1. Introduction

Since olden times, one of man's dreams has been to have a substitute which can undertake for him those jobs which are dangerous, difficult, or boring. In ancient times, this dream was realized by utilizing animals, and, unfortunately, by using his fellow men as slaves, which in some countries continued until as recently as one hundred years ago.

With the advent of electronics and progress of automation technology in recent years, it has become possible to let automated machinery replace man's labor. Robots, as the only tolerable slave from a humanitarian point of view, are expected to assume much of man's work. The "Human Use of Human Beings"[1] of N. Wiener will be truly realized only when man makes robots to replace man's dangerous, difficult, and boring tasks, marking an important achievement in the development and safety of our modern society.

The rapid development of microprocessors and semiconductive sensors has made a great impact on the intelligent industrial robot. The development of such sensors and processors, as well as the techniques utilizing them, is crucial to the advancement of the robot.

The fields to which robots can be applied are not limited to just manufacturing (secondary industry), but instead have been gradually expanding to include mining, civil engineering, and construction (also secondary industry), as well as to agriculture, forestry, and fisheries (primary industry). Robots can also be utilized in the tertiary industry areas of retailing, wholesaling, finance, insurance, real estate, warehousing, transportation, communication, nuclear power, space, ocean development, medical treatment, welfare, sanitation, disaster rescue, recreation, and household use.

With the advancement of robotics, the relationship between man and robot is becoming more and more important. This relationship is called the man-machine interface, the human interface, or man-machine communications, with slight distinctions among these terms. This is one of the most undeveloped areas of robot technology, despite being one of the most important.

In this paper, robots are classified into three generations. Technical concerns are discussed with regard to both second generation robotics, which is now coming into general use, and third generation robotics, the research and development of which has just started.

Human robot systems approach plays an important role in third generation robotics. Research and development of robotics for the augmentation of human ability and for human rehabilitation purposes will be extensively discussed in this paper.

2. Toward the Third Generation Robot

2-1. From the First Generation to the Second

With the rapid progress of science and technology after World War II, the robot, which previously had been only a dream, had begun to assume some of man's and animal's functions, despite its different shape. Versatran and Unimate, which in 1962 were the first robots made commercially available, were introduced in Japan in 1967. They are called industrial robots and can be said to be the first generation of robots finding practical use. This is considered to have resulted from a combination of two large areas of development after the war. The first area was the hardware configuration and control technology for an operational type mechanical hand (or manipulator), which had been under research and development for use in the hot (radioactive) cell of a nuclear reactor [2],and the second was the automation technology for automated machinery or NC machine tools, which resulted from the advance of electronics and control technologies. The term "industrial robot" is said to have originated under the title of "Programmed Article Transfer" which G.C.Devol applied for registration in 1954 and which was registered in 1961 in the United States. It has come to be used widely since the American Mental Market, a U.S. journal, used the expression in 1960. After passing through infancy in the latter half of the 1960s, the industrial robot reached the age of practical use in the 1970s. The Japanese government decided to promote the development of robotics through four measures. Namely, the establishment of a lease system using government funds, a special depreciation system for major equipment systems, a special loan system for industrial safety facilities, and a loan and lease system for the modernization of equipment in small and medium-size enterprises. Thus, with a rapid increase in demand, the robot entered the age of widespread usage due to economical feasibility. That is why 1980 is called "the first year of the prevalence of the industrial robot"[3].

From the technical point of view, however, the first generation robot which has found wide use is a kind of repetition machine which plays back repeatedly the positions and postures learned through a teaching process prior to commencement of operation. In essence, it is a composite system of technology based on the control techniques for various automated machines and NC machine tools and on the design and control techniques of manipulators with multiple degrees of freedom. The application of this type of robot, naturally, is limited. These robots can be most effectively used in manufacturing processes in secondary industry, especially in material handling, painting, spot welding, etc.

In other areas, such as arc welding and assembling, it is necessary for the robot to vary its actions and also to acquire information about the external environment, as well as about its internal status. First generation robots commonly monitored only their internal status. The device that can change its actions according to the existing situation, which has been monitored through sensors, is the so-called second generation adaptive robot. It came to be practical gradually in the 1970s. Since the available sensors for obtaining exterior information are limited, they can be used effectively only in very limited areas of the production site. The visual sensor is important, but at present robots are at a stage at which they can identify mainly one- or two-dimensional binary patterns under controlled illumination conditions[4]. For application in primary and tertiary industries, it is important to process visual information for recognizing three-dimensional objects in the natural environment where light conditions change frequently. This has remained an important subject of interest for the coming third generation robotics.

2-2. Movement Toward Third Generation Robotics[5]

When considering the situation where a robot operates in compliance with man's instructions, one can easily understand the following three points which are vital to the operation of a robot:

1) To understand man's instructions appropriately, to communicate its condition to man, and to obtain new knowledge, instructions, and teaching from man (communication between man and robot).
2) To know the external environment, especially conditions of the object of work (recognition of its external world).
3) To determine its own internal conditions, e.g., joint angles of its links (recognition of its internal world).

Since 3) is comparatively easy to achieve, as it is the basis of servosystems, it has been accomplished by various automated machinery or first generation robots. Main technical problems to be solved for the second generation adaptive robot are sensory perception of the external environment and the appropriate change of its action according to the external information acquired. The second generation robot is approaching the stage of practical use. This is directly related to the development of sensors and microcomputers in recent years. Visual and tactile senses are most important. They have been practically used for the wire bonding of semiconductors, for assembly in various fields, and as visual inspection machines.

The first generation robot has been related to internal sensors and servotechnology, and the second generation with external sensors and microprocessor system technologies. Then what is the main technology for the third generation robot? Though no consensus has yet been reached among researchers, the extension of the function of item 2) above to a three-dimensional natural environment and the establishment of the communication functions of item 1) can be considered important issues. The author's classification is in Fig.1.

Communications in the first and second generations are of a one-way nature, from man to machine. For example, when a robot inserts a bar into a specified hole after receiving instructions through voice input, first the robot is required to understand the meaning of the work. Even if man instructs the robot simply saying "Insert this bar in that hole," the robot cannot follow such instructions. So, it is necessary to give instructions by dividing them into small steps so that the robot can perform them. Also, since no voice is used for the first generation robot, the hand positions and postures of the robot are taught in detail by manually positioning it in its various configurations. The labor and time required for this process becomes especially great when the number of robots is increased. In the second generation, some simplification of the teaching steps is made by using robot language and an interactive system, but still the communication system is at an initial, developing stage. In the third generation, communications between robot and man should be made much more similar to that between humans. For this purpose, speech recognition, natural language understanding, question and answer system, and knowledge data base system technology should be established.

The relationship between robot and man in the third generation can be more easily understood when it is compared with the relationship between a superior and a subordinate in human society. That is, a robot, which is the subordinate, receives instructions from its superior. When it cannot understand the meaning, it will ask questions of its superior until it can fully understand (question and answer system). The robot starts working when it understands the instructions. At that time, the robot performs an operation using a manual containing knowledge on the operation obtained by other workers in the past (knowledge data base). When some matter which the robot cannnot solve using its own knowledge and judgement occurs during operation, it will consult with its superior (interaction). Checking robot conditions, the superior will then make the appropriate judgement under the circumstances which the robot will follow. When the superior finds that the subordinate or robot cannot solve a certain problem, he solves the problem himself. If the robot is working in a remote area, or in a dangerous or severe environment not easily reached by man, the robot is operated as if a human worker were in that same location, thereby easily indentifying and resolving difficulties which may arise (tele-existence)[6]. In the case of joint operation of robots, the allocation of work, and cooperation and communication between them, are also important.

In addition, it is clear from the operational standpoint there remain many important matters to be solved regarding both manipulation and locomotion for the third generation robotics. Particularly when we consider the use of the robot in primary and tertiary industries, the robot itself should have its own built-in energy source, be mobile, and have a certain level of knowledge. The three ideal requirements for a robot, which were proposed more than ten years ago[7] - that the robot be autonomous, independent, and mobile - could be provided for the first time for a practical-purpose robot in the third generation robotics.

3.Human-Robot System

There have been many discussions on what is meant by the intelligence of a robot, and so far, no consensus has been reached. And I do not suppose intelligence will be clearly defined even in the future.

Knowledge and intelligence are similar, but they are quite different in nature. It is possible to substitute knowledge for intelligence. For example, in a certain situation in shogi (Japanese chess), let us suppose that the next move, which may be said to be the best of all moves to be taken, is being considered. If it is determined only through the consideration of the possible movement of pieces, it is truly the action of very high intelligence. If, however, the same configuration of shogi pieces had been encountered before, it is possible to make the same move through the recall of set tactics, i.e., knowledge only. In this case, intelligence is not required. However, no difference in intelligence between the two cases can be seen since the chosen move is the same for both.

Machine is superior to man in remembering accurate knowledge, and it is very effective to substitute knowledge for intelligence. It is especially effective when a machine is used in an environment such as a factory. Since it was originally designed by man, the knowledge about that environment is abundant.

However, this kind of approach is not as effective in a natural environment, knowledge of which is quite limited. In this case, the most effective approach is the man-robot system which utilizes both high-level knowledge stored in the machine and man's intelligence. Then such work, which cannot be done only by man or by machine, can be performed through a combination of man and robot. The importance of technology which integrates man and machine effectively will increase more and more in the future.

4. A Human-Robot System for the Augumentation of Human Ability (TELE-EXISTENCE)

Figure 2 illustrates an example of a system of robots and human operator proposed by the author's research group[5]. Each independent, mobile, intelligent robot takes on part of the overall work and operates in conjunction with the others in a severe environment. Instructions are given to the robots by a human operator stationed in a control module. A supervisory controller takes charge of the allocation of work, as well as planning and scheduling, and the intelligent robots send it reports concerning work progress. Such information is organized at the supervisory controller and is then transmitted to the operator by voice or by visual or tactile information. If the operator instructs in a language similar to natural language, these instructions are transmitted to the respective robots through speech recognition equipment and the supervisory controller. The respective robots recognize the task description and carry it out using their own intelligence and knowledge. The information in the robots' intelligence system is an important source for their operation and can be monitored by the operator at any time.

Also, safety is checked at three levels - by the intelligent robot itself, by the supervisory controller, and by the operator - and has thus been greatly improved.

When an intelligent robot encounters difficult work which it cannot handle by its own ability, the operation mode of the robot is switched to remote control mode either by the robot's own request or by the judgement of the operator. At that time, instead of a conventional remote control system, an advanced type of teleoperation system, called tele-existence,is used. This enables the operator to control the robot as if he were inside the robot. In this case, each subsystem of the intelligent robot works like a slave-type robot which is directly and accurately controlled by the operator.

In the tele-existence system, the operator's body movement and force conditions are measured in real time, and the internal conditions of the operator are estimated. These conditions are transmitted to the robot and control directly the motion control circuit of the robot. (In the figure, the third robot is controlled by the tele-existence mode, and the thick lines show the flow of information between man and robot.) The robot controls its artificial eyes, neck, hands, and legs, faithfully reproducing man's motions. At this time, all information from the artificial sense organs of the robot is transmitted to the corresponding sense organ of man by a high fidelity display system with the sensation of presence. For example, if the operator looks to some direction intentionally, the robot also turns its face to the same direction and displays the image corresponding to the view which the man would see were he in the location of the robot. When the operator brings his arm before his eyes, the robot's arm will also take the same position in the visual field. Therefore, knowing the relation of his arm to the object and surrounding space, the operator can proceed with his work relying only on normal, basic skills rather than on control system specific ones. The sense that a robot has when it touches an object is presented to the operator's hand as a stimulus to his skin, and the operator can perform his work having the sense that he touched it himself. Therefore, the skill with which the operator controls the robot and completes the task can be increased to a level equal to that of a man working inside the robot, and, ideally, to that of a man performing the work directly (See Fig. 3).

The operator can also utilize the robot's sensor information about radiation, ultraviolet rays, infrared rays, microwaves, ultrasonic, and very low frequency waves (which are called super sense information). For example, at night infrared sensor information is converted to visible light to see an object in the dark. Or, ultrasonic information can be converted to audio frequency to obtain sound information which is not available under normal conditions. It is also possible to superimpose super sense information on a conventional visual display and/or convey information through cutaneous sensation[8]. The operator can effectively use this information to expand man's ability. If we can increase the maneuverability of a robot's arms so as to control them like our own arms, we can handle objects which are beyond our control under normal conditions. Thus, a human augmentation system can be realized.

If the knowledge base inside the control module can be utilized through a method of easy accessibility, for example, MIT's Media Room[9], the operator's command can be carried out more accurately. In addition to using the knowledge as a supplement to man's memory and decision making, it is also an interesting use to modify the movement of the operator to that of a skilled worker.

These system technologies are basic technologies having various application possibilities for work in critical and severe environments in factories, plants, and industrial complexes; inspection, repair, dangerous work, and treatment of radioactive waste in nuclear power plants; search, repair, and assembly work in space or the ocean; search and rescue operations, disaster relief, sanitation, construction, civil engineering, forestry and fisheries, law enforcement, exploration, recreation, flight or automobile testing, etc.

In order to make the systems mentioned above realizable, the following subjects for research and development are crucial:

1) Measurement or estimation of motion and conditions of a human operator.
2) Mechanism and control of an anthropomorphic robot.
3) External information detection by artificial sense

organs.
4) Display of information with sensation of presence.
5) Master assisting knowledge base.
6) Augmentation of human ability.
7) Recognition technology for intelligent robots.
8) Decision technology for intelligent robots.
9) Motion control technology for intelligent robots.
10) Maneuverability of intelligent robots.
11) Supervisory control technology[10].
12) Telecommunication.
13) Robot actuators.
14) Robot sensors.
15) Robot material.
16) Safety measures for robots.

Research on items (1) to (6) is being conducted in our division of Mechanical Engineering Laboratory[6,11].

Fig.4 shows the schematic diagram of an experimental system of the visual display with sensation of presence, and Fig.5 shows general views of the experimental hardware system built.

5. A Human-Robot System for the Human Rehabilitation
(Guide Dog Robot: MELDOG)

The author and his colleagues have been working on a Guide Dog Robot project, which is dubbed MELDOG, since fiscal year 1977. This project is a rather fundamental research project to study the control and communication problems of man-machine systems, i.e., (1) how a robot guides itself by using an organized map of the environment and registered landmarks in the environment; (2) how the robot identifies obstacles which are not registered on the map and then avoids them; (3) how the robot informs its blind master about the route and obstacles.

Two main functions of real guide dogs are obedience and intelligent disobedience, which corresponds to guidance of the blind person and obstacle detection, respectively. Also, communication between the blind master and the dog is necessary[12]. In order to achieve these main functions by machines, we have set the following specifications for the guide dog robot:

(1) In principle, the master takes the initiative. The master orders the robot by control switches through a wired link. The robot precedes the master and stops at landmarks which are set at every crossing, waits for the master's next

order (right, left, straight, or stop), and then obeys it. If the master does not know the area and wants full automatic guidance, all he has to do is assign the starting code and the destination code. The robot determines whether there is a route to reach the destination. If more than one route exists, it chooses the optimal route and guides the master accordingly[13] (See Landmark Subsystem of Fig.6).
(2) When the robot detects a dangerous situation on the road, it no longer obeys the master's command but gives him a warning. If the obstacle is moving toward the master, it stops and alerts the moving object and the master. If the obstacle is moving in the same direction but slower than the master, it asks the master to reduce speed to follow the preceding object, which is probably a human traveler. If something is crossing in front of the robot, the robot waits until it passes. If it detects an obstacle which does not move, it tries to determine if it is possible to find space around the obstacle that will permit the safe transport of the master. If space exists, it safely guides the master around the obstacle to the next landmark. If not, it tries to find a new route to the destination without using the undesirable path (See Obstacle Detection System of Fig.6).
(3) In normal travel, the speed of the robot is controlled so that it coincides with that of the master's walk. Thus if the master walks slowly or rapidly, the robot moves accordingly, keeping the distance between them almost constant. As long as the master is considered to be safe by the robot he is not warned, so that he may concentrate on his remaining senses and his own decisions. Only when he fails to detect an obstacle or is out of the safety zones, is he warned by the robot[12] (See Man-Machine Communication Sub-system of Fig.6).

The method for the navigation that enables the necessary function discussed above was proposed and demonstrated by both computer simulation and outdoor experiments using the test hardware called MELDOG MARK II.

The fundamental data base of the robot is a navigation map stored in its auxiliary memory, e.g., cassette tapes, and transferred into its main memory for use. The navigation map consists of information about intersections, i.e., names and types of intersections, distance between successive intersections, and orientations to succeeding intersections. This connection map is represented as a finite state automaton.

The first step the robot must take is to establish its location, which is specified on the map, and correct its position and orientation so that it can travel further. In order to do so, specific landmarks are chosen for each intersection.

In the initial phase (from 1977 to 1982), white painted lines on the streets with a length of about 2m and a width of 0.15m were adopted as the landmarks. These marks had to be set at every crossing at this stage of development. The automaton representation map for the robot could be automatically produced by an off-line computer from an ordinary map using picture processing techniques. Landmark laying instructions which would be used to place the landmarks on the streets could be provided at the same time. At the second stage (from 1983 to the present), preregistered natural landmarks such as poles and walls are being used as markers for the correction of the robot's position and orientation. However, the navigation method is fundamentally the same[14].

It is necessary for the robot to find various kinds of obstacles such as objects which block its path, objects which move toward the master and the robot, human travelers who are walking in front of the robot, as well as steps, street curbs, overhanging objects like awnings, etc.

Some of the obstacle detection and avoidance functions were considered theoretically and the feasibility of the method was demonstrated by the test hardware MELDOG MARK III. The robot measures the distance between an object encountered from 0.2 to 3.5m in front of it every 20ms by means of its on-board ultrasonic sensor array. Since the robot knows its own moving velocity, it can calculate the relative velocity of the object. If the relative velocity is positive, i.e., the object is moving away from the master and the robot, the robot continues to travel at the master's walking speed without any warning. If the relative velocity is negative and the absolute value is that of the robot's, i.e., the object is standing still, it stops and tells the master about it. If the absolute value of the measured negative velocity is larger than that of the robot's, i.e., the object is coming toward the master, the robot quickly stops and alerts the object and the master. If the absolute value of the negative velocity is less than that of the robot's, i.e., the object is moving in the same direction, the robot asks the master to slow down and tries to duplicate the speed of the moving object, which is probably a human traveler.

In order to guide a blind person in accordance with the information thus acquired, an information communication channel between the master and the robot must be established[15].

The first effort toward attaining this goal was made to measure the master's position and orientation in real time. We adopted the proposed ultrasonic measurement system called Master Guide, which was evaluated using the test hardware MELDOG MARK I.

It consists of an ultrasonic transmitter which is attached to the belt of the master, two ultrasonic receivers on board the robot, and a flexible wire link, one end of which is a grip with control switches to order the robot to go straight, turn, etc., and which has electrodes for electrocutaneous communication from the robot to the master. The other end is connected to the robot. An ultrasonic trigonometric measurement method is applied to measure the relative location between the master and the robot in order to control the robot's speed to coincide with that of the master's. The result of the triangulation is also used to transmit warning signals from the robot to the master when he is out of the safety zone behind the robot. When the relative orientation of the master is inadequate for the robot to receive the transmitted ultrasonic sound, the master is also warned by the robot to turn his body clockwise or counterclockwise.

Comprehensive experiments were conducted using the test hardware MELDOG MARK IV (Fig. 7). These experiments included obstacle avoidance, use of natural landmarks instead of artificial ones, and human robot communication, especially optimal presentation of the information acquired by the robot to the blind traveler[16].

6. Conclusion

When we consider the state of the robot in the 1980s, we realize that there exist three generations which greatly influence and interact with each other - the first generation of the playback robot with internal sensors, which has already reached the age of prevalence; the second generation, the adaptive robot with external sensors, which has entered the age of practical use; and the third generation, the robot which attaches importance to communication functions, the research and development of which has been started.

Though the application field has mainly been manufacturing in secondary industry,application in other fields, such as construction, civil engineering, and mining, has been investigated. Also, application to primary industry, such as agriculture, forestry and fisheries, and to tertiary industry,such as transportation, distribution, services, medical treatment and welfare, and atomic energy, has been under serious consideration.

Among these applications, great demands have been increasing for such a system to undertake critical and harmful work in very dangerous environments, such as in nuclear, ocean, or disaster areas, which are presently required to be performed by man. The Ministry of International Trade and Industry started an eight-year large-scale project of Advanced Robotics, which is also called "JUPITER" (Juvenescent Pioneering Technology for Robots) in 1983. This is considered to be an important research and development project for the third generation, and the results are anxiously awaited.

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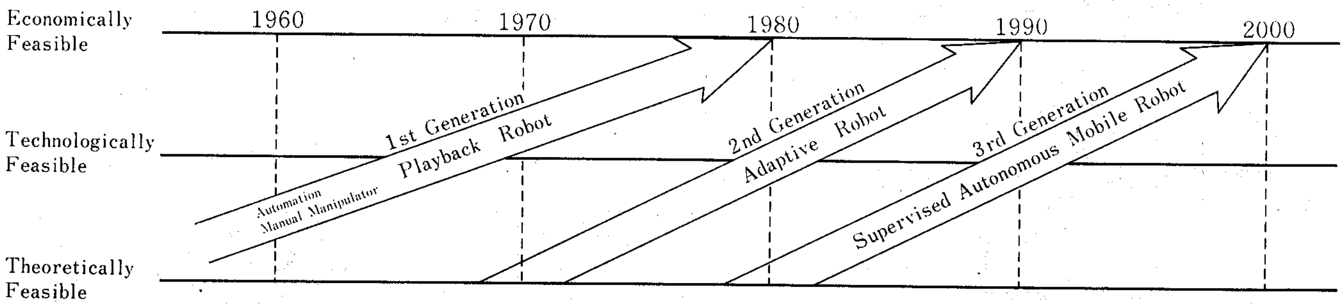

		1st Generation	2nd Generation	3rd Generation
Brain Fnnction	Intelligence	a priori [inborn] (play back)	adaptation, accomodation	a posteriori [acquired] (learning, inference, problem solving)
	Knowledge	data	date base	knowledge base
Sensor Function	Internal Information	exist	exist	exist
	External Information	none or point	1-D, 2-D (structured environment)	3-D (unstructured environment)
	Communication	unilateral (teaching, tape)	interactive (robot language)	bilateral (supervisory control, tele-existence communication between robots, natural language)
Effector Function		position control (static) 1-D (guide cable)	position control (dynamic) 2-D (plane guided)	force control (dynamic) 2-D (uneven autonomous) ;3D (stairs free space)
Application Fields		Secondary Industry (Manufacturing Industry) [Material Handling Painting Spot Welding]	Secondary Industry (Manufacturing Industry) [Arc Welding Assembly]	Secondary Industry (Non-Manufacturing Industry) Primary Industry Tertiary Industry

Fig.1 Generations of Robots and Their Features

EU : Environment Understanding
D : Decision
LP : Language Processing
MC : Motion Control

SIP : Sensory Information Processing
KDB : Knowledge Date Base
SA : Situation Assessment
MU : Mission Understanding

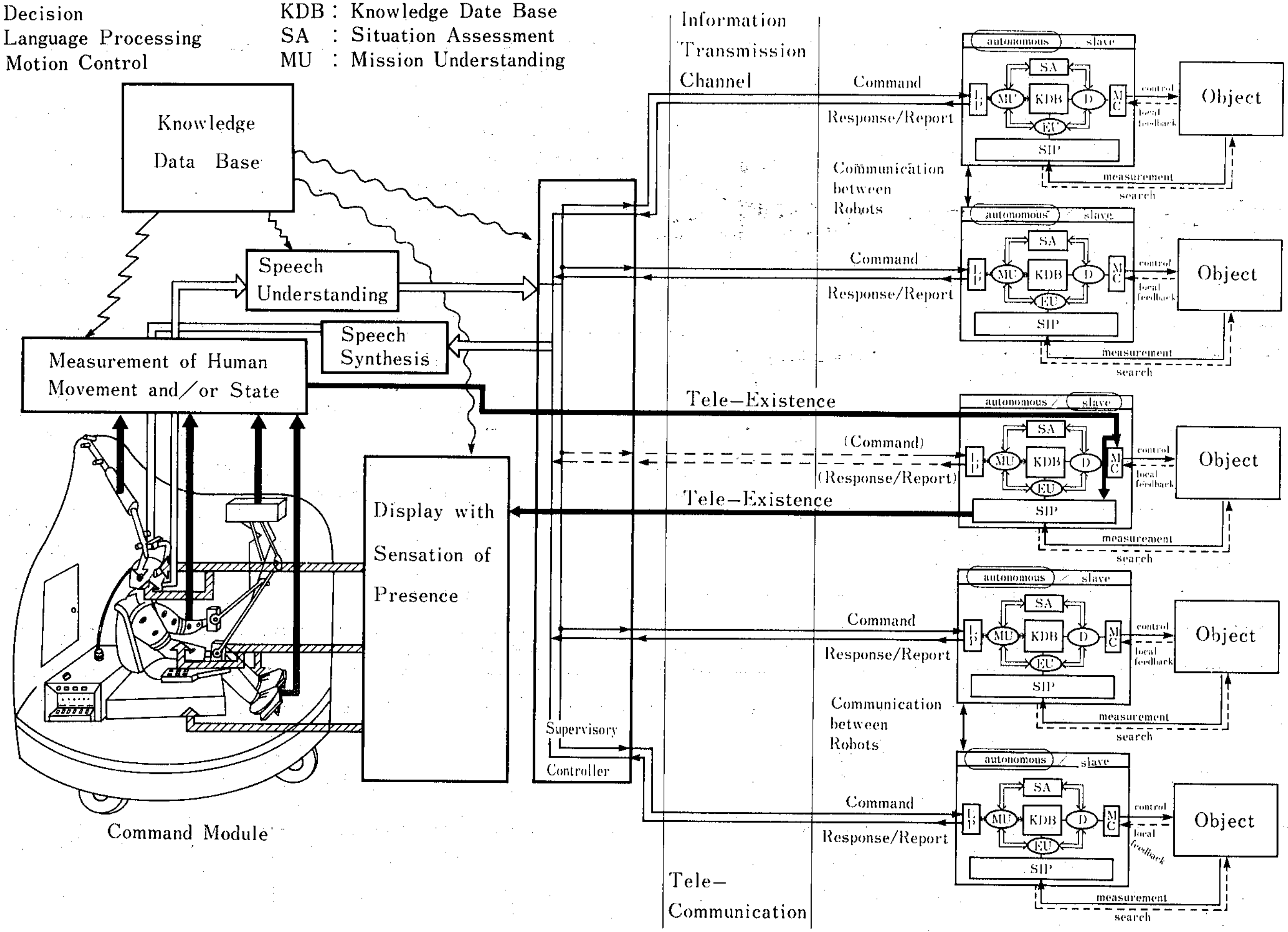

Fig.2 Schematic Diagram of the Human-Robot System Being Studied

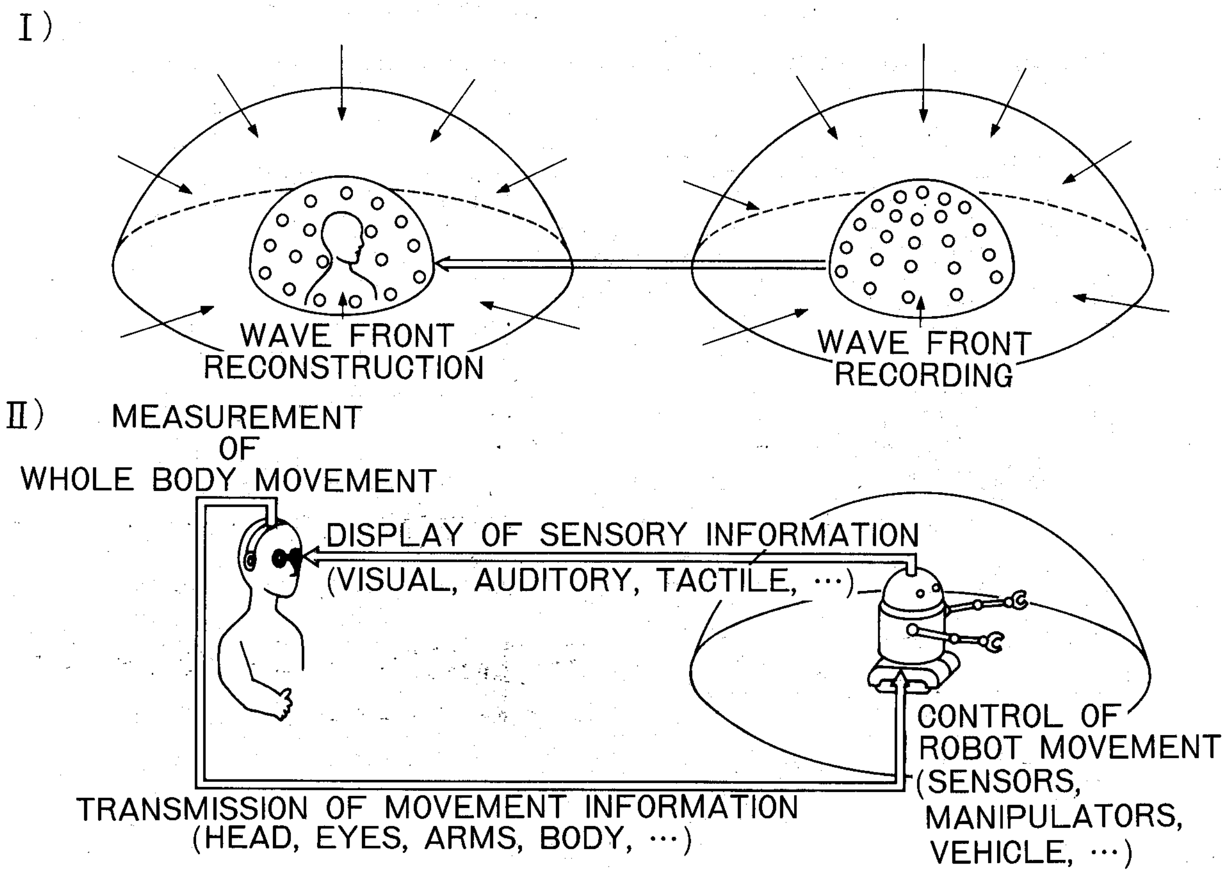

Fig.3 Concept of Wave Front Reconstruction(I) and Teleexistence Display (II)

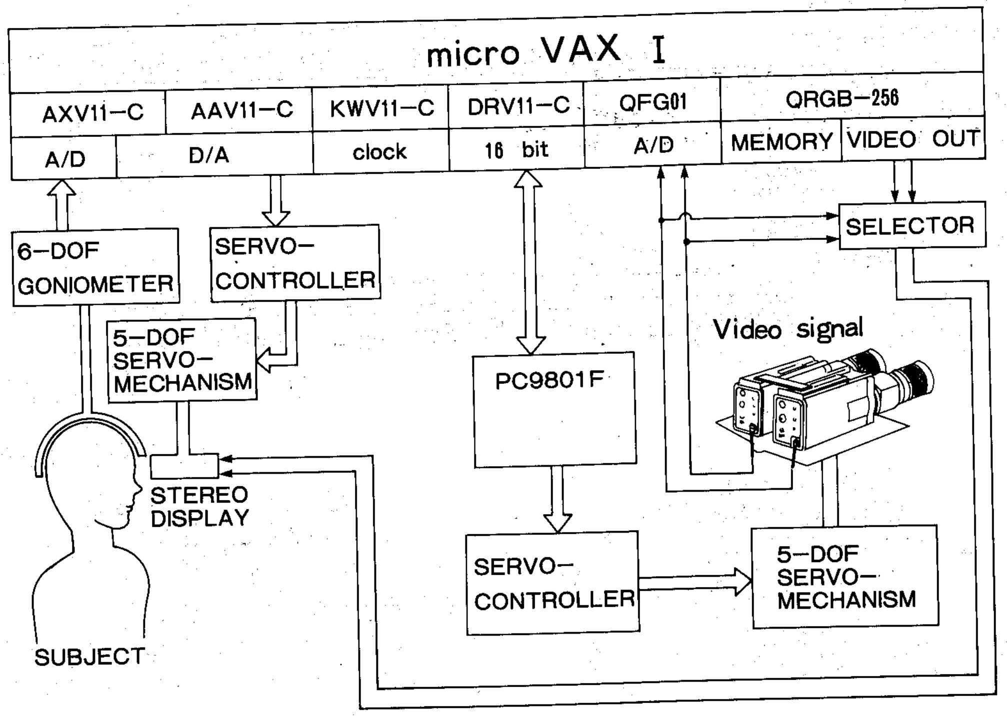

Fig.4 Schematic Diagram of the Experimental Display System with Sensation of Presence

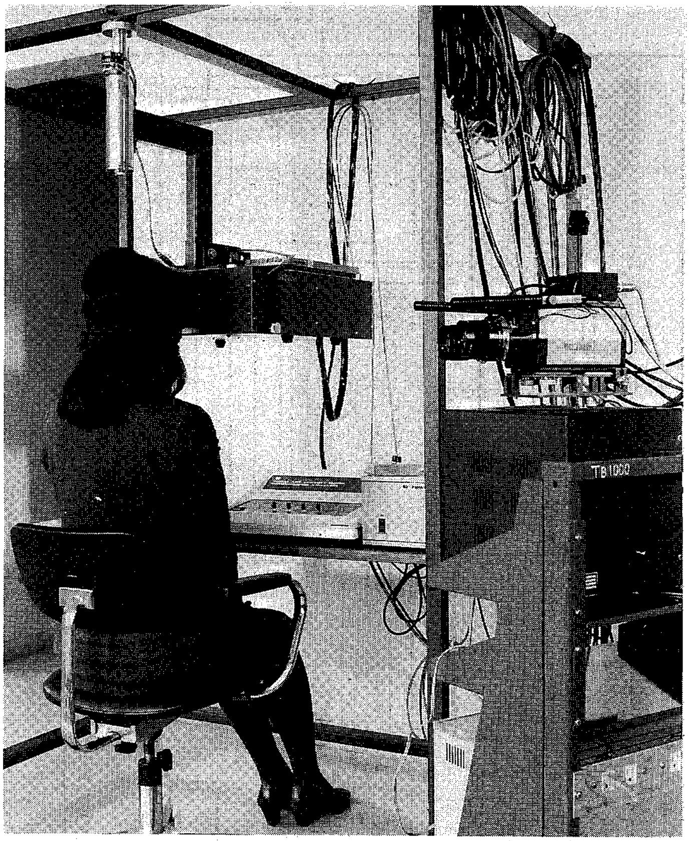

Fig.5 General View of the Experiments with Test Hardware

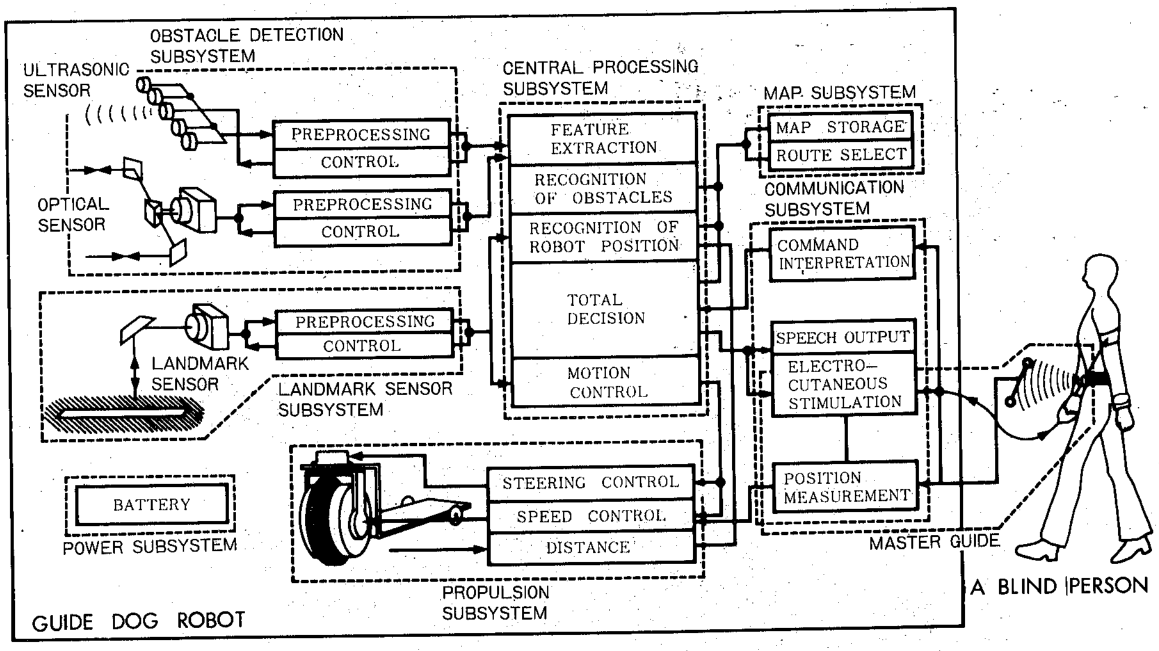

Fig.6 Schematic Diagram of the Guide Dog Robot System (MELDOG)

Fig.7 General View of the Guidance by MELDOG MARK IV