Design and Walking Control of the Humanoid Robot, KHR-2(KAIST Humanoid Robot - 2)

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Abstract: This paper describes platform overview, system integration and dynamic walking control of the humanoid robot, KHR-2 (KAIST Humanoid Robot – 2). We have developed KHR-2 since 2003. KHR-2 has totally 41 DOF (Degree Of Freedom). Each arm including a hand has 11 DOF and each leg has 6 DOF. Head and trunk also has 6 DOF and 1 DOF respectively. In head, two CCD cameras are used for eye. In order to control all joints, distributed control architecture is adopted to reduce the computation burden of the main controller and to expand the devices easily. The main controller attached its back communicates with sub-controllers in real-time by using CAN (Controller Area Network) protocol. We used Windows XP as its OS (Operating System) for fast development of main control program and easy extension of peripheral devices. And RTX, HAL(Hardware Abstraction Layer) extension program, is used to realize the real-time control in Windows XP environment. We present about real-time control of KHR-2 in Windows XP with RTX and basic walking control algorithm. Details of the KHR-2 are described in this paper.

Keywords: Humanoid, KHR-2, Real-time control, Dynamic walking

1. INTRODUCTION

The word 'Robot' is a compound word of 'Robota' (compulsory labor) and 'Robotik'(laborer) from Czech language and was used in the play in 1921 firstly. In the science fictions or movies, the robot resembles a human, but, nowadays, the robot means the industrial robot usually. The industrial robot called the manipulator is used for continuous simple and hard work instead of a man. By the way, recently, the meaning of the robot is changing from the manipulator to the intelligent robot which can adapt itself to the human society. The biped walking robot which resembles a human is very good one as a representative intelligent robot, and we call it the humanoid. Already in Japan, the first humanoid robot whose name is WABOT-1 was developed in 1973 at Waseda university.[4] After then, many humanoid robots have been developed continuously. For example, there are ASIMO of Honda[1,2], SDR-series of Sony, H7 of Tokyo university[3], HRP of AIST and so on. Also our humanoid robot, KHR-2, is one of them.

We have studied the humanoid robot since 2001. Our goal is to develop the humanoid robot which can live together with a human being and help us. First of all, humanoid robot must walk autonomously to live with a human. So we developed the biped robot in 2001 to understand the human walking[6]. But, at that time, we mainly researched about optimal robot size, weight and actuator type and capacity. Next year, we designed our first humanoid robot whose name is KHR-1[5] and succeeded in dynamic walking. Although KHR-1 was unstable by small disturbance, its walking speed was 0.8 km/h using force/torque sensor, and it was also able to turn and walk to the right side. From much experience of KHR-1, we have developed the second version of humanoid robot, KHR-2 since 2003. Because KHR-1 doesn't have a head and two hands, we designed a head with two eyes and two hands with five fingers in each hand in this version. Therefore KHR-2 has much more DOF than those of KHR-1 and complicated hardware and software architectures.

In this paper, we describe the overview of robot platform briefly and hardware/software system integration. Finally, motion control of KHR-2 and basic walking algorithm will be introduced.

2. OVERVIEW OF MECHANICAL DESIGN

2.1 Design philosophy

We summarize our design philosophy in five topics.

1) Human like shape and movement.
2) Light weight, compact size and backlash free actuator
3) Self-contained system
4) Kinematically simple structure
5) Low power consumption

According to above design concept, we designed a child-sized robot which resembles a human shape and has sufficient joints to imitate a human (Fig. 1). We used the harmonic drive gear as the reduction gear of main joints. For autonomous walking, all controllers, sensory devices and batteries etc. are equipped inside of KHR-2.

Fig 1. Photograph of KHR-2

In order to reduce the power consumption, shape and thickness of the mechanical structures are optimized. Finally, all axes of main joint cross in one single point for the closed-form solution of inverse kinematics.

2.2 Overview of KHR-2

KHR-2 has 41 DOF and its height and weight are 120 cm and 56 kg respectively. The reason why we designed the child size humanoid robot, we considered the practicality, efficiency of electric power and human-friendliness. DC motors are used in all joints as a actuator because of easy controllability and compactness. Detail specification and DOF are described in Table 1, 2 respectively. Fig. 2 shows joint structure of KHR-2.

Table 1 Specification of KHR-2

Height		120 cm
Weight		56 kg
Waking speed		0~1.0 km/h
Step period		0.9~1.0 sec
Grasping force		0.5 kg/finger
Actuator		DC servo motor + Harmonic drive gear/planetary gear
Control Unit		Walking control unit, Motor control unit, Data transmission unit
Sensory devices		3-axis Force/Torque sensor (wrist , foot) Rate Gyro/Acceleration sensor (trunk) CCD camera (eye)
Power supply	Battery	Ni-H (24V/8AH, 12V/12AH)
	External Power	12 V, 24V
Operation devices		Keyboard and mouse Notebook PC with wireless LAN

Table 2 Degree of freedom of KHR-2

Head	Eye	2 DOF x 2 = 4 DOF
	Neck	2 DOF
Arm	Shoulder	3 DOF x 2 = 6 DOF
	Elbow	1 DOF x 2 = 2 DOF
Hand	Wrist	2 DOF x 2 = 4 DOF
	Finger	1DOF x 10 = 10 DOF
Trunk		1 DOF
Leg	Hip	3 DOF x 2 = 6 DOF
	Knee	1 DOF x 2 = 2 DOF
	Ankle	2 DOF x 2 = 4 DOF
Total		41 DOF

In head two CCD cameras are used for eyes. The image is captured continuously by frame grabber with 15fps. Specification of CCD camera and frame grabber are described in Table 3, 4. Pan and tilt mechanism was applied to eyes and neck. In most joint axes, pulley/belt drive mechanism was used because of large movable range and sufficient space. In hand, there is one DOF in each finger. Finger is composed of three parts and these parts are connected each other by pulley and belt. So if the first part moves, others are move simultaneously. The reason why there are five fingers in a hand is just to mimic a human being.

We used a Ni-H battery to work the KHR-2. This battery supplies the electric power to the main computer, frame grabber, CAN Module, CCD camera, sub-controllers and fans and so on. So, KHR-2 consumes the 12V with 6~7A and the 24V with 10~15A. Therefore we can work KHR-2 for about 40 minutes.

For autonomous walking, wireless LAN was installed in the main computer. It is easy to access the main computer in Windows XP. So, we access the main computer by notebook PC with wireless LAN, and then control the robot remotely.

Table 3 Specification of CCD camera

Imaging sensor	1/4" CCD (color)
Output signal	NTSC
Image pixel size	640(H) x 480(V)
Camera Size	22 mm x 67.5(D) mm
Weight	100 g
Focal length	3.6 mm
Power consumption	12V@0.25A

Table 4 Specification of frame grabber

Bus Interface type	PC104 Plus
Input Video signal	NTSC, PAL, RS-170, CCIR
Video input number	Up to 12
Frame buffer memory	4 Mbyte
Supporting OS	Windows 98, Me,NT4.0,2000,XP

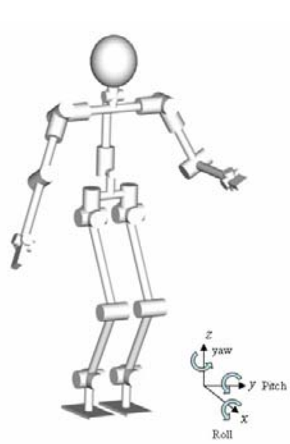

Fig. 2 Joint structure of KHR-2

3. SYSTEM INTEGRATION

3.1 Control architecture

When we developed KHR-1 in 2002, we adopted the centralized control system. So a main computer with DOS OS(Operating system) controlled all joints by using an interface card that we made. In this manner, we were able to do fast system integration and main computer knows all information easily. However it is difficult to expand joints and there is much calculation burden of main computer. Therefore, in KHR-2, we adopted the distributed control system with Windows OS environment since KHR-2 has twice as many joints than KHR-1 and many peripheral devices such as vision system, wireless LAN and CAN module and so on. By using distributed control architecture, calculation burden was decreased much, but we had to develop sub-controllers and needed communication bus line between main computer and sub controllers. Besides we had to realize real-time control in Windows environment because Windows OS is not real-time OS. Fig. 3 shows overall system configuration.

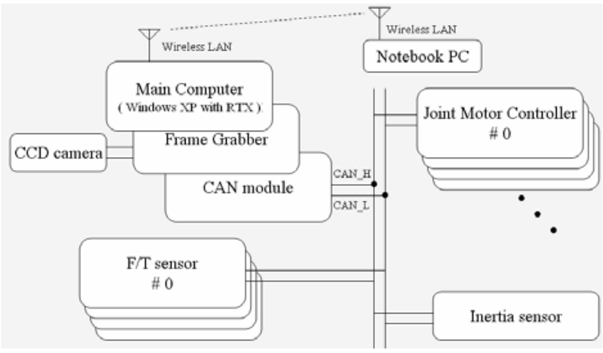

Fig. 3 Overall system configuration

3.2 Main controller

We used a commercial single board computer as a main controller. We used computer instead of DSP controller because it has various peripheral interface, 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.

3.3 CAN (Controller Area Network) protocol

In order that the main computer can give orders to sub controllers or receive the many kinds of data, there must be communication bus line between the main computer and the sub controller. Besides the communication speed also should be fast to handle 19 sub controllers. Therefore we adopted the CAN protocol which is high speed serial communication up to 1Mbit/s. The performance of CAN protocol has already been proved in automobile industry. In CAN protocol, just two lines are needed for transmission of data, so it is very simple to expand other sub controllers. The most important feature of CAN is a Multi-Master/Multi Slave feature. This means that all controllers connected with the CAN bus line can be Master, so they can transmit any data to CAN bus line. And then, all controllers can receive data in CAN bus at the same time. So if the main controller sends the data to the CAN bus line, every controller can receive the data.

Table 5 Specification of main computer

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

3.4 Sub controller

There are two kinds of sub controllers. The one is joint motor controller(JMC) and the other is sensory device (Fig.4, Fig.5, Fig. 6). All sub controllers were designed by ourselves and their MPU(Micro Processor Unit) are the same. This MPU has a CAN module and communicates with a main computer. Each controller also has several the A/D converter, so we can easily add sensors. Table 6 shows the specification of sub-controllers.

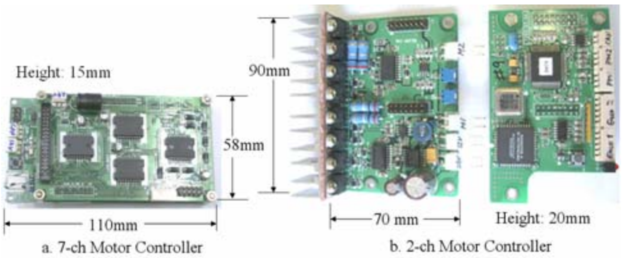

Fig. 4 Joint motor controllers

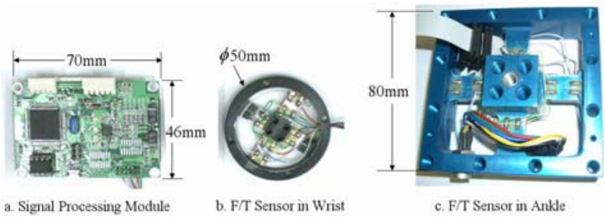

Fig. 5 3-Axis Force/Torque sensors

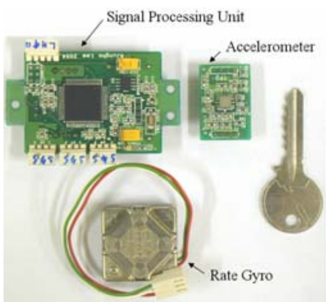

Fig. 6 Inertia sensor

Table 6. Specification of sub-controllers

JMC	Type 1 (head, hand)	CAN Module 16 bit micro controller 7 ch DC motor driver (48W/ch) 5 ch A/D converter 2 ch Digital output
	Type 2	CAN Module 16 bit micro controller 2 ch DC motor driver (400W/ch) 2 ch A/D converter
3-Axis F/T sensor		CAN Module 16 bit micro controller 1 normal force (up to 100 N), 2 moments(up to 30 Nm) Strain gage amp circuit Auto balancing function
Inertia sensor		CAN Module 16 bit micro controller 7 ch A/D converter (3 ch for 3-axis acceleration sensor 3ch for 3-axis rate gyro sensor 1 ch for temperature sensor) Tilt range : -15 ~ 15 deg

3.5 Real-time operating system of the main computer

Basically, Windows XP is not real-time operating system (RTOS). It is general purpose operating system (GPOS). So user-mode application program can not access hardware directly. And because Windows thread scheduler is not deterministic, its interrupt latency may be over 5 msec. Therefore we used the RTX(Real Time Extension) which is a HAL(Hardware Abstraction Layer) extension commercial program in order to provide real-time capability. By using RTX, we can access hardware directly. Also we can make an interrupt which has the highest priority and its maximum latency is just 12 usec. In this manner, we provided the real-time capability to the main computer easily, and were able to develop the main control program fast in Windows environment by using Visual C++ language.

4. MOTION CONTROL

KHR-2 has 41 DOF and 14 joint motor controllers. Each joint motor controller controls two or seven DC motors by encoder feedback. Since the control architecture of KHR-2 is distributed control system, the main computer sends the reference position data to the joint motor controllers repeatedly in exactly same time interval. Now the time interval is 10 msec. Namely, the system control frequency is 100 Hz. This is because we think the sufficient calculating time will be needed for the main computer. On the other hand, the joint motor controller divides the reference position into ten time slice since the control frequency of the joint motor control is 1 kHz (Fig. 7).

In this manner, the main controller sends the reference position data to 14 joint motor controllers successively in 10 msec. Also the main controller receives the sensor data in 10 msec.

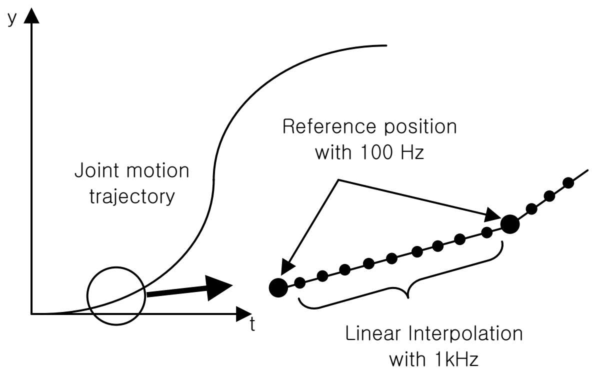

Fig. 7 Reference position and its linear interpolation

5. WALKING ALGORITHM

In this section, we introduce the basic dynamic walking algorithm. Fig. 8 shows block diagram of dynamic walking control. At the first stage, user has to set several walking parameters. They are step length, step period, double support phase ratio, lateral swing amplitude of body center and amplitude of foot lift and so on.

At the second stage, user chooses the walking types such as forward or backward walking, right/left side walking and clockwise/counterclock wise turning.

At the third stage, proper walking pattern is generated according to the walking parameters and walking types. And walking pattern is modified by trunk roll/pitch controller and landing position controller. Trunk roll/pitch controller is used to prevent the inclination of the trunk from the change of the ground inclination by using rate gyro and accelerometer. And landing position controller prevents the unstable landing by modification of position schedule, when the actual landing occurs before or after the prescribed time.

At the fourth stage, all joints angles are derived by inverse kinematics and then, also modified by damping controller and landing orientation controller. These controllers are switched each other by landing detection algorithm. We eliminated the sustained vibration in single support phase by damping control at ankle joint which is based on torque feedback. And for soft landing, we applied the landing orientation controller at ankle joint which is based on integral of torque.

Finally, the main computer sends the reference position data to all joint motor controllers and then all joint motor controllers control the DC motors by using PD control.

In this manner, we did the walking experiments. The stride was 0 ~ 60 cm and KHR-2 walked straightly on the treadmill with 0 ~ 1.0 km/h. And it was able to walk to right or left side with 0 ~ 80 cm of side step length and turn to counter clockwise or clockwise with 0 ~ 15deg a step.

6. CONCLUSION

In this paper, we developed the humanoid platform KHR-2 according to the proposed design philosophy. KHR-2 has 41 DOF, four 3-axis force/torque sensor, one inertia sensor and two CCD cameras. In order to control all joints and sensors efficiently, the distributed control architecture was adopted. As a main controller, we chose the single board computer which has fast computational speed, low power consumption, compact size and good expansion interface. We used RTX HAL extension program to realize the real-time capability in Windows OS environment. We also developed all sub-controllers such as joint motor controllers, force/torque sensors and inertia sensor. And as a communication line between the main computer and the sub controllers, CAN protocol, fast serial communication for real-time control, was used. We introduced the motion control process in distributed control system briefly. Finally, basic walking algorithm and online controller for dynamic walking were introduced.

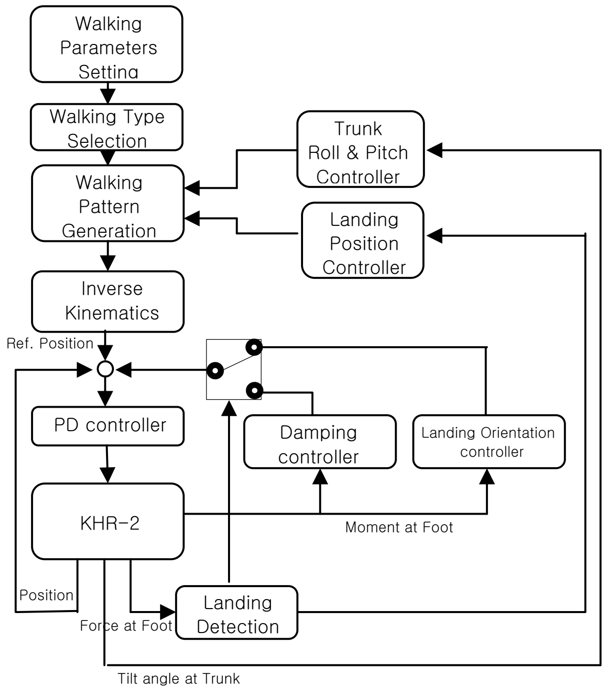

Fig. 8 Block diagram of dynamic walking control

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