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Cooperative Works by a Human and a Humanoid Robot

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Abstract — **We have developed a humanoid robot HRP-2P with a biped locomotion controller, stereo vision software and aural human interface to realize cooperative works by a human and a humanoid robot. The robot can find a target object by the vision, and carry it cooperatively with a human by biped locomotion according to the voice commands by the human. A cooperative control is applied to the arms of the robot while it carries the object, and the walking direction of the robot is controlled by the interactive force and torque through the force/torque sensor on the wrists. The experimental results are presented in the paper.**

1. Introduction

Honda first demonstrated the capability of humanoid robot 1996 through the development of P2 [1] and based on that success, this field of research has been increasing and spreading in various ways. People has slowly become more inclined and interested to use this technology in their respective fields, for example, in personal service, high-risk maintenance task, construction industries, etc.

To cope with these social needs, Ministry of Economy, Trade and Industry of Japan has promoted the Humanoid Robotics Project (HRP) since 1998 for five years [2]. The project is divided into two phases. In the first phase, the robot platform, the remote control cockpit and the virtual robot platform were developed. In the second phase from 2000 to 2002, the applications of humanoid robots have been investigated using the platforms.

In the second phase, we have been enhancing an idea of introducing a humanoid robot to work cooperatively with a human in the outdoor [3]. Figure 1 is an illustration of such a cooperative work in a construction environment. In this environment, there are many chores that are carried out by a pair of an expert and a novice. The replacement of the novice with a humanoid robot enables us to reduce the number of workers and the cost, and to supply labors to counter the shortage of manpower in the aged society, which is one of the most serious problems in Japan.

We selected two typical works that are doing by the pair - one is carrying an external wall panel, and the other is mounting the panel on the frame of a house. To replace the novice with a humanoid robot, we have been developing four technologies, mainly.

1) Hardware/software to walk on uneven surfaces, and to prevent damage in the event of tipping
2) Sensors to position the wall panel and the grasping point
3) Communication between human being and the robot conveniently
4) Software to control the arms and the legs cooperatively

In the first half of second phase, we have combined these hardware and software into a new humanoid robot HRP-2P and demonstrated to carry a panel with a human on the flat floor. This paper outlines the results of these developments.

This paper is organized as follows. Section 2 describes the above building blocks implemented on HRP-2P. Section 3 presents the experimental results. Section 4 concludes the paper.

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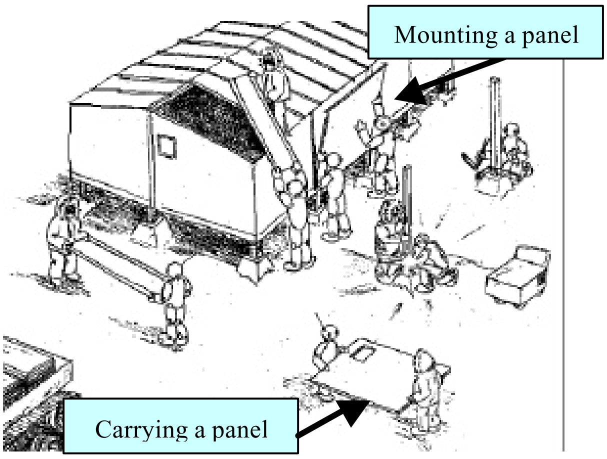


Figure 1. Outdoor Worksite

2. Building Blocks

2.1. Humanoid Robot HRP-2P

HRP-2 is a new humanoid robot platform, whose manufacturing process is in progress in phase two of HRP. The design concepts of HRP-2 are light, compact, but performable for application tasks like cooperative works in the open air shown in Fig. 1 [3]. As a result, HRP-2 is designed to be feminine size. Figure 2 shows the prototype of HRP-2 [4].

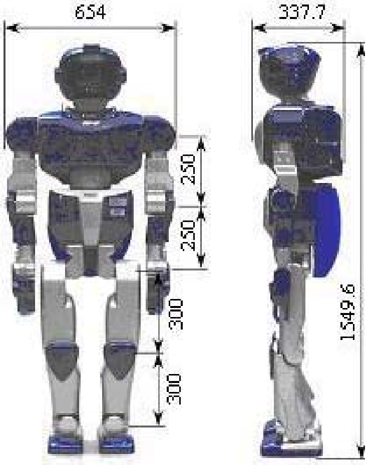


Figure 2. Humanoid Robot HRP-2P

As shown in Fig. 2, HRP-2P has unique configurations. One is that the hip joint of HRP-2P has a cantilever type structure as well as HRP-2L which is the leg module of HRP-2 [6]. The other is that HRP-2P has two waist joints.

The humanoid robot tends to tip over easily, since the area of the foot sole that supports the whole body is so small and limited. The motions of the body during tasks may easily make the humanoid robot lose its balance as well as those of the arms. From this observation, the mechanism for prevention of tipping over is a very important requisite to realize a really useful humanoid robot.

The tipping over easily occurs when the target ZMP is going to the outside of the support polygon made by supporting feet [5]. Since it is so hard to recover from a tipping over, our approach to prevent tipping over is to construct the mechanism, which easily enables to make the target ZMP to be inside of the support polygon.

A mechanism, which enables the robot to have a wide sphere of landing point for the swinging leg, would be one solution for our approach. The reason is that we can appropriately shape the support polygon for the phase of double supported legs by selecting the landing point of the swing leg. By shaping the support polygon for the phase of double supported legs immediately, the tipping over would be prevented, even if humanoid robot begins to tip over. Especially, crossing legs further can make the support polygon to be on the opposite side of supported leg. To realize a wide sphere of landing point for the swing leg, the hip joint of HRP-2P has a cantilever type structure as shown in Fig. 2. Because the cantilever type structure enables the robot to have less collision between both inside upper-limbs and also to cross legs [6].

The other factor throwing the humanoid robot off balance is caused from rolling motions of the gait. The mechanism, which makes the trajectory of the center of gravity (COG) of the upper body smooth with less rolling motion, is also effective in the prevention of tipping over. To reduce rolling motion of the gait, the cantilever type structure also plays an important role. Since the cantilever type structure can make the length between hip joints shorter, this structure can make the length between landing points of pitch axis shorter too [6].

From these discussions, we designed the cantilever type structure to achieve the mechanism for prevention of tipping over. This structure enables the robot to cross legs as well as to make a protector between legs for minimal damage in the event of tipping over.

HRP-2P would not be able to avoid tipping over, even though HRP-2P has the cantilever type structure as explained above. When HRP-2P tips over during cooperative works in open air, we request HRP-2P to get up by a humanoid robot's own self. To realize such a humanoid, a waist joint with 2 D.O.F. (pitch axis and yaw axis) is necessary for HRP-2P.

The waist joint brings several advantages. One is that the structure of HRP-2P can be lithe. The lither the upper body is, the smoother its gait is. Another is that the moment generated in the yaw axis of HRP-2P can be suppressed by using waist motion. This compensation will be done in the near future. Furthermore, the waist joint makes a working space of arm extended. Although HRP-2P has 6 D.O.F. in each arm and 1 D.O.F. in each hand, waist motion gives a redundancy to the arm motion.

2.2. Vision System on HRP-2P

HRP-2P has a stereo vision system composed of three cameras(Fig. 3). Two horizontal cameras are separated by 120 mm, and the third camera is 60mm upper than them. We adopt three cameras system since it is difficult for stereo vision composed of two cameras to detect the horizontal line. The weight of the vision system is less than 700 g. Relatively short focus lens is used in order to measure a position of an object, whose standoff is from 0.5m to 4 m. The camera's shutter speed is controlable by a computer to adapt various lightning condition. The image processing is based on VVV System [7]. VVV consists of several image processing modules and we can reconstruct 3D shape model, detect a object, measure position and track a object with it.

Figure 3. Vision System

2.2.1. Correction of Distortion

Through a plastic shield in front of the cameras, the object image is distorted. It is practically difficult to model the shield shape and the position of the camera correctly. So we make a conversion table between a distorted image to a image without the shield. On a calibration board, circle patterns are arranged at even intervals and a lager circle is arranged near the center of the board. We capture the board with and without the shield (Fig. 4) and detect the positions of each circle. The larger circle position on each image is used as positioning reference of all the other circles and gets the correspondence of all circle points between two images. Using an interpolation of this correspondence, we make each pixel conversion table. We also correct lens distortion using the same image without the shield. As a result, the distortion is reduced within 0.2 pixel.

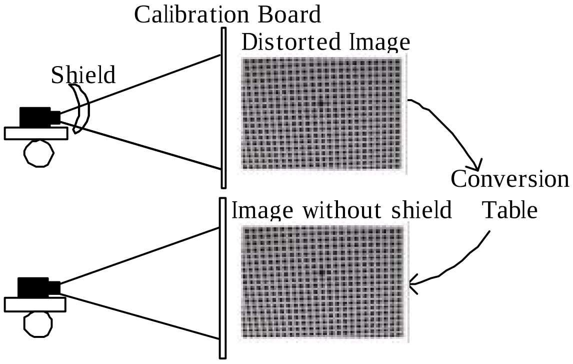


Figure 4. Correcting Shield Distortion

2.2.2. Coordinates of the Cameras and the Robot

The detected position of an object is represented by a vision coordinate system. In order to use this position data, we have to transform the vision coordinate system to the robot coordinate system.

A marker is put on the robot finger and HRP-2P moves the hand to several places in the filed of the vision (Fig. 5). HRP-2P captures image and gets the position of the finger at each place. Using the detected marker positions on the vision coordinate system and the finger positions on the robot coordinate system, we calculate the transform matrix from the vision coordinate system to the robot coordinate system.

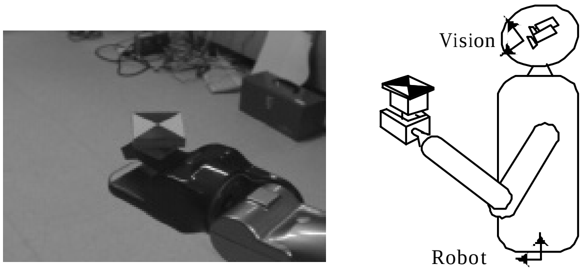
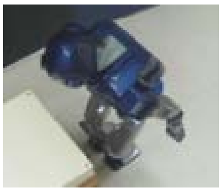


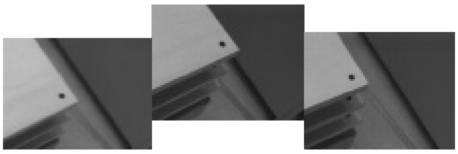
Figure 5. Calibrating Transform Matrix

2.2.3. Recognition of Panel

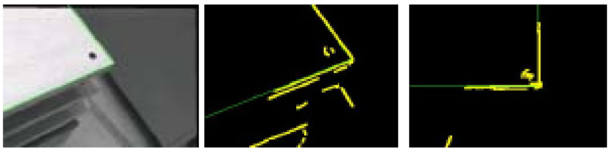
An object recognition function is necessary for HRP-2P to grasp and carry a panel with a human operator. A model based recognition system [8] is used, and the grasping point was calculated within 2 mm error from the results of recognizing the panel top edge. Figure 6 shows (a)HRP-2P detecting panel, (b) captured images and (c)a result of matching a panel model.



a) Detecting Panel



b) Captured Images



c) Matching panel model on image

Figure 6. Detecting Panel

2.3. Human Interface

In the cooperative works by a human and a robot, an user-friendly interface is important. The target work is that a human and a robot carry an exterior wall panel together as shown in Fig. 7. The human needs to use his/her both hands to carry the object. In this case, it is not suitable to use a keyboard or mouse for inputting commands and a joy-stick for operations. However, the human interface using voice has been gaining importance in practice with the advancement of speech recognition technology and the processing speed of recent CPUs. Also in the industrial robot, the direct-teaching by force sensor is already seen in practice [9]. We call this method as force sensing operation. Under these backgrounds, the keyboards or mouse and the joy-stick were replaced by the voice input method using speech recognition and the force sensing operation method respectively. This section describes the developed voice input system while section 2.4 describes the force sensing operation in detail.

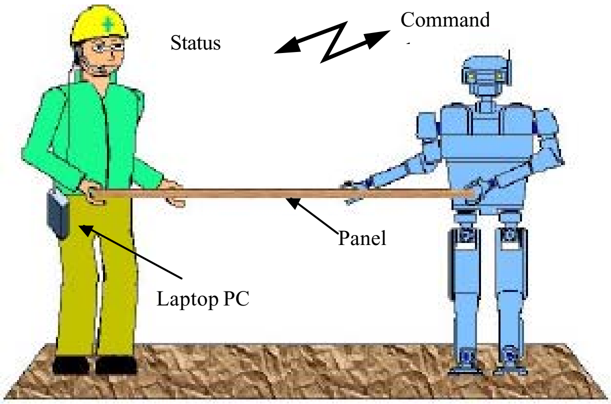


Figure 7. Work example

The voice instructions have been developed and installed on a laptop PC that has been carried by the human. The communication is taken place between PC and the robot. PC recognizes speech, converts it to generate command, and transmits to the robot. The robot executes command after interpretation. The human also gets a confirmation message from the PC through headphone that the command is sent to the robot. The human also sees the robot if it executes his command. However, the problem arises when a command has not been sent to robot due to the following failures.

1) Failure in speech recognitions
2) Failure at communications

Besides, all practical system, recognition and communication take some time period. Sometimes this time period may create a new problem. For example, if the time is long and the human is restless, the human may send the same command twice before the first command is executed by the robot. In that case, the robot will repeat the same action during the execution of second command. All these problems can be solved by developing a system that sends information at various stages as shown in the flow diagram of Fig. 8. The system tells the human using different sounds in each of the stages as shown below.

1) Speech recognition is started (Sound A)
2) Recognition is impossible (Sound B)
3) Out of commands (Sound C)
4) Under communication (Sound D)

With this development, it is possible for the human to know the state of the system without using special devices and to transmit command to the robot with certainty.

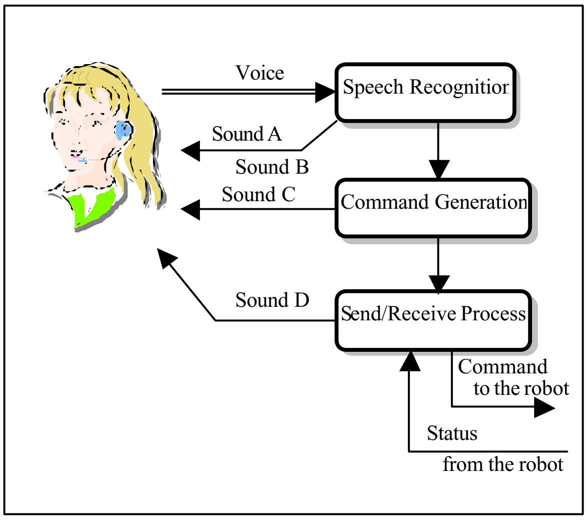


Figure 8. The flow of sound information

2.4 Force Sensing Operation System

When a human and a robot work on an object cooperatively, it is necessary to tell the robot the moving direction and speed continuously. For example, when operating a robot using voice instruction, the human must direct the robot continuously with words such as "Right", "Left", "Clockwise", "Anticlockwise", "Before", "Back", "Stop", etc. Furthermore, in addition to these commands, the speed information are also to be sent with words like "Slow", "Fast", "Medium", etc. However, the human has to speak continuously without any mistake then. This can be overcome by using force sensor. When the human moves the object, the force is transferred to the robot through the object. This force is sensed by force sensor. However, the biggest problem, using force as a prime mover to operate the robot, arises from other side. This transmitted force generates tipping moment on the robot that creates unstable movement. To overcome this difficulty some kind of cushion between the object and robot is necessary in order to use force sensing operation effectively. In this case, it is possible to apply an impedance control based on force sensing operation. Kosuge et al, adopted the impedance control to a dual-arm mobile robot, and confirmed the effectiveness [10],[11].

When dual-arm grasped one side of the object like a long panel and human moved the other side to right and left, it is difficult to recognize translation or rotation by the force sensors mounted on wrists of the robot. To cope with this problem, we took measures to change translation or rotation via voice instructions.

Hence, using voice instruction, impedance model on robot's arms, can be written by simple equation as

$$\mathbf{M_d}\,\Delta\ddot{X} + \mathbf{D_d}\,\Delta\dot{X} + \mathbf{K_d}\,\Delta X = \mathbf{F},$$

where $\mathbf{M_d}$ is an inertia matrix, $\mathbf{D_d}$ is a viscous matrix, $\mathbf{K_d}$ is a stiffness matrix, and **F** is the force and moment vector. When **F** is applied, it will produce the displacement vector $\boldsymbol{\Delta}\mathbf{X}$. And $\boldsymbol{\Delta}\mathbf{X}$ is added to target poses of robot's hands.

F applied from the human must include some factors of disturbance, like a jerk. On the other hand, the calculated $\boldsymbol{\Delta}\mathbf{X}$ from the impedance control changes continuously and smoothly. Therefore the walk velocity is expressed using the $\boldsymbol{\Delta}\mathbf{X}$ instead of **F**, and its vector $\boldsymbol{v}$ is determined by

$$\boldsymbol{v} = \mathbf{G_L}\,\boldsymbol{\Delta}\mathbf{X},$$

where $\mathbf{G_L}$ is a coefficient matrix which changes the displacement vector $\boldsymbol{\Delta}\mathbf{X}$ into walk velocity vector $\boldsymbol{v}$. The robot generates movement patterns, such as steps on case of walking robot in real time using velocity vector and moves along the direction of the force transmitted by the human.

Hence, using impedance control, the transmitted force on the robot by the human is absorbed smoothly avoiding any jerk created to tip over the robot. Therefore, applying force sensing operation, it is possible to operate the robot intuitively along the direction and speed without considering any command signals.

3. Experiments

A series of experiments have been carried out with the humanoid robot working cooperatively with a human (operator) to move an object, say panel, from the loading zone to some other place. The panel is 5kg in weight having dimension of 1.8 x 0.6 m.

The followings are the detail of experiments to demonstrate the capabilities.

a) The operator work while saying "Start work" using voice control. The robot moves in front of a panel as shown Fig. 9a.
b) The operator says "Get panel position" and the robot starts to search the panel (Fig. 9b). Based on the recognition of panel position using stereo vision, the robot automatically judges whether the current standing position is sufficient to grasp the panel or not. If not, the robot also automatically adjusts the standing position as shown in Fig. 10.
c) The operator says "Grasp panel". The robot grasp

and lifts the panel using the pose information acquired by the stereo vision. (Fig. 9c)

d) The operator lifts the panel at the same time and says "Move panel". The robot changes its mode from position control to impedance control and moves along the direction of the force applied by the operator. (Fig. 9d)

e) The operator guides the robot to move to the unloading zone and says "Put panel". (Fig. 9e)

f) The robot releases the panel after recognizing the voice command "Put panel", and finishes the work as shown in Fig. 9f.

Figure 11 shows an experiment of the cooperative work. The robot is not taught its destination, but it is possible to reach in front of a panel by the force sensing operation.

In our daily life, an interaction between humans is common and natural but that between a human and a robot through voice is far from real. This experiment shows a human, communicating with a humanoid robot, performs a work cooperatively. The work is not complex to human but complex enough to execute by a robot.

Our humanoid robot performs the task using biped locomotion, vision, cooperative handling control, and voice instructions.

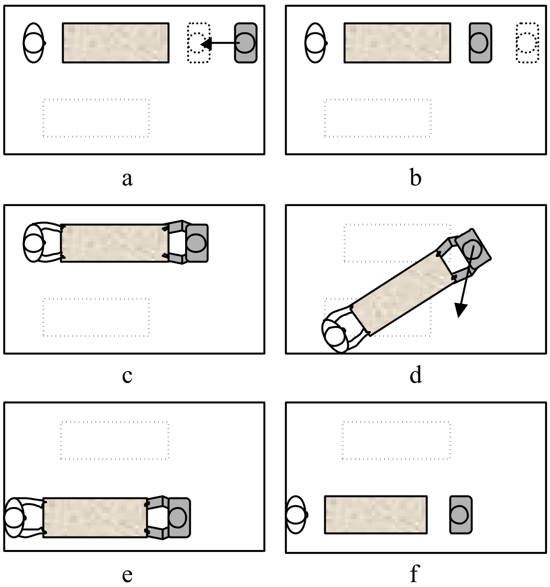


Figure 9. The scenario of an experiment

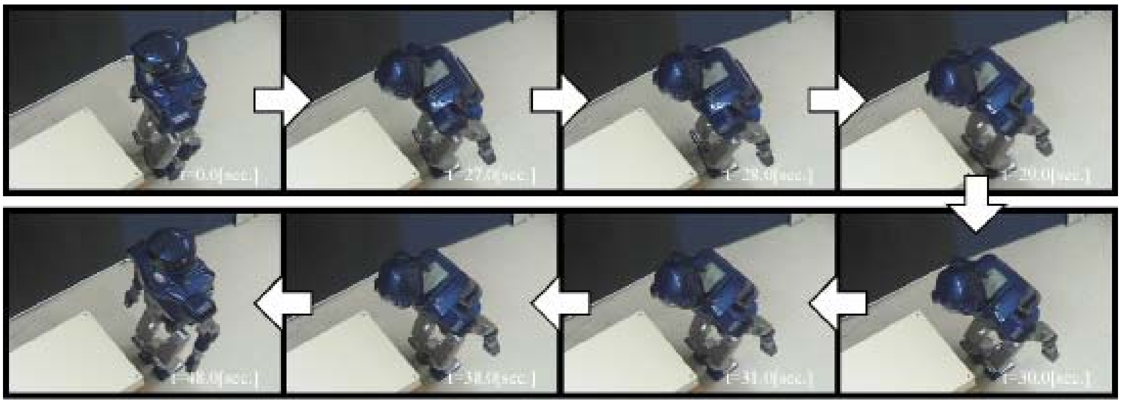


Figure 10. The recognition of panel position and the standing position adjustment

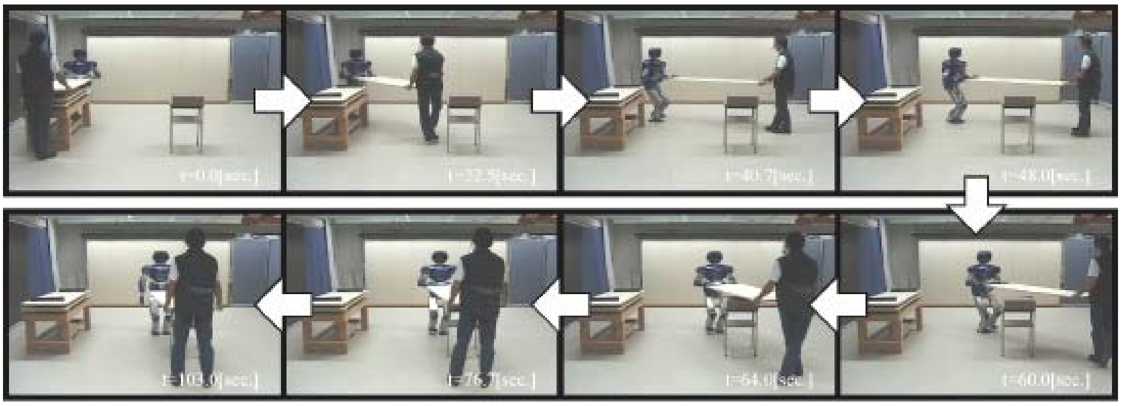


Figure 11. Cooperative work with human

4. Conclusions

In this paper, humanoid robot HRP-2P has been developed to realize the cooperative work between a human and the humanoid robot. This robot is equipped with the stereo vision system, human interface and force sensing operation system. HRP-2P is one of the first humanoid robots on which various functions are realized and can execute a significant task.

In the rest of the second phase, we plan to develop a final model HRP-2 which is designed based on the experimented results on HRP-2P. The software, for the final goal such as carrying the external wall panel on uneven surfaces, mounting it on the frame of the house, etc., has to be modified and improved accordingly. In addition, we would like to develop a robot that can minimize damage in an event of tipping and is capable of standing up, if tipped.

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