SENSORS AND SENSING SYSTEMS IN ADVANCED ROBOTICS

Susumu Tachi*

Mechanical Engineering Laboratory, MITI
Tsukuba Science City, Ibaraki 305 Japan

ABSTRACT: The present state of sensors and sensing systems in robotics is considered from the standpoint of evolution of robots. Also, the Japanese national robot projects are reviewed with special emphasis on the large scale national project of "Advanced Robot Technology" in hazardous environments. This project is considered to be the key link to the third generation of robotics. Since this project was successfully completed at the end of 1990, plans for the next generation of robotics are now being formulated. Sensors and sensing systems are expected to play an important role in the next generation of robotics.

Evolution of Robots

When we consider the state of the robot in the 1980s and in the beginning of the 1990s, we realize that three generations exist which have greatly influenced and interacted with each other. The first generation, the playback robot with internal sensors, has already reached a state of widespread use and is both technologically and economically practical. The second generation, the adaptive robot with external sensors, has entered a state of technological operability, and is becoming more economically operable. Research and development of the third generation, i.e., supervised autonomous mobile robots, began in the mid-1980s and is now becoming technologically feasible (see Fig. 1).

Though robot applications have mainly been in manufacturing, application, in other fields, such as construction, civil engineering and mining, has been investigated. Applications to primary industry such as agriculture, forestry and fisheries, and to tertiary industry such as transportation, distribution, services, atomic energy, and medical treatment and welfare, are under serious consideration. Among these applications, demand have been increasing for robots to undertake critical and hazardous work in very dangerous environments, such as in nuclear, ocean or disaster areas. Work in these areas is now performed by man.

In 1983, the Japanese Ministry of International Trade and Industry (MITI) started a large scale national project focusing on Advanced Robot Technology. The eight year project is considered to be an important effort for third generation robots, and it was successfully completed in 1990.

Several plans toward the next generation, e.g., space robotics, micro robotics, robots for natural disaster prevention and neurobotics, are being examined.

Advanced Robot Technology in Hazardous Environment

The "Advanced Robot Technology" project is an eight year project which started in 1983. It aims at establishing technologies necessary for the development of advanced robot systems capable of carrying out inspection, maintenance, emergency operations and other highly complex tasks in environments that preclude any direct human intervention because of high radiation levels, high water pressures or high temperatures. Nuclear power plants, undersea operations and fire fighting/ prevention are the three major areas of application, and both generic technologies and application specific technologies are being researched and developed.

The AIST (Agency of Industrial Science and Technology) which belongs to MITI is in charge of planning and coordination of the whole project. The two national laboratories, i.e., MEL (Mechanical Engineering Laboratory) and ETL (Electrotechnical Laboratory) are engaged in generic technologies, while the application specific technologies are being developed at ARTRA(Advanced Robot Technology Research Association), an association of private companies.

Generic technologies being studied at MEL and ETL are as follows:

(1) Legged Locomotion
(2) Dexterous Manipulation
(3) Vision
(4) Autonomous Control
(5) Tele-Existence
(6) Advanced Teleoperation
(7) Simulation

The application oriented research items being conducted at ARTRA are as follows:

A. Nuclear Power Plant Robot

i) Total system for the experimental robot
ii) Optical wireless communication system
iii) Movement (a: Quadruped motion system, b: Actuator, c: Locomotion-on-wall)
iv) Manipulation (a:Manipulator, b: Actuator, c: Tactile sensor)
v) Vision (a:Binocular vision, b:3D vision system using motion stereo and spherical mapping)

B. Undersea Robot

i) Total system for the experimental robot

---

*Present Address: RCAST, The University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153 Japan*

91CH2817-5/91/0000-0601$01.00 © 1991IEEE

ii) Movement (a: Motion control, b: Variable vector propellers, Fiber optic gyroscope, d: Attachment legs)
iii) Manipulation (a: Manipulation system, b: Seawater hydraulic actuators)
iv) Vision (a: Acoustic imaging system, b: Three dimensional position detecting system, c: 3d location measurement)

C. Fire Fighting/Prevention Robot

i) Movement (Six leg/wheel hybrid locomotives)
ii) Manipulation
iii) Middle range laser vision
iv) Short range ultrasonic vision

The aggregate R&D capital investment will amount to approximately \ 15 billion .

The project ended at the end of 1990. In the fy. 1988, interim evaluation was conducted, and most of the basic research for the robots in the three fields (nuclear power plant, undersea and fire fighting) had been finished. In addition, detail design and fabrication of the experimental robots started.

In October, 1989 and in June, 1990, ETL and MEL demonstrated generic technologies of the third generation of robotics, respectively. An experimental nuclear power plant robot and an experimental undersea robot for feasibility studies were constructed by ARTRA. The ARTRA demonstrated the feasibility of the technology in December, 1990.

International Advanced Robot Program (IARP)

At the Versailles Economic Summit in June 1982, it was agreed that further international scientific and technological cooperation would be required for the revitalization and growth of the world economy. In support of this, the "advanced robotics" project was initiated together with 17 other projects. Progress reports on these projects were made at subsequent Economic Summits, and a final report at the summit level was submitted at the Tokyo Economic Summit in May 1986.

In keeping with the original intent of the Economic Summit, the continued pursuit of the "Advanced Robotics" project as the "International Advanced Robot Program" was unanimously approved by all countries attending the 5th Joint Coordinating Forum (JCF) held in Hawaii in April, 1986.

The objective of the program is to encourage development of advanced robotic systems that can perform the work of humans in harsh dangerous environments, and contribute to the revitalization and growth of the world economy.

The activities include holding JCF and workshops, exchange of study missions and researchers, and implementation of joint site studies.

Member countries are Austria, Canada, EC, France, Germany, Italy, Japan, United Kingdom and United States. Japan serves as Secretariat.

The area of international cooperation consists of both application fields and elementary technologies. The former includes nuclear power, underwater operations, fire fighting and rescue operations, agriculture, mining and tunnelling, civil engineering and construction, domestic services, space and medical and health care. The latter includes intelligence, sensors, man-machine systems, manipulation and locomotion.

Intelligent Manufacturing System (IMS)

Changes in today's social environment are giving rise to a number of problems that could threaten the foundation of the manufacturing industry in the advanced industrialized nations. One of these is an outright shortage of skilled workers and technicians. Adding to this, workers are aging and becoming better-educated, and many are leaving the manufacturing industry for jobs in the tertiary sector because of its more attractive working conditions.

In view of this situation, it is urgent to make manufacturing industry a more attractive field to ensure its healthy development in the world economy. Japan decided to take initiative in developing new technologies and sharing the results with other countries, and has proposed the establishment of a joint international research program for developing a manufacturing system aimed at the 21st century for global use.

In the project's initial year, beginning April, 1990, an international Committee, which is made up of leading researchers and experts in the field of production technologies from Japan, North America and Europe, was formed to discuss the details of the project and how best to carry out the program's goals.

The Japanese government has also agreed to participate, and a budget of approximately 110 million yen has been set aside by MITI to cover expenses for the international Committee meetings.

The total budget for ten years is expected to be 150 billion from Japan, the U. S. and Europe.

Human Frontier Science Program (HFSP)

This international program was proposed at the Venice Economic Summit by Japan.It is aimed at promoting, through international cooperation, basic research on biological functions, i.e., the elucidation of brain functions and molecular functions.

The former research includes perception and cognition, movement and behavior, memory and learning, and language and thinking. Although this program does not have any application in mind, the results can be used for the basis of the next generation of robotics.

A. Basic Research for the Elucidation of Brain Functions

A-1. Perception and Cognition
(1) Visual Perception
(2) Non-visual Perception
(3) Multi-modal Perception
(4) Supra-modal Cognition
(5) Cognitive Psychology
(6) Models of Perception and Cognition

A-2. Movement and Behavior
(1) Mechanism of Motor Programing
(2) Cognitive Control of Movement
(3) Adaptive Control of Movement
(4) Innate Behavior
(5) Emotional Behavior
(6) Intellectual Behavior
(7) Functional Molecules in Behavior

A-3. Memory and Learning
(1) Procedural Memory and Skill Learning
(2) Cognitive Memory
(3) Cognitive Learning
(4) Development and Aging of Memory
(5) Development of Learning
(6) Synaptic Mechanism of Memory and Learning
(7) Models of Memory and Learning

A-4. Language and Thinking
(1) Animal Communication
(2) Neuropsychology of Language
(3) Neural Mechanism of Thinking
(4) Attention and Consciousness
(5) Language Learning
(6) Functional Localization of Language and Thinking
(7) Models of Learning and Thinking

Toward the Next Generation of Robotics

The large scale national project toward the third generation of robotics, i.e., "Advanced Robot Technology" program, ended in December, 1990. Since the generic technologies for the robots in hazardous environments has been established, it is high time to step further. We are now planning several robotics programs for the next generation, which include space robotics, micro robotics, sensor fusion and neurobotics.

In the next generation of robotics, learning and artificial reality will be two key technologies (See Fig.1). Advanced sensor and sensing system will be inevitable for the realization of these technologies, especially for the realization of artificial reality and tele-existence [1-9].

Tele-Existence and Artificial Reality

Tele-existence is a concept named for the technology which enables a human being to have a real time sensation of being at the place other than the place where he or she actually is, and is able to interact with the remote and/or virtual environment. He or she can tele-exist in a real world where the robot exists or in a virtual world which a computer generates. It is possible to tele-exist in a combined environment of real and virtual.

It has long been a desire of human beings to project themselves in the remote environment, i.e., to have a sensation of being present or exist in a different place other than the place that they are really exist at the same time.

Another dream has been to amplify human muscle power and sensing capability by using machines while reserving human dexterity with a sensation of direct operation. In the late 1960s research and development program was planned on a powered exoskeleton that a man would wear as a garment, typical example of which was the Hardiman proposed by General Electric Co. It was proposed that a man wearing the Hardiman exsoskeleton would be able to command a set of mechanical muscle that multiply his strength by a factor of 25, yet that in this union of man and machine he would feel object and force almost as if he were in direct contact. However, the project was unsuccessful because of the following reasons:
(1) It is potentially quite dangerous to wear the exsoskeleton when we consider the possible malfunction of the machine.
(2) Space inside the machine is quite valuable to store computers, actuators and energy source of the machine. Thus it is not at all a practical design to use it for a human operator.

With the advent of science and technology it has become possible to challenge for the realization of the dream. The concept of projecting ourselves by using robots, computers and cybernetic interface is called Tele-Existence, Telepresence.

The final version of tele-existence system will be consisted of intelligent robots, their supervisory subsystem, a remote-presence subsystem and a sensory augmentation subsystem, which allows an operator to use robot's ultrasonic, infrared and other, otherwise invisible, sensory information with the computer-generated quasi realistic sensation of presence. In the remote-presence subsystem, realistic visual, auditory, tactile, kinesthetic display must be realized [1].

Using this system, a human operator can be in a safe and comfortable place and at the same time be present or exist at other environment where the robots are working. He or she will monitor the work through robots' sensors, and if necessary conduct the task on behalf of the robot as if he were working directly (ideally) or he were working inside the robot (practically).

The basic configuration of the tele-existence system is shown in Fig.2. Take vision as an example to explain the principle of the display which gives a sensation of presence [1]. The system is based on the principle that the world we see is reconstructed by the human brain using only two real time images on the two retinae of a human. What we get from the environment are only two-dimensional pictures on the retina changing in real time according to the movement of the eyeballs and the head. We reconstruct the three-dimensional world in the brain and project the reconstructed world to the real three dimensional world [1].

In the new type of robotic display; (a) human movements including a head movement are precisely measured in real time, (b) robot sensors and effectors are constructed anthropomorphically in function and size, (c) movements of the robot sensors are controlled to to follow precisely to the human operator's movement, and (d) the picture taken by the robots sensors are displayed directly to the human eyes in a manner which assures the same visual space as is observed directly at the robot's location.

The display enables the operator to see the robot's upper extremities, which are controlled to track in real time precisely the same movement of the operator's, instead of his/hers at the position where his/her upper extremities should be.

In order to realize the tele-existence, the following technologies must be developed, which are all advanced problems of sensor and/or sensing systems technologies.

(1) Technology to measure human movements including a head, arms, fingers and eyeballs in real time without constraints,

(2) Technology to construct visual, auditory and tactile sensors with human size and human functions,

(3) Technology for the control of anthropomorphic robots,

(4) Technology for the display of the remote environmental information in a manner which produces the feeling of presence.

According to the concept, an experimental tele-existence system in real and/or virtual environment has designed and developed, and an evaluation experiment of a tele-existence system has been conducted and efficacy of the tele-existence system has been verified and the superiority of the tele-existence method has demonstrated through several experimental tasks at MEL and RCAST of the University of Tokyo (See Fig.3 and Fig.4).

Three experiments which demonstrate the typical characteristics of the tele-existence master slave system have been conducted.

(1)The most important features of the tele-existence include the natural three dimensional vision (close to direct observation), which follows an operator's head movement in real time. Another feature is the natural correspondence of visual information and kinesthetic information, i.e., an operator observes the slave's anthropomorphic arm at the position where his/her arm is supposed to be. This allows the operator at the control to perform tasks which need coordination of hand and eye quickly as in the case of direct operation. Figure 5 shows a general view of an experimental manipulation task of building blocks randomly placed on a table against a natural background under natural lighting condition. Block building is usually done within few seconds without training, whereas conventional teleoperation using the same master, the slave and a conventional two dimensional TV as a monitor takes training. A trained operator takes several minutes to attain the same task.

(2)The combination of fundamental tele-existence technology with other advanced technology such as virtual environment display and impedance control makes it possible to use robots in hazardous environments. Figure 6 shows that the robot works on the supposition that a pipe of a chemical plant is leaking and the plant is filled with toxic gas. The operator analyzes the situation using a virtual model environment of the plant generated by the computer according to the blueprint of the plant while the robot goes to the plant. The model environment is displayed by using the same display which is used for the tele-existence operation. When the robot arrives at the plant, the operator observes the situation through the robot's sensors as if he/she were at the spot. The operator conducts the emergency action by closing the valve and pushing the switch of the exhaust fan. The model environment can be superimposed on the real scenery. Impedance control of the slave robot's manipulator helps conduct quick manipulation tasks like closing valves and pushing switches.

(3)By using tele-existence, natural human robot communication becomes possible. In other words, robots can be used in such situations that human robot collaboration is necessary. Figure 7 shows an example of human robot communication. The robot presents a bunch of flower to a lady on behalf of a person at the control.

Conclusions

Current status and future prospects of advanced robotics were outlined from the stand point of generation of robotics with special emphasis on sensor technology. The last two decades have witnessed a worldwide effort to realize robots for manufacturing factories. The use of the robot for the service of humanity needs the third generation robot technologies, which can be made possible by the extensive study of measurement and control. Above all sensors will be of vital importance for the next generation of robotics, which includes neurobotics and artificial reality.

References

[1]S.Tachi et al.,"Tele-existence (I) -Design and evaluation of a visual display with sensation of presence-," Proceedings of the 5th Symposium on Theory and Practice of Robots and Manipulators (RoManSy 84), pp.245-254, CISM-IFToMM, Udine, Italy, June 1984.

[2]S.Tachi, H.Arai, I.Morimoto and G.Seet,"Feasibility experiments on a mobile tele-existence system," The International Symposium and Exposition on Robots (19th ISIR), Sydney, Australia, November 1988.

[3]H.Arai, S.Tachi and I.Miyazima, Development of a power-assisted head-coupled display system using a direct-drive motor," Advanced Robotics, vol.3, no.2, pp.123-130, 1989.

[4]S.Tachi, H.Arai and T.Maeda, "Development of an Anthropomorphic tele-existence slave robot, "Proceedings of the International Conference on Advanced Mechatronics (ICAM), pp.385-390, Tokyo, Japan, May 1989.

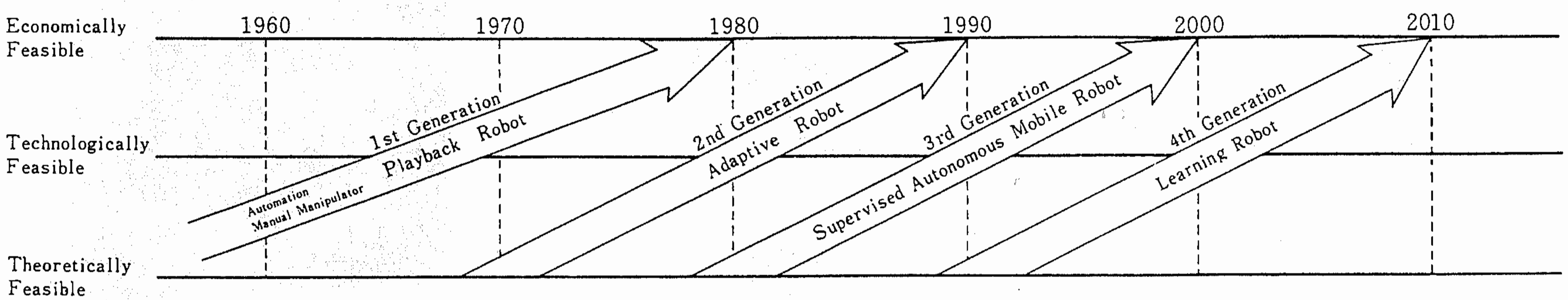
[5]S.Tachi, H.Arai and T.Maeda, "Tele-existence simulator with artificial reality (1), -Design and evaluation of a binocular visual display using solid models -," Proceedings of the IEEE International Workshop on Intelligent Robots and Systems (IROS'88), pp.719-724, 1988.

[6]S.Tachi, H.Arai and T.Maeda,"Tele-Existence Master Slave System for Remote Manipulation," IEEE International Workshop on Intelligent Robots and Systems (IROS'90), pp.343-348, 1990.

[7]J.D.Hightower, E.H.Spain et al., "Telepresence: A hybrid approach to high-performance robots," Proceedings of the '87 International Conference on Advanced Robotics (ICAR), pp.563-573, Versailles, France, October 1987.

[8]L.Stark et al.,"Telerobotics: Display, Control, and Communication Problems," IEEE Journal of Robotics and Automation, vol.RA-3,no.1,pp.67-75 ,1987.

[9]S.S.Fisher et al., "Virtual environment display system," ACM 1986 Workshop on Interactive 3D Graphics, pp.1-11, Chapel Hill, North Carolina, October 1986.



		1st Generation	2nd Generation	3rd Generation	4th Generation
Brain Fnnction	Intelligence	a priori [inborn] (play back)	adaptation, accomodation	inference, problem solving	a posteriori [acquired]
	Knowledge	data	date base	knowledge base	learning knowledge base neural network
Sensor Function	Internal Information	exist	exist	exist	exist
	External Information	none or point	1–D, 2–D (structured environment)	3–D (structured natural environment)	3–D (unstructured environment)
	Communication	unilateral (teaching, tape)	interactive (robot language)	bilateral (supervisory control, tele-existence)	autonomous bilateral (natural language, communication between robots)
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)	coordinated control (dynamic) 3–D
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 [Inspection Maintenance]	Secondary Industry (Non-Manufacturing Industry) Primary Industry Tertiary Industry
Technological Characteristics		Internal Sensor + Servo Technology	External Sensor + Microprocessor Technology	Knowledge Processing + Man-Machine Interface Technology	Learning + Simulation with Artificial Reality

Fig.1 Generation of Robotics and Their Features.

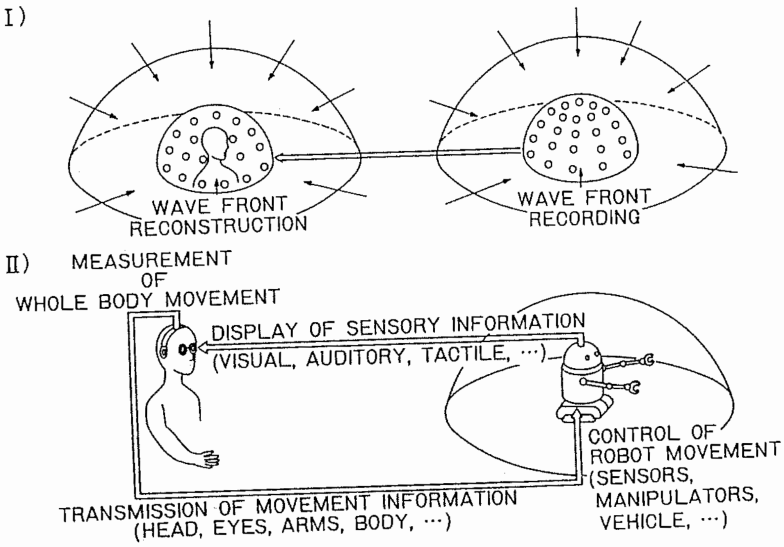


Fig.2 Concept of Tele-Existence.

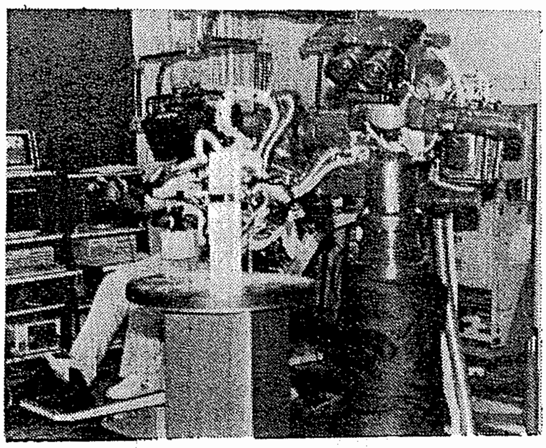


Fig.5 Experiment of Handling Blocks.

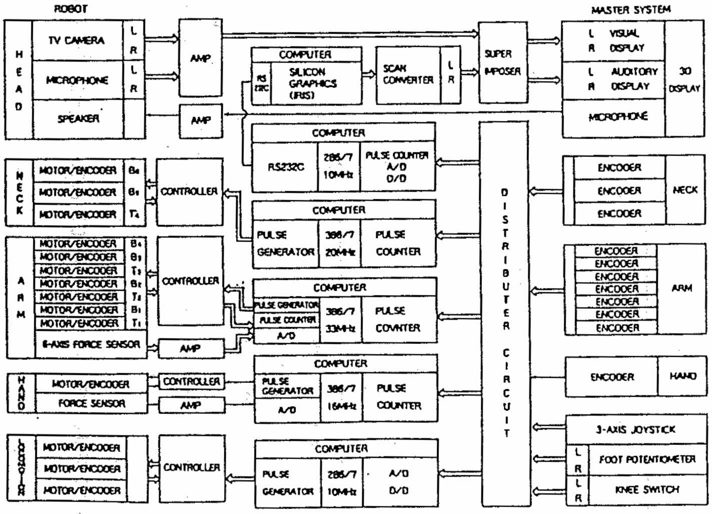


Fig.3 Schematic Diagram of a Tele-Existence System.

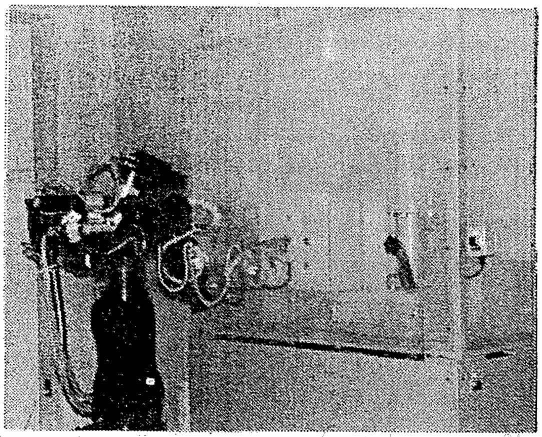


Fig.6 Experiment in Hazardous Environment.

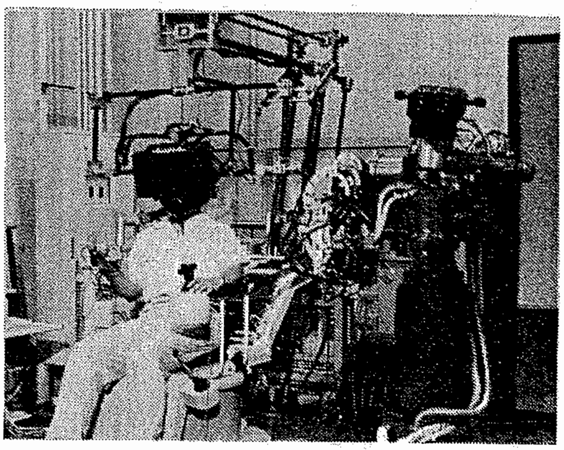


Fig.4 General View of a Tele-Existence System.

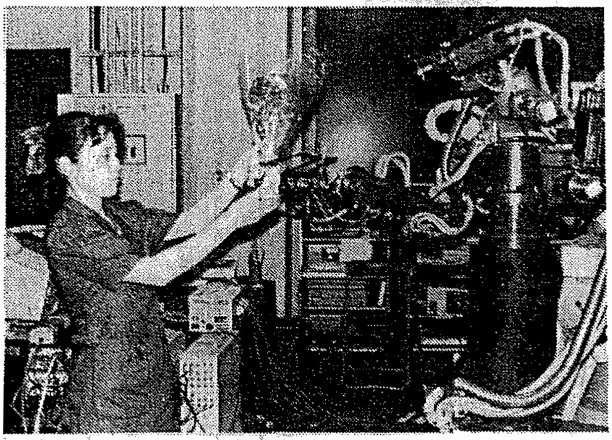


Fig.7 Human Robot Communication.