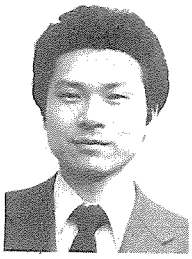
The Third Generation Robot



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1. Preface

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, the dream was realized by utilizing animals, and unfortunately, by using his fellowman as a slave. In some countries such conditions continued until nearly a hundred years ago.

With the advance of electronics and progress of automation technology in recent years, it has become possible to let automated machinery replace man's labor. Robots are expected to replace man's work as the only tolerable slave from a humanitarian point of view.[1-3] The "Human Use of Human Beings"[4] of N. Wiener will be truely realized only when man makes robots to replace man's dangerous, difficult and boring tasks, supporting an important end in the development and safety of our modern society.

The rapid development of microprocessors and semiconductive sensors have given a great impact toward the intelligent industrial robot. It is no exaggeration to say that the development of a robot in the true meaning depends on the development of such sensors and the progress of techniques utilizing them.

The application fields are not limited only to usual manufacturing in secondary industry, but have been expanding gradually to mining, civil engineering, construction in the same secondary industry, as well as to agriculture, forestry and fisheries in primary industry. They are expanding also to retailing, wholesaling, finance, insurance, real estate, warehousing, transportation, communications, nuclear power, space, ocean development, to social work, such as medical treatment, welfare and sanitation, and to rescue in disasters, leisure, household, and other tertiary industry-related fields. As it progresses, our relations with the robot are becoming more and more important. These are called man-machine interface, human interface, or man-machine communications although they have slightly different meanings. They are one of the most undeveloped areas despite being one of the most important of robot technology.

Since the latter half of the 1960s, robots have been brought from the world of fiction to the practical world, and the development of the robot is also called by generation, as in the case of the computer.

In this article, technical problems to be solved are discussed and application examples are presented, concerning both the second generation robot which is coming into general use from practical application, and the third generation robot, the R&D of which has just started. An example of the man-robot cooperation system which will play an important role in the third generation robot, as well as some subjects for realizing such a system will be presented and intensively discussed.

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 had been only a dream, has come to realize some of man's or animal's functions although it has a different shape. Versatran and Unimate which were first robots made commercially available in 1962 and were introduced to 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, i.e., hardware configuration and control technology for an operational type mechanical hand (or manipulator)[5] which had been under research and development for use in the hot (radioactive) cell of a nuclear reactor, and automation technology for automated machinery or NC machine tools, as a result of the advance of cybernetics. 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

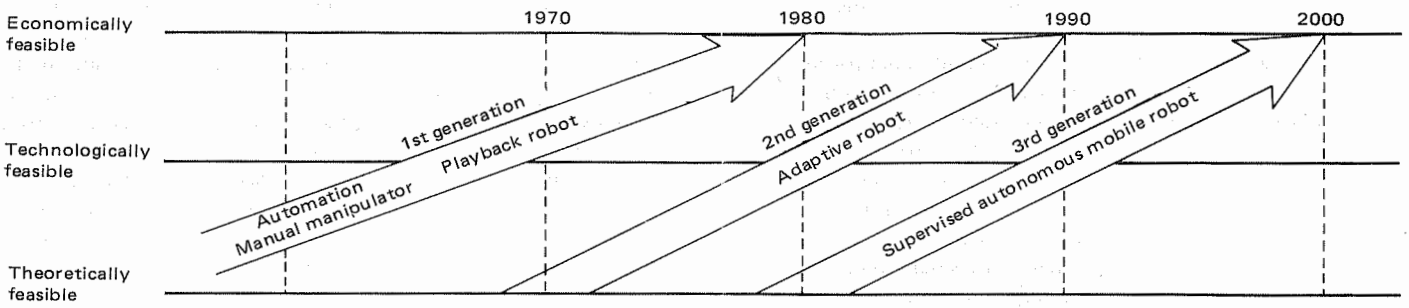
to take four promotional measures, i.e., establishment of a lease system by fiscal investment and loan, a special depreciation system for important composite machinery and equipment, a special loan system for industrial safety and health facilities, a loan system for the modernization of equipment of medium and small enterprises and the designation of beneficiaries of the equipment lease system. Thus the robot entered the age of prevalence in anticipation of a rapid increase in demand. That is why 1980 is called "the first year of the prevalence of the industrial robot."[6]

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 its position and posture taught in a teaching process before commencement of operation. In essence, it is a composite system of technology based on control techniques for various automated machines and NC machine tools and designing and control technique of manipulators with multiple degrees of freedom. The application area, 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 to vary actions or better understand man's instructions by using not only knowledge from within like for the first generation robot, but also to acquire external information by sensor. The device that could change its actions using a sensor according to situation is the so-called second generation adaptive robot. It came to prevail gradually in the 1970s. Although available sensors for obtaining exterior information are limited, it can be used effectively only in very limited areas of the production site. For such purpose, the visual sensor is important, but at present robots are in a stage in which they identify mainly one- or two-dimensional binary patterns under controlled illumination conditions. 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 momentarily. This has remained as an important subject for the coming third generation robots.

2-2. Movement Toward Third Generation Robot

When considering the situation where a robot works in compliance with man's instructions, one will easily understand the following three points are vital to the operation of a robot:[8]



		1st generation	2nd generation	3rd generation
Brain function	Intelligence	A priori [inborn] (playback)	Adaptation, accommodation	A posteriori [acquired] (learning, inference, problem solving)
	Knowledge	Data	Data 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)	Position control (dynamic)	Force control (dynamic)
		1-D (guide cable)	2-D (plane, guided)	2-D (uneven, autonomous); 3-D (stairs, free space)
Application fields		Secondary industry (Manufacturing industry)	Secondary industry (Manufacturing industry)	Secondary industry (Nonmanufacturing industry)
		Material handling Painting Spot welding	Arc welding Assembly	Primary industry Tertiary industry

Fig. 1. Robot generations and their features

1) To understand man's instructions appropriately, communicate the condition of itself to man, and to obtain new knowledge, instructions and teaching from man (communication between man and robot).
2) To know external circumstances, especially conditions of the object of work (recognition of its external world).
3) To understand its own internal conditions (arm angle of robot, for example) (recognition of its internal world).

Since 3) is comparatively easy, as it is the basis of servosystem it is realized in various automated machinery or the first generation robot. Main technical problems to be solved for the second generation adaptive robot with sense 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 has a direct relationship on the development of sensors and microcomputers in recent years. Visual and tactile senses are most important. They have been practically used for wire bonding of semiconductors[9], assembling in various fields,[10] or as visual inspection machines.[11]

Granting that the first generation robot has been related with internal sensors and servotechnology, and the second generation with external sensors and microprocessor system technologies, 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) to a three-dimensional natural environment and establishmet of communication functions of item 1) would be considered to become important themes. The author's opinion is summerized 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, at 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 at present. So, it is necessary to give instructions by dividing them into small steps so that the robot can perform them. Especially, no voice is used for the first generation robot, and the hand positions and postures of the robot are taught in detail like holding it by its hands and feet. And the labor and time required for this process becomes abnormally great when the number of robots is increased. In the second generation, some simplification of the teaching steps is made by using robot language[12] and an interactive system, but the communication system is at a groping stage. In the third generation, communications between robot and man should be made much closer to that between humans. For this purpose, speech recognition,[13] natural language understanding,[14] question and answer system, and knowledge data base system technology should be established.[15]

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 subordinates in human society.[16] That is, a robot, which subordinates, receives instructions from the 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 and know-how on the operation obtained by other workers in the past (knowledge data base). When some matter which the robot cannot solve occurs during operation with the knowledge and robot judgement, it will consult with its superior (interaction). Checking robot conditions, the superior will then make optimum judgement under the circumstances which the robot will follow. When the superior considers 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 should operate with such presence as if a man were with it so as to get out of the difficulty (tele-existence). In the case of joint operation of some robots, the allocation of work to each, and cooperation and communication between them are also important.

In addition, it is clear from the point of operational function that both manipulation and movement have many important matters to be solved for the third generation robot. Especially when we consider the use of the robot in primary and tertiary industries, the robot itself should have its own built-in energy source and be required to move with a certain level of knowledge. Three conditions for a robot,[17] autonomous, independent, and mobile, which were proposed more than ten years ago, could be provided for the first time for a practical-purpose robot in the third generation robotics.

3. Technical Problems and Application Field of Robots

There are many scientific and technical problems to be solved regarding the robot. Table 1 lists problems the author have prepared on trial. The table shows in a column man's functions, i.e., faculty of sense corresponding to measurement, function of hands and feet to control, function of head for information processing, maintenance of life indispensable to a living thing and communications between man and robot or between robots and on its side analysis and configuration.

Table 2 lists relationships between application field and basic technology, and arranges the same items with those of Table 1 in a column and general classification of industry on its side.

4. Man-Robot System

There have been many disputes on what the intelligence of a robot is,[18-21] and so far, no consensus has been reached. And I do not suppose intelligence will be clearly defined even in the future.

Knowledge is similar to intelligence, but they are quite different in nature. For example, if only definitions and axioms are provided as knowledge in Euclidean geometry and various theorems can be resolved, ability may be supposed as the work of intelligence due to the creation of new knowledge. From this point, intelligence can be regarded as the power to generate new and unknown knowledge from known knowledge or the power to make new judgement. In the case of machinery, the power is supposed to greatly depend on the architecture of computer hardware and its supplementary software. For example, if such a computer is configured as having architecture like a learning machine that easily absorbs knowledge, its learning ability can be increased and exceeds that of the usual computer.

On the other hand, it is also possible to supplement intelligence with knowledge. For example, in a certain situation in shogi (Japanese chess), let us suppose that the next move, which may be said as the best of all moves to be taken, is

Table 1. Robot functions and scientific and technical problems to be solved.

Function required for robot / Science and technology		Analysis	Synthesis		
Functions	Details of functions	Learning from man, creatures, and nature	Hardware	Signal processing, control	System
Senses	Visual sense (incl. electric wave, infrared, ultraviolet, X-ray)	Three-dimensional view, pattern recognition, situation recognition	High density, high resolution sensor, image memory, parallel operation	Multiprocessor, parallel processing technology	External real-time scene analysis
	Auditory sense (incl. ultrasonic and low-frequency vibration)	Language understanding	High-performance microphone, speech recognition IC chip		Language understanding system
	Tactile sense (incl. temperature)	Skin structure and mechanism of sensorium	Densely distributed tactile sensor element	Detection of contact condition on distribution type tactile sensor	Tactile sense diagnosing system
	Sense of smell	Mechanism of sensorium			
	Sense of taste	,,			
Hand (manipulation)	Human type	Arm control mechanism by neural impulse	Mechanism similar to a man's arm, new material, new actuators	Control similar to nervous system, control of multiple degrees of freedom system, real-time dynamic control	Artificial hand which moves at man's will, tele-operator
	Animal type	,,	Soft gripper mechanism	,,	
	Non-animal type		General-purpose gripper with multiple degrees of freedom	,,	Flexible arm applicable to various tasks (avoidance of obstacles)
Foot (move)	Human type (2 feet)	Two feet moving control mechanism by neural impulse	Mechanism similar to human leg	Control similar to nervous system, dynamic control	Artificial foot which moves at man's will
	Animal type (multipede, chaetopod)	Coordinative control of multipede walking		,,	Movement on stairway, ungraded ground, wall surface, etc.
	Non-animal type (wheel, caterpillar, etc.)				Avoidance of obstacles, navigation by using natural landmarks
Head	Intellect	Recognition, memory, learning, association	5th generation computer	Non-Neumann architecture	Highly advanced intelligent information processing system
	Emotion	Feeling		Quantification of feeling	
	Volition	Judgement, volition, creation		Intention deciding theory	
Communication	Man–machine–man	Language understanding			Automatic simul-interpreter
	Man–machine	Man's space recognition mechanism	Man, machine, environment simulator	Real-time measurement of man's action	Tele-existence
	Machine–machine				
Maintenance of individual	Intake of energy				
	Self-recovery and preservation	Regeneration		Theory of self-recovery	Self-recovery machine
Preservation of the species	Reproduction	DNA		Theory of self-reproduction	Self-reproducing machine

Table 2. Application fields and basic technologies of robot

Application field	Primary industry			Secondary industry			Tertiary industry					
	Agriculture	Forestry	Fisheries	Mining	Construction	Manufacturing	Wholesale and retail business	Finance, insurance, real estate	Transportation, communication	Electricity, gas, water supply	Service ind. repair, amusement, medical care, education	Public works, administration affairs
1. Faculty of sense						Products inspect., maintenance, failure diagnosis						
Visual sense (incl. electric wave, infrared rays, ultraviolet rays, X-rays)	Forecast of yield and harvest-time, Discovery of blight	Presumption of forest condition		Prospecting of mineral veins		Printed-circuit board, IC mask	Acceptance inspection of merchandise				Automatic diagnosis, Artificial eye	
Auditory sense (incl. ultrasonic wave, low frequency vibration)	Discovery of blight		Fish finding		Inspection of structures	AE detection				Nuclear reactor maintenance robot, Detection of the buried	Artificial ear	Prediction of earthquakes
Tactile sense (incl. temperature, the sense of equilibrium)						Thermography inspection						
Sense of smell	Extermination of blight by pheromone		Fish-luring	Explosion sensor		Gas leak detection				Gas leak detector		
Sense of taste	Quantification of rice grade			Oxygen deficiency predictor		Automatic blender, Automatic sorting of grade	Merchandise control					
2. Manipulation						Production process of various products						
Human type	Weeding selection				Carpenter robot					Manipulator for nuclear reactor	Assistance system, Artificial hand	
Animal type	Shearing sheep						Automatic price marker				Manipulator for surgical operations	
Non-animal type	Cultivation seeding, Harvest	Timber-felling	Automatic fishing gear	Automatic excavator	Framing for concrete	Hand of industrial robot, Transistor bonder	Vending machine				Massage robot	Document arranging robot, Fire-fighting robot
3. Function of movement						Transfer of products, shifting of machine						
Human type (2 feet)											Lower extremity prosthesis	
Animal type (multipede, chaetopod)			Lure	Level shifting machine								
Non-aminal type (wheel, caterpillar, etc.)	Cultivation, seeding, weeding, spreading of agricultural chemicals	Transportation of timber			Cleaning and painting of structure	Factory transfer machine, ceiling traveling robot	In-house shopping cart, automatic display machine		Unmanned car, unmanned tanker		Hospital transfer cart, cleaning robot	

Application field	Primary industry			Secondary industry			Tertiary industry					
	Agriculture	Forestry	Fisheries	Mining	Construction	Manufacturing	Wholesale and retail business	Finance, insurance, real estate	Transportation, communication	Electricity, gas, water supply	Service ind. repair, amusement, medical care, education	Public works, administration affairs
4. Function of head												
Intellect	Agricultural data base	Forestry data base	Fisheries data base			Control computer, direct numerical control, centralized control	Intelligent vending machine				Automatic teaching machine	Census registration robot
Emotion							Purchase intention control system				Reception robot	
Volition							Inventory control and ordering system					
5. Function of communication												
Man–machine–man (animal)			Underwater farming			Communication system in factory			Voice facsimile		Guide robot	Disaster alarm system
Man–machine				Teleoperator	Teleoperator	Teaching system, alarm system, monitor system	Voice input/output for vending machine	Deposit dispensing system			ICU	
Machine–machine						Various information transmission system			Automatic landing system	Automatic inspection with telemeter		
6. Maintenance of individual												
Intake of energy	Vegetation plant		Automatic breeding unit			Automatic energy providing cutter					Automatic cooker	
Self-recovery and preservation		Automatic forestry environment preservation system				Self-diagnosis and recovery unit					Patrol robot	Police robot
7. Preservation of the species												
Reproduction	Automatic mating unit		Automatic fertilization, Incubation			Automatic factory, automatic machine manufacturing system					Artificial womb, Incubator	

thought out. If it is thought out only from the movement of pieces, it is truly the action of very high intelligence. If the same situation had already appeared before and the move is taken as set tactics, it is posible to take the same move as set tactics can be remembered as knowledge in advance. In that case, such high intelligence is not required. No difference in intelligence between the two players can be found as far as the next move is concerned.

Machine is superior to man particularly in remembering accurate knowledge and it is very effective to supplement intelligence with this knowledge. Especially it is effective when a machine is used in such environment as factory which is originally designed by man. The knowledge about that environment is abundant.

However, it is a fact that this kind of approach is greatly limited 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 in advance and man's intelligence, in order to perform such work, which cannot be done only by man or machine, but as a combination of man and robot. The importance of such man-machine technology which cooperates them effectively will increase more and more in the future.

4-1. Example of Man-Robot System

Fig.2 illustrates an example of a composite work system with a man and a number of robots proposed by the author's study group. A number of independent mobile intelligent robots divide work among themselves and cooperate with each other in the case of necessity under critical and severe environment in compliance with instructions from a human operator stationed in a control capsule. A management control unit (a kind of supervisory controller) takes charge of dividing work, planning and scheduling, and the respective intelligent robots send reports concerning the work progress one after another. Such information is put in order at the supervisory controller and is transmitted to the operator by voice (or by visual or tactile sense) for example. When the operator instructs in a language very close to natural language and transmits the results of its judgement, these are transmitted to the respective robots through speech recognition equipment and supervisory controller, and the respective robots understand and pursue the purpose using their own intelligence and knowledge. The information in the robots' intelligence system is an important information source for their intelligent operation and can be monitored by the operator at anytime.

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

When an intelligent robot encounters any difficult work which it cannot handle by its own ability, the operation mode of the robot is switched to remote control mode either at the robot's request or by judgement of the operator. At that time, instead of conventional remote control system, advanced type of the telepresence system,[22] called tele-existence system,[23,24] are adopted. This enables the operator to control the robot as if he were inside the robot. In this case each subsystem of an intelligent robot works like a slave-type robot which is freely controlled by man's instructions.

In the tele-existence system, the operator's body actions and force condition are measured in real time and the internal conditions of the operator are presumed. The internal condition is transmitted to a robot and controls 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.) It controls artificial eyes, neck, hands and legs of the robot, faithfully reproducing man's motions. At this time, all information from artificial sense organs of the robot is transmitted to the corresponding sense organ of man by a direct presentation system. For example, if the operator looks to some direction intentionally, the robot also turns its face to the same direction and makes the image corresponding to the view which the man would see, appear on the man's retinae as a real image. When the operator brings his arm before his eyes, the robot's arm will also adopt the same position in the visual field. Therefore, man can proceed with his work understanding the relation of his arm with the object and also with the surrounding space in the same relationship with his experience. The sense that a robot has when it touches an object is presented to man's hand as a stimulus to his skin, and the operator can perform his work having the sense as if he touches it himself, and can conduct such work that will promote man's skillfulness with operability, ideally to the same extent with man's direct work, or practically of the same extent with a man working inside a robot.

The operator can also utilize the robot's sensor information by radial rays, ultraviolet rays, infrared rays, microwaves, ultrasonic, and very low frequency waves (which are called super sense information). For example, infrared sensor information is converted to visible light at night to see an object in the dark or ultrasonic information can be converted to audio frequency to obtain sound information which is not available in normal conditions. It is also possible to superimpose super sense information on usual visual display and/or to utilize skin sense channels which are not normally used. The operator can effectively use this information to expand man's ability.[25-27] If we can increase the maneuverability of a robot's arms so as to control them like our own arms, we can handle such objects which are out of our control under the normal conditions. From this point of view, human augmentation system can be realized.

If the knowledge base inside the capsule can be used by a method of high accessibility, for example, MIT's Media Room,[28] the operator's judgement will be realized more accurately. It is also an interesting subject to transmit the knowledge base after having modified it to actions of a skilled worker, not transmitting man's action as it is, in addition to using it as a supplementary means of man's memory or for calculation.

These system technologies are basic technologies having various application possibilities for work under critical and severe environments in factories, plants, and industrial complexes; inspection, repair, dangerous work and treatment of radioactive waste in nuclear power plants; searching, repair and assembling work in space or ocean; searching, rescue operations, restoration work at the time of a disaster; cleaning work, construction and civil engineering work, forestry and fisheries, police, exploration, leisure, substitutes for test pilots or drivers, etc.

4-2. Study Subjects

In order to make the systems mentioned in 4-1 possible, the following subjects for research and development are given:

1) Measurement or estimation technology of motion and condi-

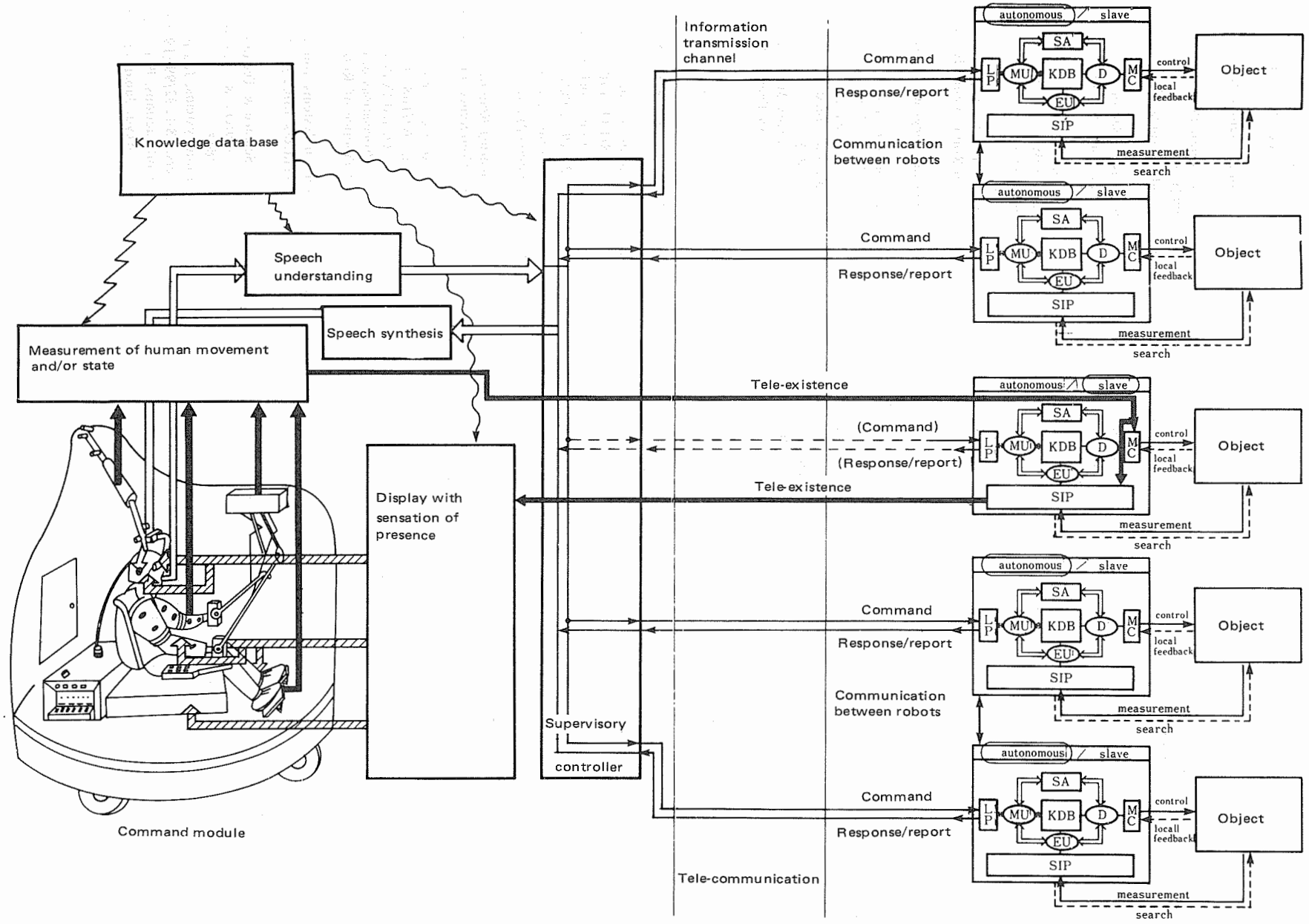


Fig. 2. An example of composition of man-robot system

tions of a human operator.
2) Mechanism and control of an anthropomorphic robot.
3) External information detection technique 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.
12) Telecommunication.
13) Robot actuators.
14) Robot sensors.
15) Robot material.
16) Safety measures for robots.

5. Conclusion

When we consider the situation of robot in the 1980s, we realize that there exists three generations, i.e., the first generation of the playback robot, mainly 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 robot which attaches importance to communication functions, R&D of which has been started, exerting great influences on each other.

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, and 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 earnest consideration.

Among them, great demands have been increasing for such a system to undertake critical and severe work in very dangerous environments, as in nuclear, ocean or disaster areas which are indispensably performed by man. The Ministry of International Trade and Industry has just started an eight-year large-scale project called "JUPITER" (Juvenescent Pioneering Technology for Robots). This project is positioned as an R&D in the third generation, and the results are anxiously awaited.

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