor Controller) module, F/T sensor module, inertia sensor module. All the electrical modules are designed to have CAN communication protocol compatibility.

The control system adopted in KHR-2 is distributed control architecture based on CAN protocol.

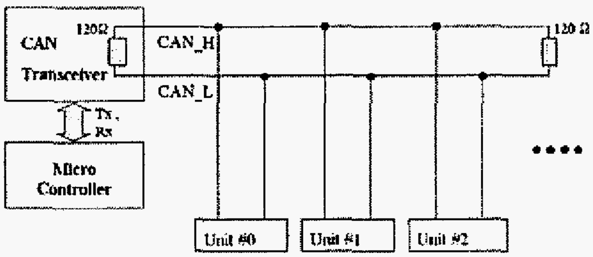


Fig. 6 Simplified CAN Communication Hardware Architecture

As shown in Fig. 6, CAN communication needs two wires, CAN high and CAN low. Devices are connected like in Fig. 6.

When the number of devices is increased, wiring problem becomes more complex. The more wiring complexity is increased and the lesser chance of system hardware improvement. Because the communication system have much space in the point of not only wiring, but also message arbitration, as shown in Fig. 6, it is easy to maintain the system and to expand the system hardware. The communication speed of CAN used in KHR-2 is 1Mbps[1]. This is enough to control the robot, but all the devices which are to be attached to this system have CAN communication function. So, we designed micro

[1] 14-servo controller board, 4-F/T sensor board and 1-inertia sensor board are attached in KHR-2. The message has the length 8-byte/board. So, 152-byte message is transmitted 1 time. Because the message is transmitted every 10ms, the total message transmit ion speed is 15200byte/sec = 121600bps. So, 1Mbps communication speed is enough in KHR-2.

processor units such as servo controller and sensor module. The details are to be explained in this section.

5.1 Controller Hardware Architecture

As mentioned above, the robot controller hardware architecture is based on CAN communication. Overview of the hardware structure is in Fig. 7. The main controller (PC) mainly uses PC104 BUS. Vision capture board for CCD cameras, CAN interface board and PC for main controller are piled up on the BUS. Through the CAN interface card, we can control the joint angle and get the sensor data.

OS of main controller is Windows XP. Because windows is not a real time OS, we used the RTX software. We can use the OS like a real time OS because it provides a real-time environment sub-system. The software architecture is shown in Fig. 8. As shown in Fig. 8, we can program the real time schedule in RTX HAL extension. Because the data transfer between Windows API and RTX can be done by RTX sheared memory, we can monitor the real-time data in Windows GUI easily. This familiar software environment made the developing time of the controller software of KHR-2 short.

There are two kinds of clocks in KHR-2. One is 1ms clock for servo controller for DC motor controller, and the other is 10ms for main controller PC. Every 1ms servo controller interpolates the position data from the main controller as linear position data[2], and controls the actuator position with PD controller. Every 10ms, on main controller side, the PC updates the sensor data, calculates the control laws and the angular position of the joint and sends the joint position data through CAN.

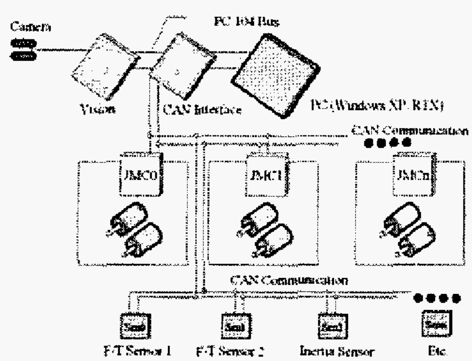


Fig. 7 Controller Hardware Architecture

[2] This dual clock control method has 10ms control output delay. But considering the walking frequency of the robot is around 1Hz and the natural frequency of the system has the same order of walking frequency, 10ms control command delay is in the acceptable range.

We used a commercial single board computer as a main controller. We used computer instead of DSP controller because it has various peripheral interface such as audio and Ethernet, easy and fast programming environment and good graphic user interface (GUI). Selecting criterions are fast CPU speed, low power consumption, compact size and expansion interface. Table 5 shows specification of the main computer (PC).

Table 6. Specification of Main Controller (PC)

CPU	EBX Ezra – 800 MHz
System memory	512 MB
Chipset	VIA 8606T(Twister T)/82C686
Expansion	PC104+, PC104 and PCI slot
Power consumption	Typical 5V @ 3.8A Max 5V @ 4.5 A
Size/Weight	EBX form factor, 203 x 146 mm 0.27 kg
I/O	2 x EIDE (Ultra DMA 100), 1 x FDD, 1 x K/B, 1x RS-232/422/485 3 x RS-232, 1 x LPT Ethernet(IEEE 802.3u 100BAS0E-T) Audio(Mic in, Speaker out) 2 x USB 1.1

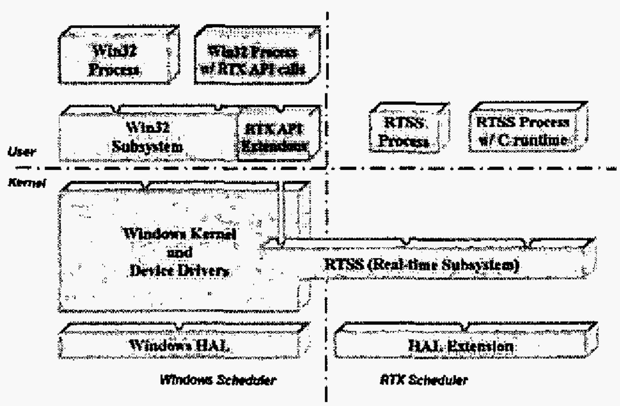


Fig. 8 RTX Software Architecture

5.2 Servo Controller of the Joints (JMC)

As mentioned above, we developed the servo controller of the robot joint which controls the actuator every 1ms by linear interpolating given position commands from main PC in every 10ms through CAN communication. The detailed hardware configuration is shown in Fig. 9.

There are two kinds of JMC shown in Fig 10a and 10b. Both are composed of microcontroller module and power amplification module. The one which controls the low power actuators like the joints in the head and hand can control 7-ch DC motors and it has also 5-ch A/D port for additional sensors such as a pressure sensor for finger tip. The other one which controls the high power actuators like the joints in the leg, arm and trunk can handle 2-ch DC motors and 2-ch A/D port for additional sensors. Its power capacity is about 400W-ch.

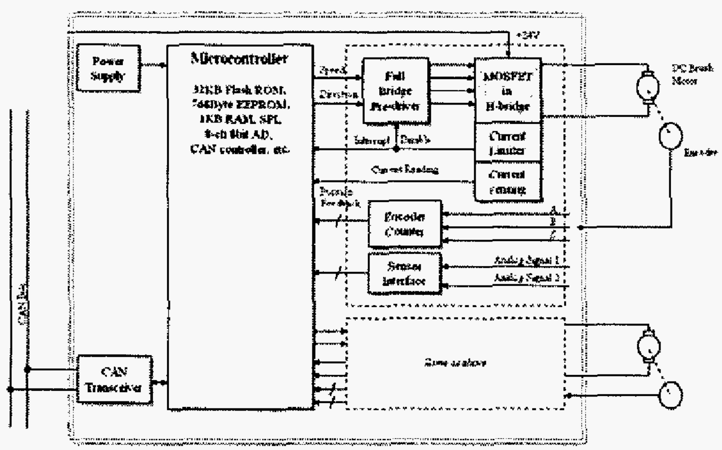
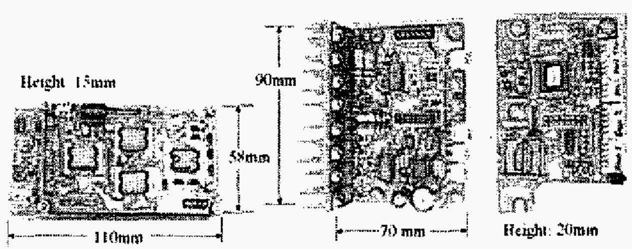


Fig. 9 Hardware Configuration of the Servo Controller of the Joint (JMC)



a 7-ch Motor Controller b 2-ch Motor Controller

Fig. 10 Servo Motor Controller

There are two kinds of input voltage sources in KHR-2. One is 12V-DC for the microcontroller module, PC and sensors, and the other is 24V-DC only for the motor power amplification module. Those power sources are supplied by external power supply or batteries and we can select these power sources by simple switching.

6. Sensors

We developed F/T sensor and inertia sensor systems for KHR-2. It is known that to compensate the designed ZMP path or to sense the ground contact condition of the foot, F/T sensor is important for walking. In addition to the case of KHR-1, we added the F/T sensor at the wrist to corporate with external environment including human interaction. For the more robust walking control of the platform, we also designed the inertia sensor system. The inertia sensor system is made by accelerometer and rate gyro[11]. Details will be explained about these sensor systems.

6.1 F/T Sensor

We developed 3-axis F/T sensors which can measure 1-normal force and 2-moment (roll & pitch). When the sensor is used to calculate ZMP, it is acceptable to use 3-axis F/T sensor[3] with the assumption that the distance between the sole and the sensor is negligible and transversal forces in x-y plane are small.

There are two kinds of F/T sensors in KHR-2 as shown in Fig. 11, but both are using the same signal processing module which is shown in Fig. 11a. The first one, shown in Fig. 11b, is attached on the wrist joint in the hand. It can be used in the hand manipulation of the robot. The sensor may be used in cooperative work with environment or human, for example, carrying a bag or pushing a cart. The second one, shown in Fig. 11c, is attached on the ankle joint. It is mainly used for stabilization control and ground condition detection. Its maximum sensing values are 100Kg-normal

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[3] From the principle of equivalent force-moment,

$$M_{Sensor} = M_{ZMP} + r \times F_{ZMP} \quad \text{where} \quad F_{ZMP} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}, \quad M_{Sensor} = \begin{bmatrix} M_{s,x} \\ M_{s,y} \\ M_{s,z} \end{bmatrix}, \quad r = \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix}$$

This sensor can only sense F_z, $M_{s,x}$, $M_{s,y}$.

By the definition of ZMP,

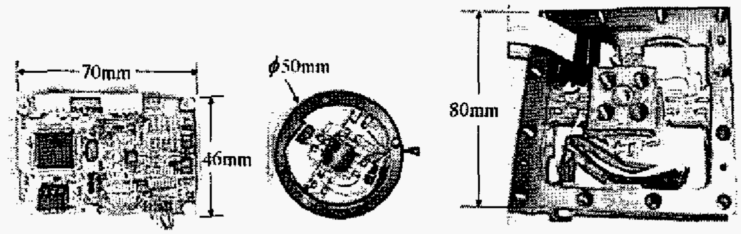
$$M_{ZMP} = 0$$

We can assume that the F/T sensor is on the sole and transversal forces in the x-y plain are small.
Then, $r_z F_x$ and $r_z F_y$ are negligible.

By simple calculation, we can get the following equation

$$r_x \approx -\frac{M_y}{F_z}, \quad r_y \approx \frac{M_x}{F_z}$$

force, 30Nm-roll & pitch moment.



a. Signal Processing Module b. F/T Sensor in Wrist c. F/T Sensor in Ankle

Fig. 11 F/T Sensor Module

6.2 Inertia Sensor System Module

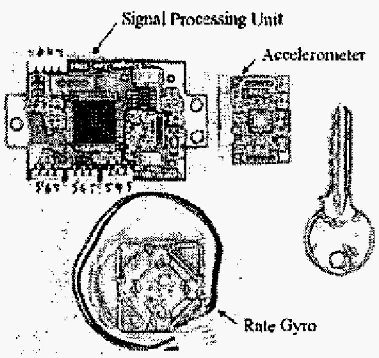


Fig. 12 Inertia Sensor System

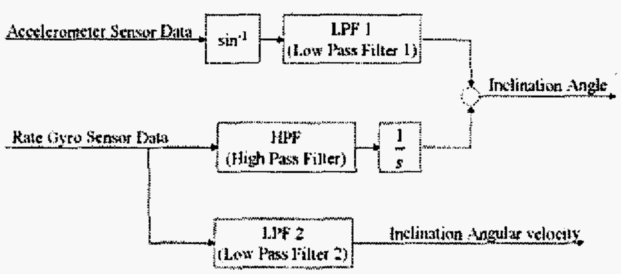


Fig. 13 Signal Processing Block Diagram of the Inertia Sensor System

KHR-2 has inertia sensor system in its chest, which is stated below. The walking control algorithm of KHR-1 does not use the attitude sensor actively. In KHR-2, we have a plan to use it actively.

The inertia sensor system is composed of 2-ch accelerometer, 2-ch rate gyro[4] and signal condition processor board as shown in Fig. 12. In practice, accelerometer can sense the inclination using arcsine function. But it is very sensitive in unwanted acceleration such as shock or jerk, and rate gyro is good for sensing the angular velocity, but it drifts in low frequency. So, we need to have some signal processing methods. As shown above in Fig. 13, we can get the attitude and the change rate of attitude of the robot. The detailed algorithm is out of scope in this paper.

7. Conclusion and Future Work

We have presented how we developed the humanoid robot platform KHR-2, which is designed to have human like appearance and movement. This paper also presents the design concepts of KHR-2 and the details about the mechanical design including the movable joint angle range, electrical component design including the control system hardware architecture and sensor system design.

Future work includes the improvement of platform performance which is realized by actuator, mechanical design and sensor improvement and walking experiments. By utilizing the inertia sensor and vision sensor actively, better walking experiment results will be presented in the future.

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