Paper:

Development of Human-Symbiotic Robot "EMIEW" – Design Concept and System Construction –

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We are developing a robot that will support people in their daily lives, i.e., a human-symbiotic robot. This kind of robot is required to coexist with users, be user friendly, and be capable of supporting them. As a first step to achieving the last goal, we have developed an autonomous mobile robot that makes use of a self-balancing two-wheeled mobility system and a body swing mechanism to shift its center of gravity. This allows it to move nimbly at up to six kilometers per hour. It also has capabilities that enable it to avoid collisions with obstacles and move safely through complex environments. It is able to interact with people naturally without special tools by means of distant-speech recognition and high-quality speech-synthesis technologies. These capabilities were demonstrated at the 2005 World Exposition Aichi Japan.

Keywords: human-symbiotic robot, inverted pendulum, collision avoidance, distant-speech recognition

1. Introduction

A robot that can make our daily lives safer, more convenient, and more comfortable has been demanded by the public to solve the problem of aging societies or to improve the quality of our lives. The development of a robot that can be used for entertainment, housework, and office work [1–3] has commenced based on this social background.

We are currently developing a robot that can support people in their daily lives, i.e., a human-symbiotic robot that coexists with users, is user friendly, and is capable of supporting them. As a first step to achieving the last goal, we developed a human-symbiotic robot that we called the "Excellent Mobility and Interactive Existence as a Workmate (EMIEW)" [4].

The design concept and the construction of the system for EMIEW are introduced in this paper.

2. Design Concept

There are conceptual images of future applications for EMIEW in **Fig.1**. We expect that its first applications will be in office support services, such as being a guide for customers at information desks, and providing logistics support in offices or security services in buildings.

As the first step to achieving these applications, we decided to develop:

(1) Nimble-mobility,
(2) Collision-avoidance, and
(3) Communication technologies.

A robot used in these applications will be required to move rapidly, i.e., as fast as a person who is walking quickly. If a guide robot cannot move quickly, the people following it may become irritated. Moreover, capabilities to follow rapidly moving people are essential in security applications. It is also important to guarantee the safety of people near moving robots. A moving robot's capabilities for avoiding collisions with humans will be indispensable in cooperative human-symbiotic work. To achieve this, we decided to develop a mobility-control technology that enabled quick acceleration and deceleration without the robot falling over. And it is also able to recognize wandering obstacles and plan an optimum collision- avoiding path in real time.

The robots used for the applications in **Fig.1** have to receive instructions from humans and be friendly with them. Therefore, they need to be able to have an intelligible conversation with whoever is cooperating with them in human-symbiotic work. For this purpose, we decided to develop a distant-speech recognition technology that recognizes human voices from about one meter away and a nonverbal communication function using the body motion of the whole robot to achieve more intimate communications with humans.

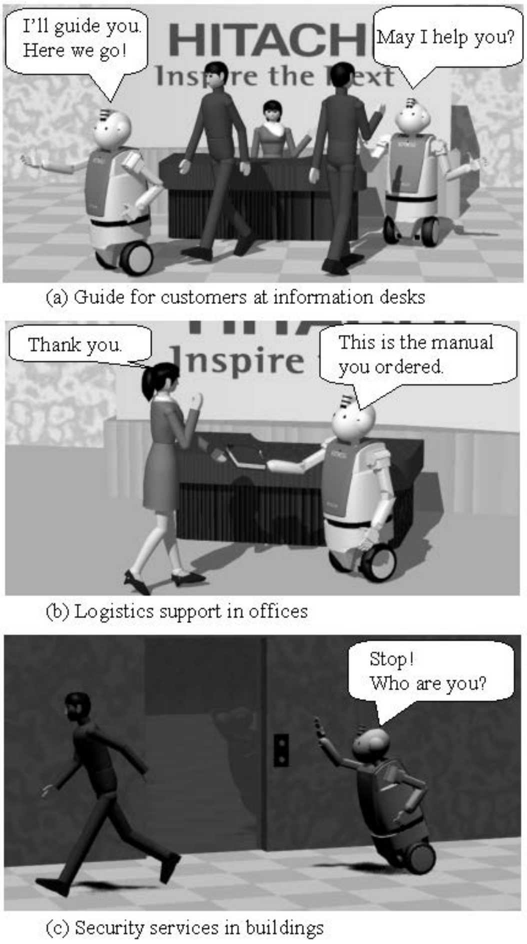


Fig. 1. Conceptual images of applications.

3. Functions and System Construction

This section introduces some typical functions of EMIEW and provides details on its construction with the three technologies.

3.1. Specifications and Functions of EMIEW

The specifications for EMIEW are listed in **Table 1**. Its height is 1.3m, roughly the same as that of an average human child. We determined this height because the goal of development was cooperation in an environment with human dimensions. Its total mass is approximately 70kg.

One of the most important features EMIEW has is its moving agility. Its maximum speed was set to 6km/h (1.7m/s). This speed is as fast as a human walking rapidly. Moreover, its maximum acceleration and deceleration was set to 4m/s^2 for quick starts, and safe, fast stops. Its maximum permissible centrifugal acceleration in turning was also set to 4m/s^2. Under these conditions, it is able to turn small curves whose minimum radius is approximately 0.5m at a maximum speed of 6km/h.

Another important feature EMIEW has is its capability to move safely. It is able to avoid collisions with people walking around it at a maximum speed of 6km/h. It always searches for people in front of it, and modifies its moving trajectory to avoid collisions based on the locations of people found.

Table 1. EMIEW specifications.

Height	1.3 m
Mass	Approx. 70 kg
Moving agility	・Max. speed: 6 km/h (1.7 m/s) ・Max. acceleration: 4 m/s^2 ・Min. turning radius: 0.5 m (at 6 km/h)
Safety capabilities	Avoids collisions with people walking around it
Communication capabilities	・Distant-speech dialog without user microphone: Approx. 1 m away ・Detects sound direction from 360 degrees around robot ・High-quality synthetic voice
	Nonverbal communication by manipulators and body motion ・Manipulator: 6 D.O.F. ・Hand: 1 D.O.F. ・Head: 2 D.O.F.

The last important feature EMIEW has is its capability to communicate with humans. It uses two methods, and the main one is voice conversation. A natural dialog without special tools is required for smooth and friendly conversation. By means of a method to suppress noise in distant-speech, EMIEW talks with anyone who is not holding a microphone from a distance of up to approximately one meter. Furthermore, it is able to detect the direction of sound omni-directionally from 360° around it, to detect the first utterance, and to start a dialog automatically. EMIEW also has a high-quality speech synthesizer that enables fluent and smooth conversation. The second method is sub-communication, which is nonverbal communication using manipulators and body motion. EMIEW has two manipulators with five fingers that are able to copy human arm motions. It is able to express friendly feelings just like humans do using whole body actions, manipulator motion, and its high-quality synthetic voice.

3.2. Construction of EMIEW

There is an overview of EMIEW in **Fig.2**.

(1) Nimble mobility system:

The robot has a self-balancing two-wheeled mobility system controlled by an inverted pendulum control algorithm. One reason we selected this system was because it conformed to human-symbiotic environments. Another reason was because it had both stability and agility during movement. We considered that the footprint of a robot working in human-symbiotic environments had to be compact so that it did not interfere with humans and avoided collisions. However, reducing the footprint of the robot would increase the height for the center of gravity because the robot's body volume had to be fixed to guarantee the necessary functions. However, robots with a high center of gravity are generally unstable during quick

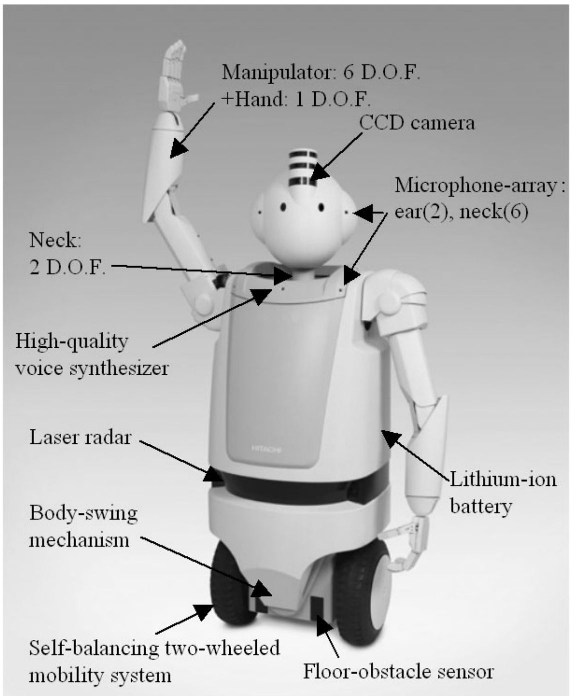


Fig. 2. Overview of EMIEW.

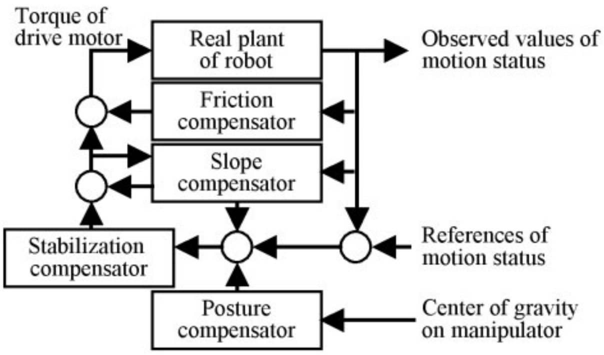


Fig. 3. Block diagram of self-balancing two-wheeled mobility control.

motion. A solution was found in adopting a self-balancing two-wheeled mobility system. This always maintained the posture of the upright robot thereby ensuring stability. Another advantage of this system is that the stability in motion is robust to unexpected destabilization, such as humans pushing the robot, due to dynamic balancing control. With this system, the robot quickly accelerates and decelerates by changing its optimum posture.

The mobility mechanism has two drive wheels with a diameter of 300mm. Two wheel-drive motors are mounted in the chassis with highly precise planetary gears to drive the wheels. And a vertical gyro sensor used to control the posture of the mobility mechanism is mounted on the wheel drive mechanism.

The position, velocity and posture of the robot are controlled by a system using feedback and feedforward control [5] shown in **Fig.3**. A friction compensator uses

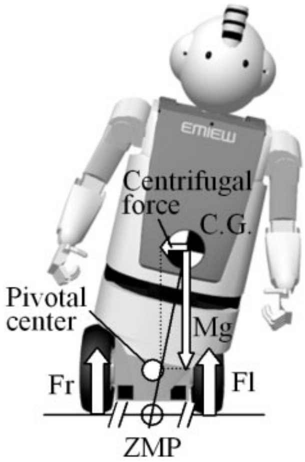


Fig. 4. Concept of body swing control.

a friction model to suppresses instability caused by the friction of the wheel-drive gears, a slope compensator estimates slope inclination and generates optimum bias torque to maintain the position of the robot, and a posture compensator suppresses the position deviation of the robot caused by movement of a center of gravity of the manipulators. The main feedback unit is a stabilization compensator that uses a Linear Quadratic Regulator (LQR) to suppress vibration caused by noise of the sensors and backlash of the wheel-drive gears.

The mobility system has another unique capability with a body swing mechanism that shifts the robot's center of gravity to the right or the left. This mechanism controls the position of the center of gravity according to the acceleration that acts on the robot when it turns. The concept of the body swing control is shown in **Fig.4**. The maximum range of body swing is 25°, and the pivotal center of the body swing mechanism is adjusted to match the centers of the drive wheels. With this control, a zero moment point (ZMP) projected onto the ground is kept midway between the two drive wheels, and the contact forces of the right and left wheels are kept equal. The lateral posture balance is thus kept stable, and the wheel-slip-free condition important to guarantee the stability of the inverted pendulum control becomes optimum. The robot can therefore turn quickly and stably.

(2) Collision avoidance and navigation control system

The robot has collision-avoidance capabilities for moving safely through complex environments. The main sensor for avoiding collisions is a laser-radar mounted on the front, and it detects obstacles in the front of the robot. The range of the laser-radar is 8m and the scanning range is 180°. The robot avoids moving obstacles (including walking people) by using the algorithm shown in **Fig.5**. The left figure shows a motion of the robot and an obstacle on world coordinates, and the right figure shows their relative motion on robot coordinates. When the robot finds moving obstacles, it evaluates possibility of collision based on relative trajectories between the robot and obstacles.

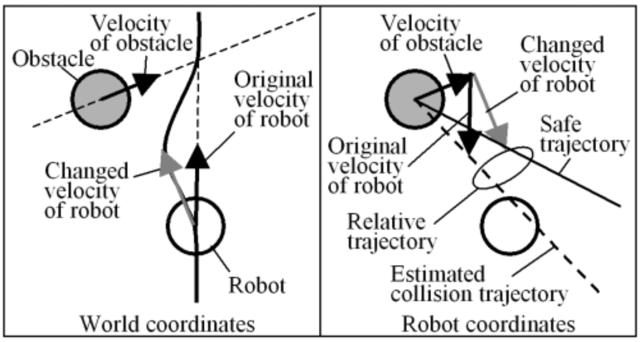


Fig. 5. Collision-avoidance algorithm.

If the robot predicts their collision, it changes direction of the velocity until it finds a safe trajectory. The robot generates a new collision-avoiding trajectory by repeating this process. In this development, the time required for generating a new trajectory was about 100ms.

In addition, the robot has floor obstacle sensors at the bottom of the mobility mechanism for sub-sensing obstacles. These are infrared proximity sensors that detect low obstacles on the floor that cannot be detected by the laser-radar.

Navigation is controlled by using odometry control based on the rotational data obtained from the wheel-drive motors and on the yaw-rate data detected by the vertical gyro sensor. The estimated position and direction of the robot that includes the accumulated error is calibrated based on the absolute position of the robot that is measured by the laser-radar with using cylindrical landmarks set in a mobile environment.

(3) Communication system

The robot has a microphone-array system constructed with two microphones mounted in its ears and six microphones mounted on its neck to identify the three-dimensional position of a sound source. The listening field is focused on the vocal direction, and ambient noise is suppressed by the processing flow [6] shown in **Fig.6**. Each sound signal detected by the microphone-array is segmented into frequency domain elements by multi channel frequency analysis processing. Sound source localization processing classifies the frequency domain elements into some sound direction categories. Sound source separation processing filters out noise by reproducing a sound signal from a frequency domain element belongs to a target sound direction category that does not include noise signal. Finally, words are recognized by speech-recognition processing using the filtered sound signal. An example of filtering effect of sound source separation is shown in **Fig.7**. In this case, noise signals from two directions are suppressed well.

Furthermore, when the robot finds a face with its head-mounted CCD camera facing the vocal direction, it recognizes the sound source as a human being. It can also distinguish machine sounds such as those made by audio instruments. It can recognize the voice of any person

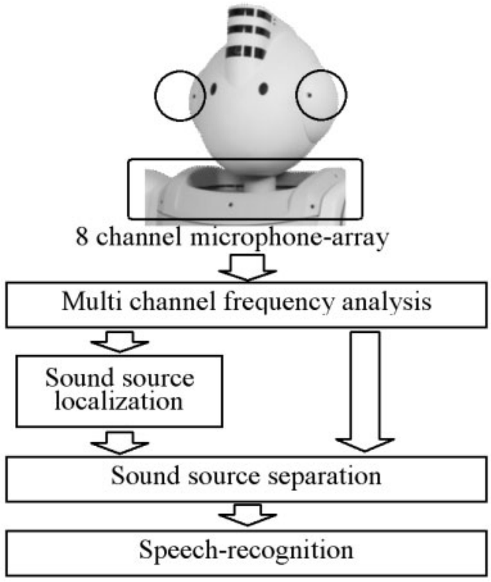


Fig. 6. Processing flow of speech-recognition.

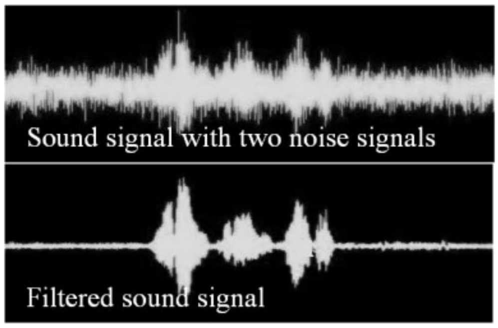


Fig. 7. Example of sound source separation.

from a distance of up to 1m. Its own voice is generated by a speech-synthesizer and sounds as natural as a human voice. The robot has two manipulators (6 D.O.F.) with five fingers (1 D.O.F.). The motion of the manipulators, the head (2 D.O.F.), and the body swing mechanism are used for nonverbal communication. The robot can have a smoothly flowing conversation with humans through these technologies.

4. Control System

The construction of EMIEW's control system is described in this section.

4.1. Hardware for Control System

There is a block diagram of EMIEW's control system in **Fig.8**. It has a hierarchical structure and the main controller is at the top. Subsystems controlled by the main controller are a communication controller used as a human-interface, a mobility system controller and a manipulator controller, in which the last two are mechanism

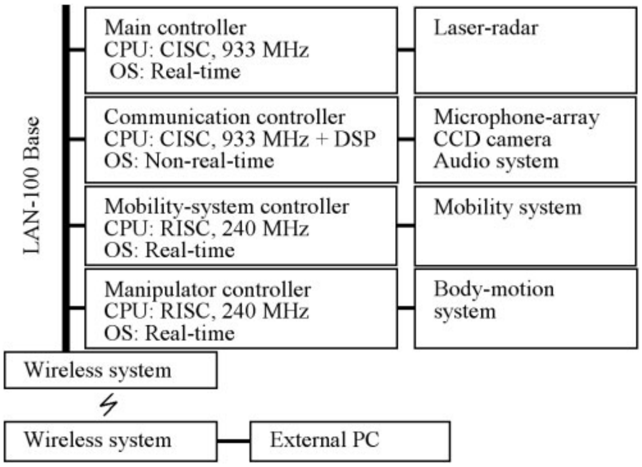


Fig. 8. Control system of EMIEW.

control devices. In addition, the system has a wireless system for communicating with external PCs. The main controller and the subsystems connect with one another through a 100-base LAN. As shown in **Fig.8**, real-time operating systems are used in the main controller, the mobility system controller, and the manipulator controller to totally control the motion of the robot. In this development, sampling time of a total control with adopting the LAN network was approximately 50ms. The communication controller has a DSP unit that was developed for high-speed signal processing of the frequency analysis and the sound source localization. Basically, most actions of the robot are based on autonomous control and an external PC is used for monitoring its status and emergency stops.

Moreover, EMIEW's energy source is a lithium-ion battery. The capacity of the battery is 830Wh and its duration is about 40 min with continued mobile operation.

4.2. Software for Control System

The main controller and the subsystems have their own special software modules. **Fig.9** outlines the software modules for all the hardware and their relationships. A scenario-control module, a motion-planning module, and an environment-recognition module are embedded in the main controller. A dialog-control, a speech-recognition, and a facial-recognition module, as well as a voice-synthesizer module are embedded in the communication controller. Moreover, a mobility-control module and a manipulator-control module are embedded in the mobility-system controller and the manipulator controller, respectively.

The scenario-control module in the main controller controls the subsystems according to an event-driven job scenario that changes the job flow in response to action requests and execution status sent from the subsystems. Application contents of the robot are described in the job scenario.

The motion-planning module is controlled directly by the scenario-control module. It controls the motion of all robot systems in real time and the dialog-control module that processes whole human-interface jobs.

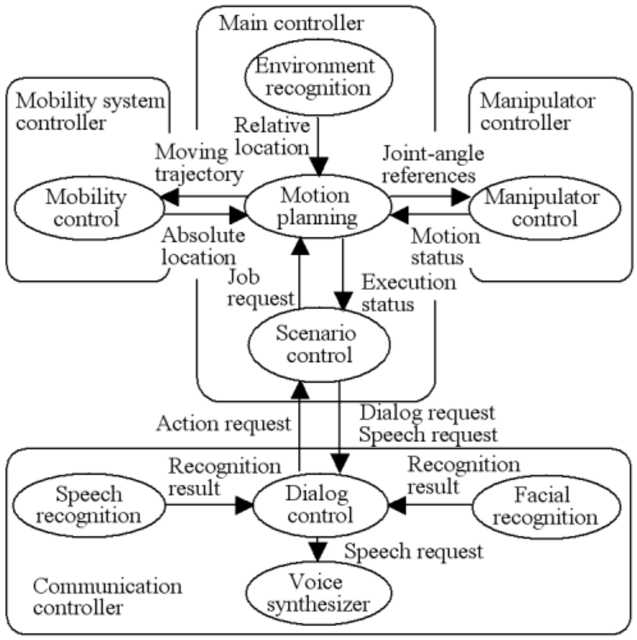
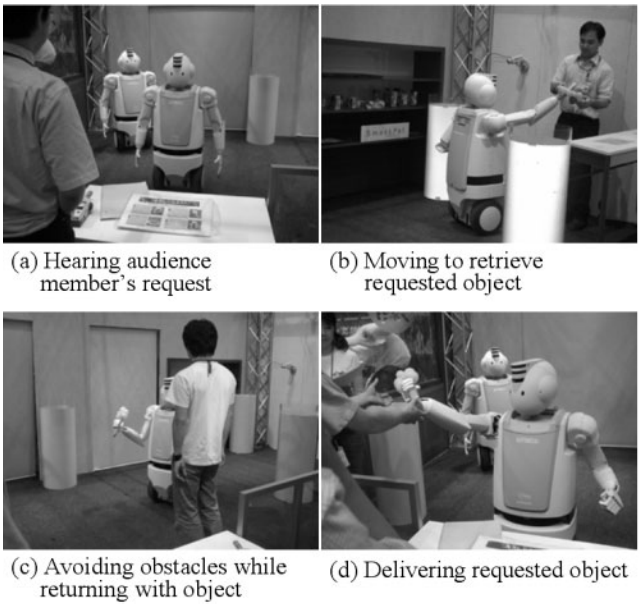


Fig. 9. Relation of software modules.

The environment-recognition module obtains scanning data from the laser-radar and estimates the location of obstacles such as moving people or walls as well as the location of landmarks used to calibrate the robot location.

The mobility-control module controls the two-wheeled mobility system and the body-swing mechanism. It estimates the absolute location of the robot from odometry data calculated from the data of the gyro sensor and the rotation of the two wheels, and it sends the estimated result to the motion-planning module.

The motion-planning module generates a moving trajectory based on data on the relative location of the obstacles and the landmarks provided by the environment-recognition module and the data on the absolute location of the robot provided by the mobility-control module. The moving trajectory is sent to the mobility-control module as a job request. Through these processes, the motion-planning module calibrates the location of the robot, and navigates the robot to the goal according to the moving trajectory, and executes collision-avoidance control. The motion-planning module has a database that stores numerous motion patterns for the mobility mechanism, manipulator, and head-drive mechanism. These patterns were created by the motion editor to synchronize the motions of all the mechanisms of the robot. The motion-planning module selects a motion pattern from the database, according to the request made by the scenario-control module, and delivers the moving trajectory to the mobility-control module and joint-angle reference data to the manipulator-control module at the same time. Through this process, the robot can perform whole body motions as well as move.



(a) Hearing audience member's request
(b) Moving to retrieve requested object
(c) Avoiding obstacles while returning with object
(d) Delivering requested object

Fig. 10. Demonstrating EMIEW's capabilities at EXPO 2005 AICHI JAPAN.

The dialog-control module processes information from dialogs with humans. It has the following functions:

a) Distant-speech recognition based on signals from the microphone-array,
b) Facial recognition through the CCD camera,
c) Speaker-identification processing based on facial and distant-speech recognition,
d) Dialog generation based on the results of the processing above and various dialog rules, and
e) High-quality voice synthesis.

The speech-recognition and facial recognition modules execute the distant-speech recognition and the facial recognition, the dialog-control module executes the speaker-identification and dialog generation, and the voice-synthesizer module executes high-quality voice synthesis.

The communication controller has two processing modes. The first is a dialog mode and the second is a command mode. The dialog-control module in the dialog mode selects a dialog rule stored in the dialog database according to a request made by the scenario-control module. If vocal key words are recognized, the dialog-control module requests the voice-synthesizer module for a reply through speech corresponding to the vocal key word. In place of speech, the dialog-control module may request a reply through body motion. Simple verbal or nonverbal communication with humans can be carried out through these processes. In the command mode, on the other hand, the dialog control module requests the voice-synthesizer module for speech that corresponds to the words selected by the scenario-control module.

5. Demonstrating Capabilities

EMIEW was on exhibit, and demonstrated at the Morizo and Kiccoro Exhibition Center from the 9th to the 19th of June at the 2005 World Exposition, Aichi, Japan (EXPO 2005 AICHI JAPAN). This demonstration was supported by the New Energy and Industrial Technology Development Organization (NEDO).

A purpose of this demonstration was verification of the basic functions of EMIEW.

Some scenarios used to demonstrate the basic capabilities of EMIEW are shown in **Fig.10**. The concept behind the demonstration was for the "robot coffee waiter" to deliver an object. Each action of EMIEW was based on programmed scenarios and was triggered by voice commands of audience members and the demonstration staffs.

The situation in **Fig.10(a)** was listening to a request being made by a member of the audience. EMIEW exhibited its excellent capability for distant-speech recognition in this demonstration. Even in a noisy environment, it was able to recognize voices from audience of a wide generation. The average ambient noise level of the demonstration area was approximately 70dB, and EMIEW was able to recognize voice commands from a distance of up to approximately 4m.

The situation in **Fig.10(b)** was moving to retrieve the requested object, and the situation in **Fig.10(c)** demonstrates the collision-avoidance function. The purpose of these demonstrations was verification of the EMIEW's mobility functions. The dimensions of the demonstration space were 3.5 by 6m. And five white cylinders with a diameter of 0.4m set in each corner of the space were laser-radar landmarks used for localization of EMIEW. EMIEW moved toward a staff member at 6km/h and returned to the audience while avoiding a disturbance created by another staff member in this condition. The running posture of EMIEW was kept stably and the turning motion was kept smooth by the body swing motion. The real-time collision avoidance control functioned for human interrupt safely. The navigation control's positioning accuracy was approximately 100mm and direction accuracy was approximately 1°.

The situation in **Fig.10(d)** is EMIEW delivering the object to the audience. It handed the object to a third staff member, and in this demonstration the manipulator control was based on programmed scenarios.

6. Summary

We developed a human-symbiotic robot called "EMIEW". It is able to nimbly and safely move as fast as humans, talk with them while maintaining a natural distance, and act in a very friendly manner. These capabilities were demonstrated and verified at EXPO 2005 AICHI JAPAN.

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