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

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The mechanical and electrical system designs and system integration including controllers and sensory devices of the humanoid KHR-2 are presented. The design concept and the objective are also discussed. Since last year (2003), we have been developing KHR-2, which has 41 DOF (degrees of freedom). Each arm of KHR-2 has 11 DOF in total that amounts to 5 DOF/hand (i.e. fingers), 2DOF/wrist, and 4 DOF/arm. Each leg constitutes 6 DOF. Head constitutes 6 DOF (2 DOF for eyes and 2 DOF at the neck), and trunk has 1 DOF. KHR-2 has been mechanically designed to have a human friendly appearance and also wide ranges of angular motions. Its joint actuators have been designed in order to reduce motion uncertainties such as backlash. All axes of KHR-2 are under the distributed control, which reduces the computation burden on the main controller (PC) and also to facilitate device expansions. We have developed a microprocessor-based sub-controller for servo motor operations, onto which sensory feedback is interfaced. The main controller (PC), which is mounted on the back of the robot communicates with sub-controllers in real-time through CAN (Controller Area Network). Windows XP is used as the OS (Operating System), which enables rapid program development. 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 such as 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 crucially important for stable walking. The inertia sensor system is essential to determine the inclination of the robot with respect to the ground.

Keywords: Humanoid robot, KHR-2, biped locomotion.

1. Introduction

The research in humanoid robots is now on its way of diverging into various categories. The research on such areas as artificial intelligence, robot 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 robotics 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 that looks similar to a 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 similar to human behavior.

The objective of this project is to develop a reliable 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. We used Windows XP as the OS, which is the most familiar OS to design, implement, and maintain those theories easily. The mechanical parts have been designed to have simple shapes that can be easily machined by the 2-D process. The electrical system was designed with concern to easy upgrading, replacement, and reprogramming.

The 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 of the robot is a different research problem. 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] design, we designed KHR-2, the latest version of KHR series. Compared to KHR-1, KHR-2 is different in size, and it has updated designs in the mechanical and electrical systems. In mechanical design, the joint stiffness and the movable joint angle ranges have been improved, and its appearance has become more human-like and human friendly. It has hands, head and neck, eyes, and fingers. In electrical design, control hardware system has changed from centralized control in that the joints are directly controlled by the main PC, to decentralized control through CAN communication protocol. While developing the platform of KHR-2, walking control algorithm has been studied on the KHR-1 platform.

2. KHR-2: KAIST Humanoid Robot – 2

Fig. 1. Humanoid Robot KHR-2

KHR-2 shown in Fig. 1 is a new humanoid robot platform. The height is 1.2m and the weight is 56Kg. Its design concepts are human-like shape, stiff joints with no backlash, self-contained controller system, and simple kinematics. We wanted to make it to have a human-like appearance, wide motion capability, and adequate number of degrees of freedom (DOF) to perform human-like motions. Using harmonic drive reduction gear, we designed backlash free joints. Its joint controller, motor drive, battery and main controller (PC) are installed in the robot itself. KHR-2 has simple kinematics by crossing the joint axis in the shoulder, wrist, hip and ankle joint. Windows XP and RTX provide many references for developing the hardware and software, and it is a convenient programming environment for the KHR-2. The specifications of KHR-2 are given in Table 1.

Table 1. KHR-2 specifications

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

3. The KHR-2 Design: Concepts and Objectives

In this section, we introduce the concepts and objectives of the KHR-2 design. As briefly mentioned above, there are four design concepts as follows.

(1) Human like shape and movement
(2) Negligible uncertainty of actuators – Stiffness and no backlash
(3) Self-contained system
(4) Simple kinematics

3.1 Human like shape and movement

Being human-like refers to two concerns: The human-like appearance and human-like motion. Regarding the first, the appearance of the robot should consist of both human and robot characteristics. The second, the robot should be able to imitate the human movements. To be human-like, a humanoid robot needs to have an adequate number of DOF, sufficient power, and wide ranges of joint motions.

3.2 Negligible uncertainty of actuators

The major joints such as all the joints of legs should be robust. In other words, the output side of the major joint should have a negligible motion uncertainty such as backlash and noise. This is the reason why harmonic drive reduction gears are used in the joints such as legs, arms and trunk. Moreover, the motor drive units such as servo controllers and amplifiers are mounted close to the actuators to reduce cable noise. It is important to design reliable actuators as actuator uncertainty could destabilize the robot system.

3.3 Self-contained system

The main controller, servo controller units, sensor units and batteries are stored inside the robot to accomplish autonomous movement and human-like appearance. It further makes KHR-s free of having a backpack. The robot should be able to be operated remotely through wireless LAN using a portable PC. In the future, using the wireless protocol, we may be able to operate the robot by various kinds of devices that are operable with wireless LAN modules.

3.4 Simple kinematics

The robot joints have been designed to have simple kinematics. By intersecting the joint axes such as hip (3-axis), ankle (2-axis), shoulder (3-axis), and wrist (2-axis), a simple closed form inverse kinematics solution has been created [10]. In this closed form solution, trigonometric functions such as sin() and cos() are involved, but no Jacobean inverse involved. Therefore, path generation and controller design became simple

4. Mechanical Design

The mechanical design concerns the cost, development time, wiring, and movable joint angle ranges in particular. Mechanical design should concern the convenience of manufacturing the robot, therefore, 3-D manufacturing process such as die casting, CNC machining have been avoided to reduce development time, maintenance, and cost. Only 2-D machining process such as turning, milling, wire cutting and drilling processes have been considered.

There is lot of wiring in the robot. Communication cables, power supply cables (which are used in controllers and actuators), and sensor signal cables should have organized paths with proper tradeoffs between moving joint paths, good appearance, line length, etc. To make the wiring as simple as possible, cable paths were designed to go through the center of joint axes. And, length was shortened using small slacks.

Table 2 lists up the 41 DOF of KHR-2. There are 12 DOF in legs for walking and 19 DOF are 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 at the neck. The eyes have been designed to move independently so that to perform 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 ranges. A wider range of angular motions are used in KHR-2 joints that makes it capable of performing walking, running, as well as various other human-like movements such as sitting down on a chair and floor, and crawling on the ground. It enables other features of KHR-2, such as being able to sit in the car to take a ride with its human companion. As a matter of fact, a wider range of movable joint angles allows a robot platform to extend its application area.

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°

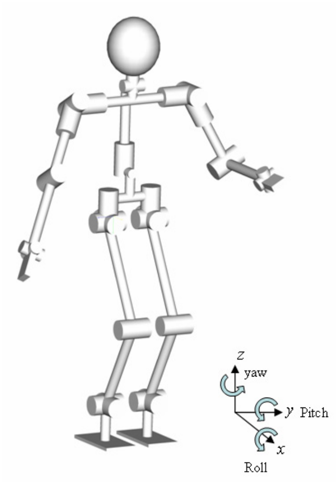

Fig.2 Schematic of KHR-2

4.1 Upper Body Design

For the vision system, pan and tilt mechanism is used in the neck and eye as shown in Fig. 3 and Table 4. The mechanism of a DC motor coupled to a planetary gear is used as pan actuator in the neck and eye. The same mechanism further coupled with a pulley-belt is used as tilt actuators. There is space for a PC which could be used for vision processing as shown in Fig. 3. At present, the robot has one PC as the main controller which is used for walking (scheduling and control), but may need more PCs to realize the vision processing algorithm such as recognition and tracking.

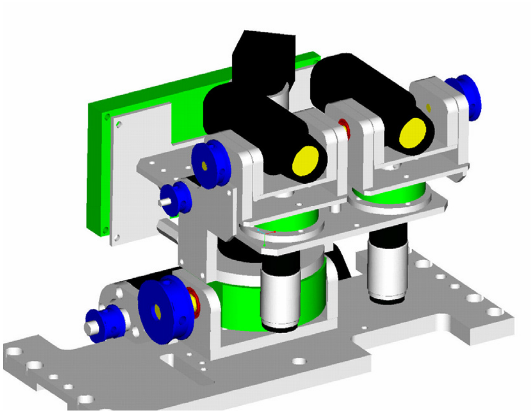

Fig. 3 Head mechanism

The objective of the finger design is to imitate the human hand. The important factor when designing the hand is not manipulation but dexterity. For this purpose, 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 hand is somewhat inclined with respect to other fingers. In the robot hand, however, the thumb is parallel to the other fingers for the sake of design simplicity.

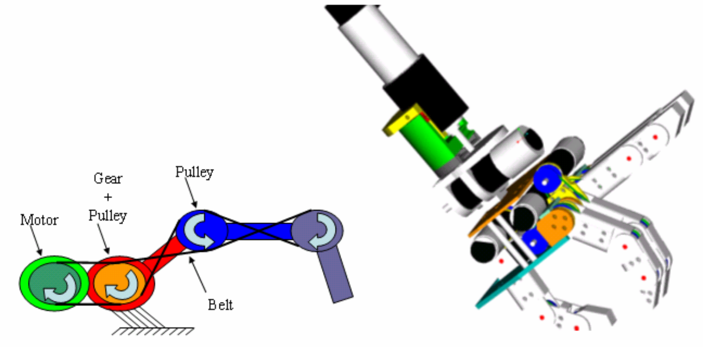

Fig. 4 Schematic of finger mechanism

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 has been excluded in the design of head and hands after considering the compactness and cost issues. Therefore, backlash may be observed in the head and hand motions, yet, it is considered a minor factor in the system stability. When backlash free smooth motion is required, the head and hands can be redesigned easily.

There is only one joint located in the trunk as pitch and roll motions are considered redundant. The pitch joints are located in the shoulder, hip, knee, and ankle and the roll joints are located in the shoulder, hip and ankle. The DOF and the length and mass of the link for moment compensation may be adequate in lateral and frontal view, but the yaw joints, which are necessary when walking direction has to be changed are only located in the hip. Using the hip yaw joint, it may be difficult to compensate the yaw moment in top view. The yaw motion in the trunk is needed for yaw moment compensation in walking. Other platforms such as HRP[5] series and WABIAN[9] series have trunk joints, where pitch and yaw or pitch and roll motions are included.

In KHR-2, the trunk encloses servo controllers and amplifiers, inertia senor system module, main controller PC, and batteries. As shown in Fig. 2, all the upper body components stated including the head and arms produce inertial effect on the trunk joint. If the trunk joints (Roll, Pitch and Yaw) are not controlled actively they may generate oscillatory motion and even become unstable. In other words, all the upper body inertia that affects on the trunk joint may cause such problem due to backlash or compliance of the actuator itself. If roll and pitch motions are required, it is possible to redesign the trunk, which is a future issue to be investigated. At present, the walking control algorithm of KHR-2 (same as in KHR-1) does not use roll and pitch motions.

4.2 Lower Body Design

As shown in Table 5, pulley-belt, DC motor and harmonic drive reduction gear system are used as the leg joint actuator. Pulley-belt is used mainly for compactness and reduction ratio adjustments. Except for the hip yaw joint, unit type harmonic drive is used. The leg joints should be stiff against the load exerted moments and forces. 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 sufficiently robust.

As shown in Table 5, FB series harmonic drive is used in the hip yaw actuator. High power actuator is not needed in this joint. This joint is used for changing the direction of walking where the leg's rotational inertia has to be resisted. However, care has to be taken in designing the joint bearing as the loads exerted on this joint are complicated. When the robot walks, compression from the upper body and tension of the non-supporting leg are exerted along the axis, and pitch and roll moments are exerted perpendicular to the axis simultaneously. On the other hand, its size should be compact because of the limited space for the components in the upper body.

It is known that the highest torque and angular velocity are required at the knee joint. To achieve these requirements simultaneously, as shown in Fig. 5, two DC motors and one harmonic drive reduction gear are used similar to the hip joint design of JOHNNIE[6]. This way, the actuator power can be doubled in the ideal case, which allows to increase the angular velocity without loss of torque performance, or increasing both torque and angular velocity of the joint. 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	

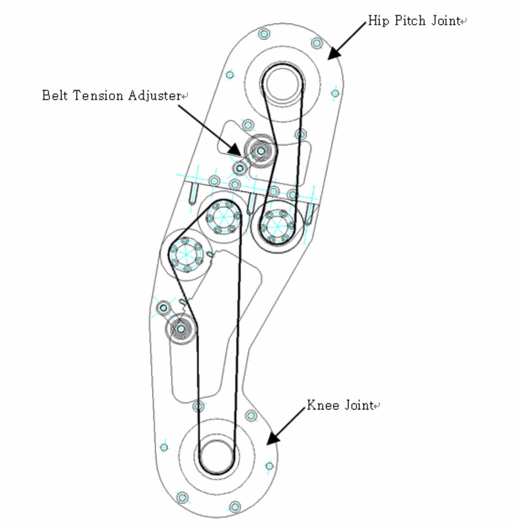

Fig. 5 Thigh Design (Hip Pitch Joint & Knee Pitch Joint)

5. Electrical Design

The electrical parts that we have designed are JMC (Joint Motor Controller) module, F/T sensor module, and inertia sensor module. All the electrical modules are designed to have CAN communication protocol compatibility as KHR-2 uses distributed control architecture based on CAN protocol.

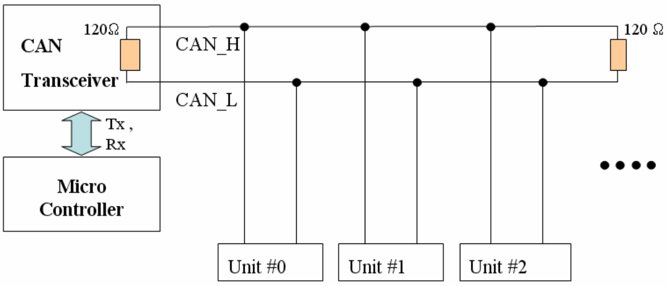

Fig. 6 Simplified CAN Communication Hardware Architecture

The devices are connected as shown in Fig. 6. The CAN communication needs two wires; CAN high and CAN low. When the number of devices is increased, wiring becomes more complex, which resists the hardware improvement. However, CAN communication system saves much space in wiring and message arbitration as shown in Fig. 6, provisions are retained for maintenance and hardware expansions. The communication speed of CAN used in KHR-2 is 1Mbps[1], which is adequate to control the robot provided that all devices which are to be attached to the system have CAN communication function. Therefore, we designed microprocessor units such as servo controller and sensor module, which are to be explained shortly.

5.1 Controller Hardware Architecture

As mentioned above, the robot controller hardware architecture is based on CAN communication. Overview of the hardware structure is illustrated 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 read the sensor data.

The OS of main controller is Windows XP. Because windows is not a real time OS, we

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[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.

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 shown in Fig. 8 can be programmed for real time tasks using schedules in RTX HAL extension. Because the data transfer between Windows API and RTX can be accomplished by RTX sheared memory, we can monitor the real-time data in Windows GUI easily. This familiar software environment allowed rapid development of the controller software of KHR-2.

There are two kinds of clocks in KHR-2. One is 1ms clock for servo controller for DC motor control, 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 through a 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.

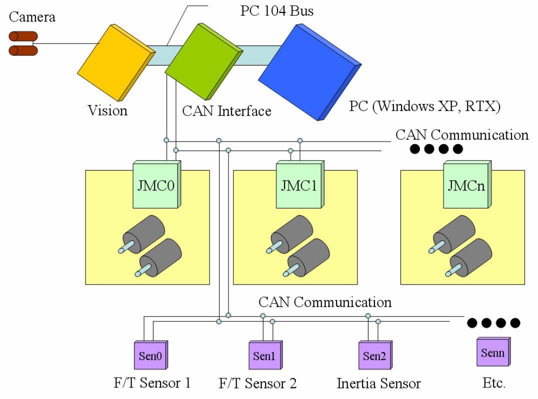

Fig. 7 Controller Hardware Architecture

We used a commercial single board computer as the main controller instead of a DSP controller for that purpose. This decision was made for the sake of having various peripheral interfaces such as audio and Ethernet, easy and fast programming environment and good graphical user interface (GUI). The selecting criteria are fast CPU speed, low power consumption, compact size and expansion interfaces. 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

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[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.

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

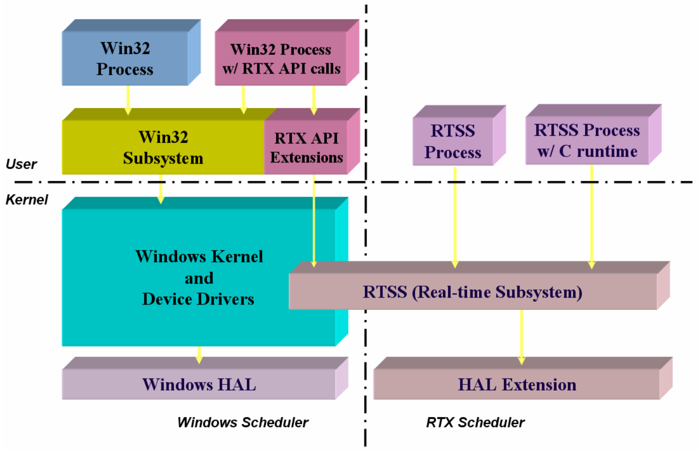


Fig. 8 RTX Software Architecture

5.2 Joint Servo Controller (JMC)

The joint servo controllers operate at 1000Hz, which interpolates linearly the position commands issued by the main PC at a frequency of 100Hz. The detailed hardware configuration is shown in Fig. 9.

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

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.

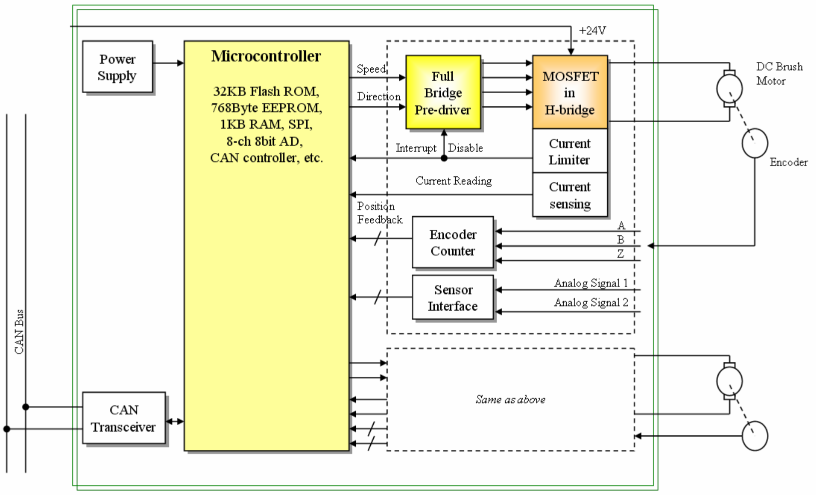
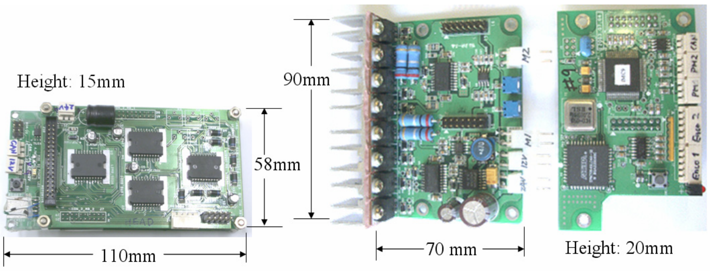


Fig. 9 Hardware Configuration of the Servo Controller of the Joint (JMC)



a. 7-ch Motor Controller

b. 2-ch Motor Controller

Fig. 10 Servo Motor Controller

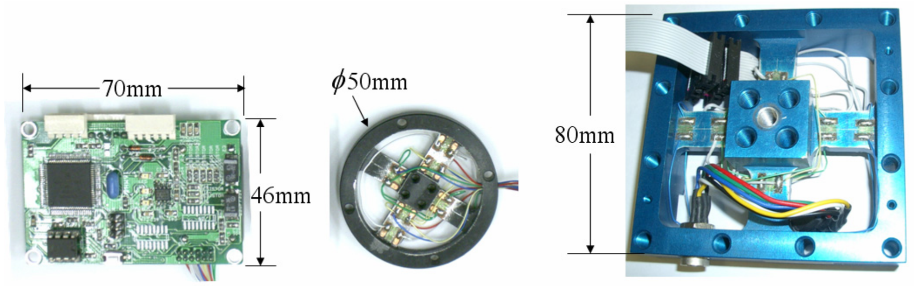
6. Sensors

We developed F/T sensor and inertia sensor systems for KHR-2. The F/T sensor data are essential to compensate the designed ZMP path, and also to feel the ground contact condition, which are critical issues in stable walking. The F/T sensors are also mounted at the wrists of KHR-2 to enable it to interact with the external environment, and also to cooperate with human companions. For the more robust walking control of the platform, we also designed the inertia sensor system. The inertia sensor system is composed of an accelerometer and a rate gyro[11]. These sensor systems are explained below in detail.

6.1 F/T Sensor

We developed 3-axis F/T sensors which can measure 1-normal force and 2-moment (roll and 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. Both of these use 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 for hand manipulations of the robot. The wrist F/T sensor is also useful in interactions with the environment such as carrying a bag or pushing a cart, or in corporative work with a human. The second one, shown in Fig. 11c, is attached onto the ankle joint. It is mainly used for stabilization control and to detect ground condition. Its maximum readings are 100Kg-normal 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

As for a future development, we intend to attach pressure sensors on finger tips so that to make KHR-2 capable of feeling touch sense.

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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

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

6.2 Inertia Sensor System Module

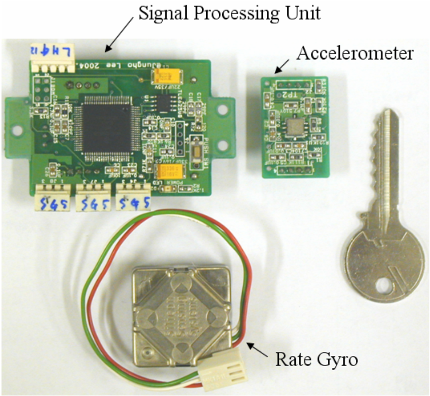

Fig. 12 Inertia Sensor System

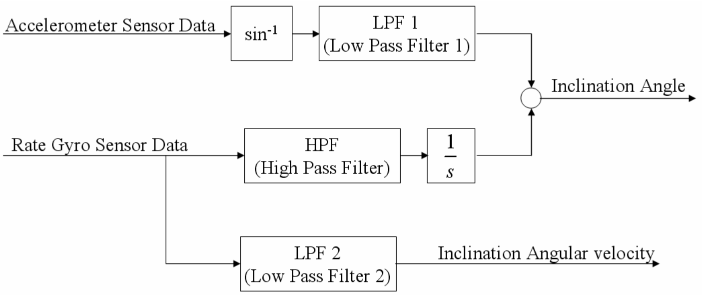

Fig. 13 Signal Processing Block Diagram of the Inertia Sensor System

KHR-2 has inertia sensor system enclosed in its chest. The walking control algorithm of KHR-2 uses the attitude sensor actively, which was not there in KHR-1. The inertia sensor system is composed of 2-channel accelerometer, 2-channel 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 to the 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 use robot's attitude and its rate of change instead. The detailed algorithm of the inertia sensor is out of scope of this paper.

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[4] These two channels are roll and pitch of the trunk

7. Conclusion and Future Work

We have presented the development process of KAIST humanoid robot platform KHR-2, which intends to have human-like appearance and movements. This paper has also presented 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 of KHR-2 aims at the improvement of platform performance such as walking. By utilizing the inertia sensor and vision sensor actively, better walking performance will be demonstrated in the future.

8. Acknowledgement

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