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2 . 5 Rehabilitative Robotics

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Abstract

Robotics and robot technology are making an impact on rehabilitative engineering. Two approaches are evident: using robots as substitutes for human/animal helpers, and substituting for lost human functions by robot technology. The latter approach has a rather long history of accomplishing cybernetic prostheses while the former is quite new.

Current status and future prospects of these efforts in Japan are discussed. The topics cover the Patient Care Robot (MELKONG), environment control systems, the Guide Dog Robot (MELDOG), upper and lower extremity prostheses, electrocutaneous communication technology, and real-time, human-interactive, prostheses simulation technology.

2.5.1 Introduction

Rehabilitative robotics means the use of robot or robot technology for the medical care and rehabilitation of human individuals.

Two approaches can be conceived. One is using robots for medical labor, e.g., mobile robots that automatically carry linen or meals to inpatients. The other approach is a prosthetic one. This includes human limb prostheses and sensory prostheses.

Enormous efforts have been made since World War II toward these ends. It is, however, only quite recently that this technology has become feasible. With the advent of electronics and micro-processing technology, it is becoming possible to apply robotics for medical and rehabilitative purposes.

In this paper, the present status and future prospects of rehabilitative robotics in Japan are outlined and discussed from two points of view, i.e., the robotics approach and the cybernetic prosthetic approach. A Guide Dog Robot is intensively discussed, for it is a typical example of a rehabilitative robot that integrates the above two methodologies.

Communication between humans and robots is very important in human-robot systems, especially rehabilitative robot systems. Fundamental results obtained from electrocutaneous communication systems are discussed.

A human-robot-environment computer simulation study is also discussed. This approach will shorten the otherwise lengthy process of design and development of field-worthy prostheses.

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2.5.2 Rehabilitative Robotics in Japan

Using robots as substitutes for human/animal helpers

Patient Care Robot,[1)] Environment Control System for a Handicapped Bedridden Patient,[2)] and Guide Dog Robot[3)] are three typical technological efforts toward this end in Japan.

A large number of nurses suffer from lumbago because of the hard labor of lifting and carrying patients and handicapped individuals in their arms. The situation is the same at home for the family members who take care of their elders or disabled relatives.

It is believed that this occupational disease, lumbago, is the main cause of the shortage of nurses in rehabilitation hospitals. Nakano and his colleagues are motivated by this fact and are developing the patient care robot dubbed MELKONG to substitute in this hard physical labor, e.g., lifting a patient from his/her bed to take to the bathroom by machine or robot.[1)]

The robot approaches the hospital bed on which the patient lies and docks with it under the manual control of a nurse. The robot's precise positioning for the docking is achieved by means of its omni-directional wheel system.[4)] The robot streches out its specially designed arms to the bed and inserts them into a special board under the patient's body, lifts him/her, turns him/her around, and puts him/her on a wheeled stretcher (Fig. 2.5.1).

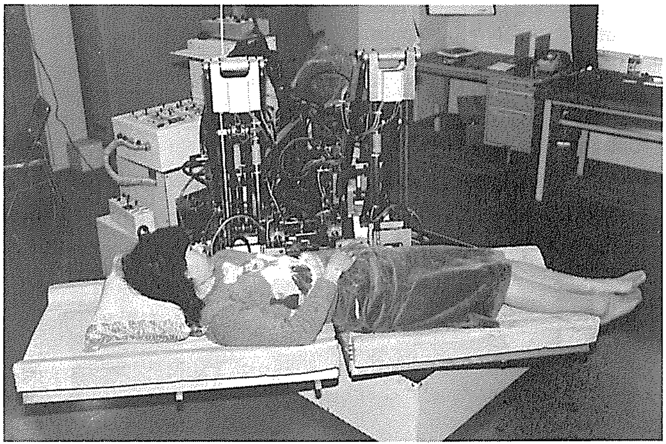

Fig. 2.5.1 General view of the patient care robot MELKONG (Courtesy of the Mechanical Engineering Laboratory).

MELKONG is now in the second stage of development, i.e., to make the system practical.

It is estimated that there are more than 500 000 bedridden patients in Japan and most of them are living in their homes with their family. This imposes on the members of those families the heavy task of taking care of them twenty four hours a day. It also causes a psychological burden for the bedridden patients themselves.

In order to reduce this burden, Funakubo and his colleagues have been developing a mechanical or robot system to provide assistance in the daily activities of bedridden handicapped persons.[2)]

Figure 2.5.2 shows a prototype system. It consists of an integrated control apparatus, a television monitor, a command apparatus, an articulated robot arm, a convenience rack, an automatic transport vehicle and a television camera. The second stage, the development of a system with two arms, is now being planned.

Guide Dog Robot will be discussed in Section 2.5.3.

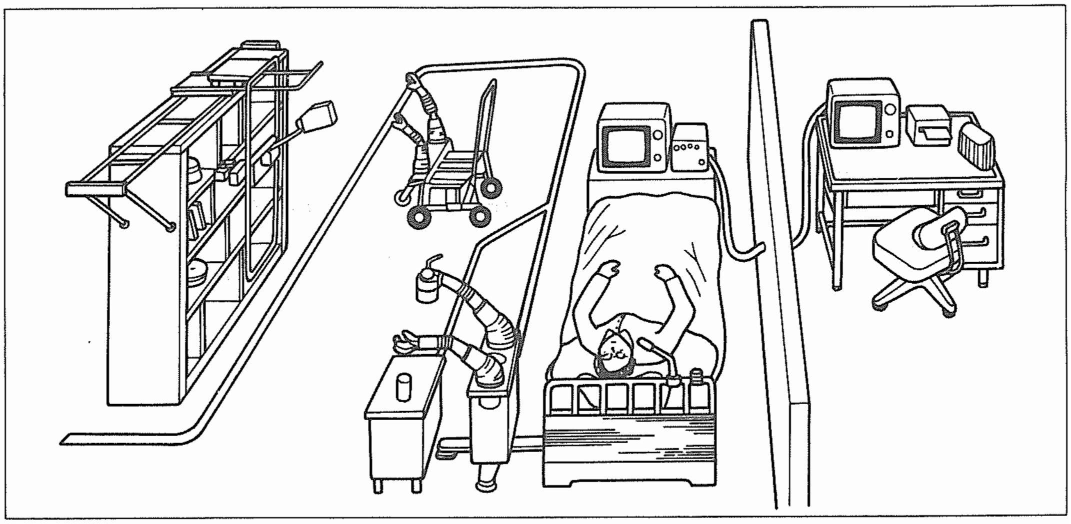

Fig. 2.5.2 General view of the environment control system of bed ridden patients in private house. [after H. Funakubo, Precision Engineering, *46-1* (1980) 18 ~ 22]

Substitution of lost functions

A typical example of this prosthetic approach is upper extremity prosthesis, like an artificial arm or hand. Pioneering work for this field in Japan was done by Kato and his colleages

Fig. 2.5.3 General view of the myo-electrically controlled whole arm prosthesis with seven degrees of freedom.

as WIME HAND,[5] which is now commercially available via Imasen Electric Company. As for an above elbow prosthesis, there are no commercially available active prosthetic arms having several degrees of freedom.

Funakubo and Saito made an experiment with a total arm prosthesis driven by twelve micro-motors.[6] It is controlled by signals associated with the vibration of the vocal cords.

The Mechanical Engineering Laboratory also experimentally developed a whole arm prosthesis with seven degrees of freedom in 1979.[7] It has four degrees of freedom driven by hydraulics and three degrees of freedom driven by electric servo motors. It was demonstrated that an anthropomorphic mechanism of the same size and of less weight than a human's arm can be achieved by a machine and can be controlled by myo-electric signals associated with the shoulder movements (Fig. 2.5.3). Still, many problems, including fitting and control, remain

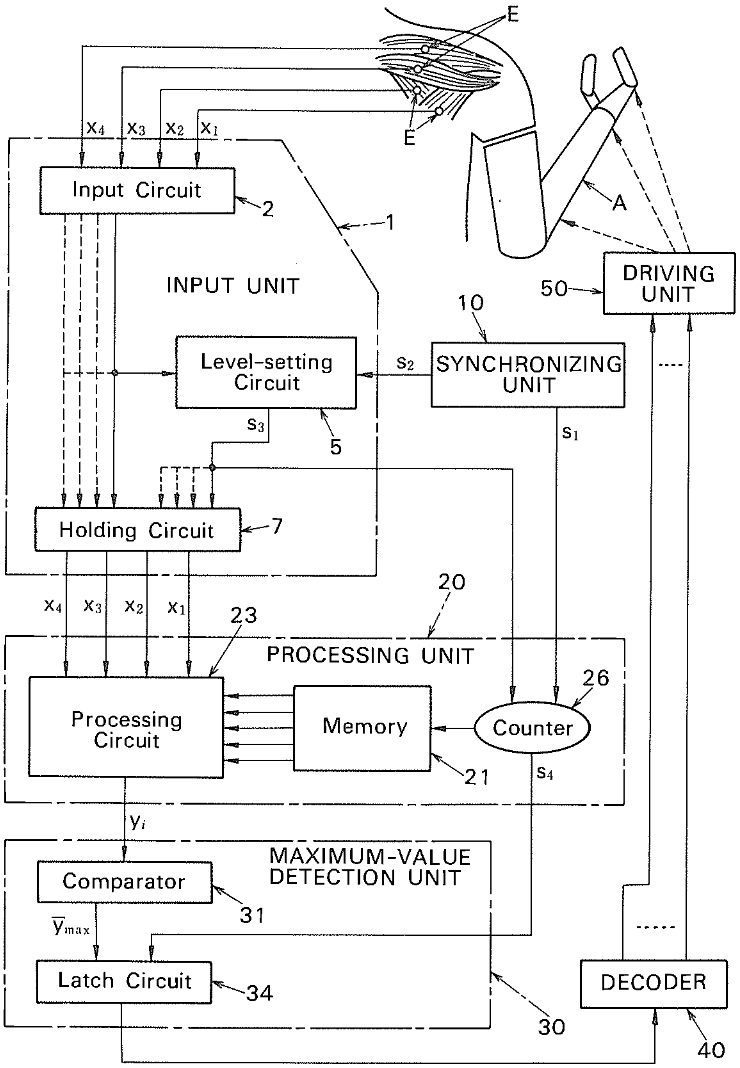

Fig. 2.5.4 Block diagram schematically illustrating the apparatus for the discrimination of EMG patterns. [after K. Tanie and S. Tachi[8]]

unsolved. Figure 2.5.4 shows a proposed control scheme using myo-electric signals (MES's).[8]

For the lower extremities, research and development are being conducted for exoskeletal active orthoses and active prostheses by Sakurai and Miyamoto[9] and Tsuchiya et al.,[10] respectively.

Figure 2.5.5 shows an experimental model of exoskeletal active orthosis for paraplegics.

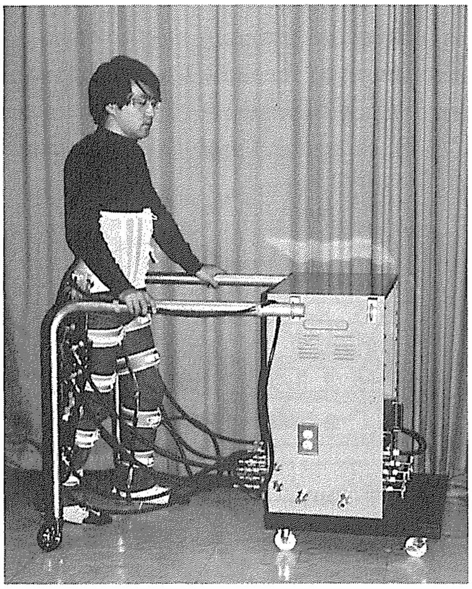

Fig. 2.5.5 Experimental model of exoskeletal active orthosis for paraplegics (Courtesy of Yasuhisa Sakurai and Hiroyuki Miyamoto of the Tokyo Women's Medical College).

Fig. 2.5.6 General view of the powered artificial lower limb (Courtesy of Kazuo Tsuchiya of Labor Accident Prosthetic and Orthotics Center).

Posture control of the orthosis is based on triangulations made by the two transmitters on the subject and a receiver on a movable control unit in front of the subject.

Figure 2.5.6 shows the powered artificial lower limb being developed by Tsuchiya et al. funded by the Agency of Industrial Science and Technology. One of the main research goals is to develop a small light weight hydraulic actuator. An RSA (Rotary Servo Actuator) with a diameter of 80 mm and weight of 1.47 kg can now achieve 12 kg-m torque at a pressure of 100 $\mathrm{kg/cm^2}$. A hydraulic pump of small size and light weight is also under development.

Electrocutaneous communication

Various investigations of electrocutaneous communication systems and studies on human responses to electrocutaneous stimulation have been conducted for applications in various fields, including the augumentation, substitution, and replacement of human sensory functions using the cutaneous sense as an auxiliary or alternative sensory communication channel from devices/machines to humans.[11~14)]

These are, quite simply, informative displays that utilize the skin senses as an input channel to the human by passing small currents through the skin from external electrodes.

They can be used widely for an extra communication channel from machines to humans because of their potential advantage of small size, light weight, low power consumption, silence, and fixability to the human anatomy as compared to vibro-tactil display systems.

The author and his colleagues have been systematically studying the electrocutaneous sensation that is elicited by monopolar pulse trains to identify the stimulus-response system by means of computer controlled psychophysical experimentation. This is an effort to determine how the physical stimulus parameters, of pulse height, pulse width, pulse interval, and spatial configuration, relate with human response parameters or informative dimensions of display, e.g., perceived magnitude, perceived frequency, and perceived location of sensation including the location of phantom images produced by the simultaneous stimulation of plural channels. The capacity of the human electrocutaneous channel has also been determined both for each informative dimension of display and for combinations of independent display dimensions.

Most important findings are:

(1) The most relevant parameter for the perceived magnitude sensation is found to be the energy of the pulse when the pulse width is less than 1 ms.[15)]

$$\text{Perceived Magnitude} = f\left(\int_0^T Z \cdot I(t)^2\, dt\right) \qquad T < 1\ \text{ms} \qquad (2.5.1)$$

where Z is the skin impedance and $I(t)$ is the current passed through the skin from external electrodes.

(2) The channel capacity of a magnitude information transmission system is measured by using a constant energy stimulator,[16)] and is calculated by the following formula:

$$R = \log_2 \int_{\min E}^{\max E} \frac{1}{\triangle E(E)}\, dE \qquad (2.5.2)$$

where $\triangle E(E)$ is the just noticeable difference measured as a function of energy E, and $\min E$ and $\max E$ are the energies that give minimum and maximum thresholds of perceived magnitude, respectively. The channel capacity is 3.0 to 4.0 bits per symbol.[17)]

(3) The channel capacity of a pitch information transmission system is estimated to be 2.5 to 3.0 bits per symbol using jnd's measured as a function of frequency in the frequency range of 10 pps to 100 pps, and the maximum information transmission rate is estimated to be about 2.1 bits per symbol from the results of forced choice tests.[18)]

(4) The channel capacity of a two-variable electrocutaneous information transmission system is estimated from the number of cross points of equal magnitude curves and equal pitch sensation lines. Its value ranges from 5.6 to 6.0 bits per symbol. The maximum information transmission rate estimated from the forced choice test is 2.7 to 3.2 bits per symbol.[19)]

(5) Two equally loud electrocutaneous stimuli simultaneously presented to adjacent locations on the skin are not felt separately but rather combine to form a sensation midway between the two electrodes, just as in the case of binaural sound localization in hearing and the vibrotactile phantom sensation on the skin. This phantom location can be controlled by relative magnitudes of the two stimuli and by the time delay between them.[20)] Thus the number of electrodes can be reduced by using the phantom sensation display in comparison to a display requiring a discrete electrode for each position desired. The channel capacity of a location information transmission system using the phantom sensation depends on the distance *d* between the two electrodes and ranges from 2.0 to 3.0 bits for *d* between 50 to 150 mm.[21)]

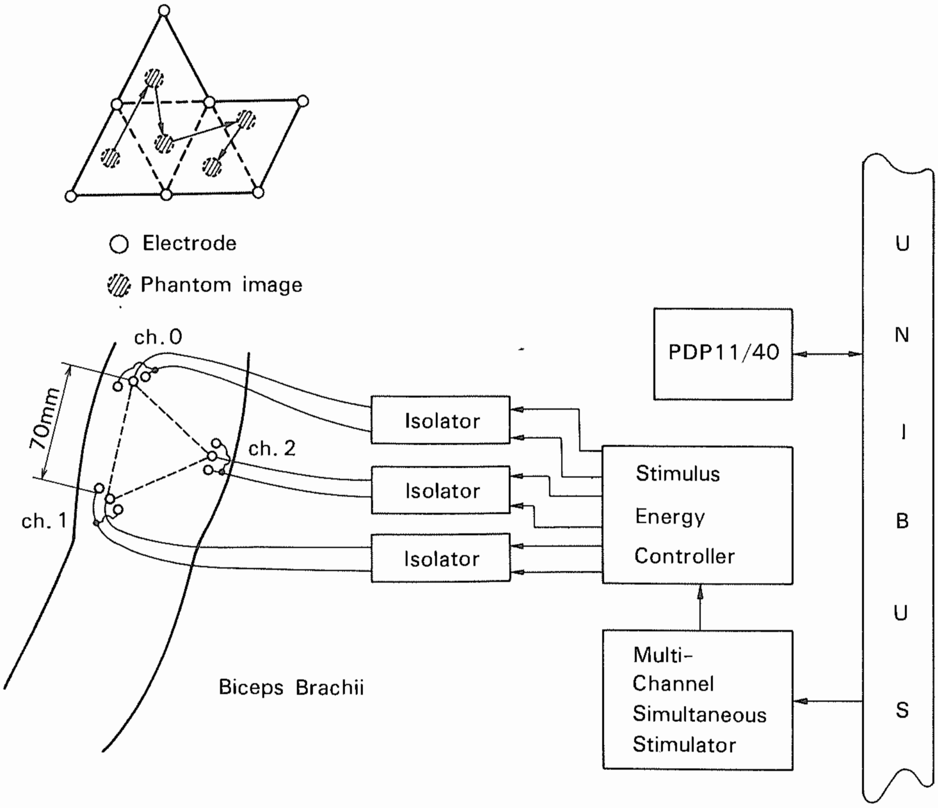

Fig. 2.5.7 Information transmission by the two-dimensional phantom sensation display. [after S. Tachi et al.[3)]]

(6) The phantom image by three sets of electrodes is the basis of a two-dimensional display because phantom display areas can easily be extended as in Fig. 2.5.7. The channel capacity of a two-dimensional phantom location information transmission system is estimated to be about 4 bits per symbol from the jnd's of the perceived location. The maximum information transmission rate is about 2.8 bits per symbol.[22)]

2.5.3 Guide Dog Robot

The author and his colleagues have been working on a Guide Dog Robot project, which is dubbed MELDOG, since fiscal year 1977.[23)] 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 finds obstacles which are not registered on the map and avoids them; (3) how the robot informs the blind master about the route and the 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. Adding to them, communication between the blind master and the dog is also necessary.[3)] In order to realize 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, and waits for the master's next order (right, left, straight, or stop) and 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 [24)] (See Landmark Subsystem of Fig. 2.5.8).

(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, probably a human traveler. If something is crossing in front of the robot, the robot waits till it passes. If it detects an obstacle which does not move, it tries to determine if it is possible to find space that will permit the safe transport of the master around the obstacle. 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[25)] (See Obstacle Detection System of Fig. 2.5.8).

(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

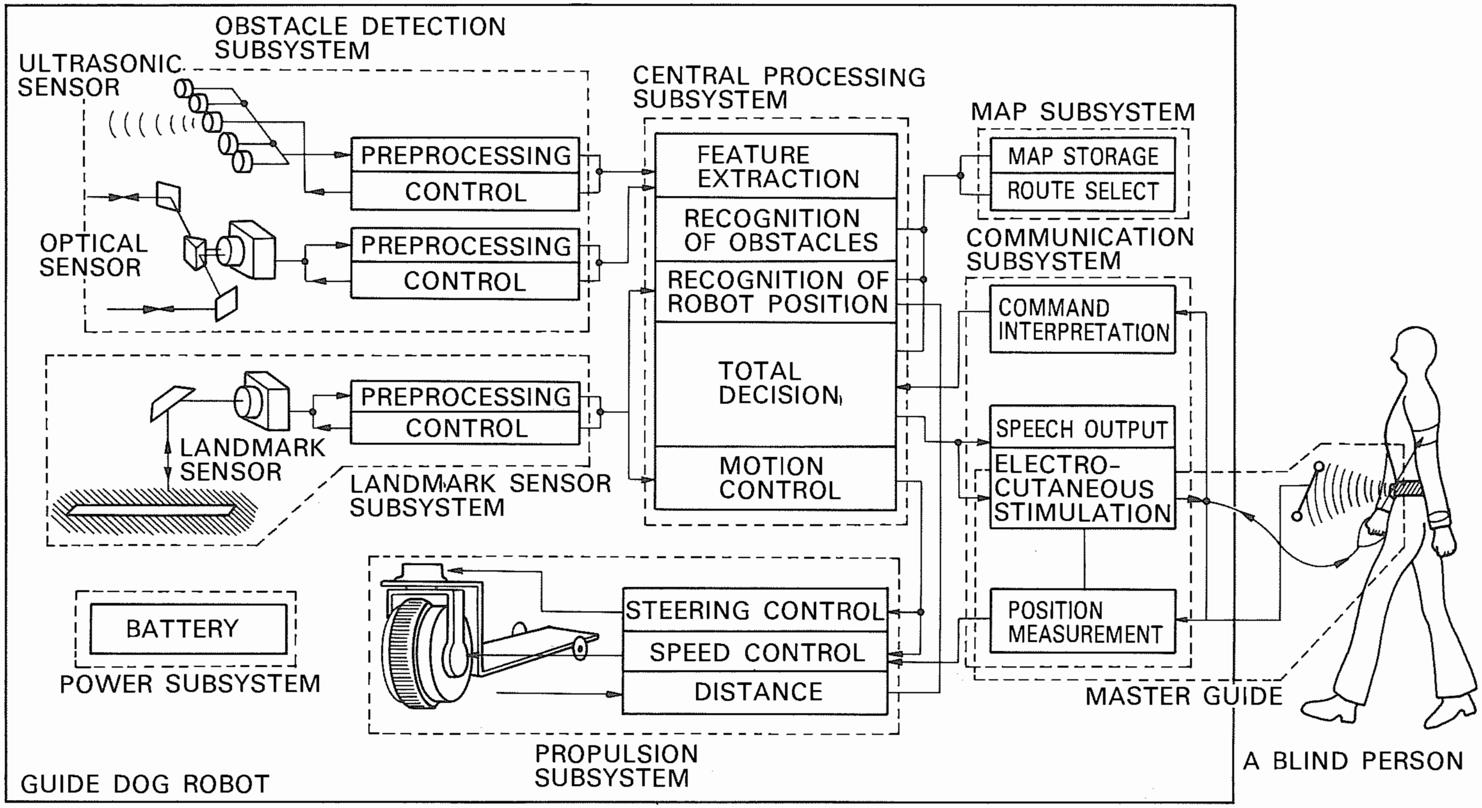

Fig. 2.5.8 Schematic diagram of the guide dog robot system (MELDOG). [after S. Tachi et al.[3]]

safety zones, is he warned by the robot[23] (See Man-Machine Communication Subsystem of Fig. 2.5.8).

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.[24]

The fundamental data base of the robot is a navigation map stored in its auxiliary memory, e.g., cassette tapes, and transfered 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 an automaton.[24]

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. Although it is very desirable to use natural landmarks, such as buildings, poles, trees, etc., technological limitations forced us to use artificial landmarks during our first approach. We adopted white painted lines on the streets with lengths of about 2 m and widths of about 0.15 m as our landmarks. At this stage of development, these marks must be set at every crossing. The automaton representation map for the robot can be automatically made by an off-line computer from an ordinary map using picture processing techniques. Landmark laying instructions, which will be used to place the landmarks on the streets, can be made at the same time.

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, 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 the object in front of it (from 0.2 to 3.5 m) and itself every 20 ms 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, probably a human traveler.[25~26]

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

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.[23]

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 (See the third section of 2.5.2). 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.

Further experiments are being conducted using the newly designed test hardware MELDOG MARK IV (Fig. 2.5.9). These experiments include 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. This problem of optimal information presentation is discussed in the next section.

Fig. 2.5.9 General view of the guide dog robot MELDOG MARK IV. (Courtesy of the Mechanical Engineering Laboratory)

2.5.4 Real-Time, Human-Interactive Prostheses Simulation

A long cyclic process of development and evaluation is usually necessary for the development of truly field-worthy prosthetic devices. In that cyclic process, enormous amounts of trial hardware must be made, which makes the process long and costly.

With the advent of computer and sensor technology, it is becoming possible to substitute computer-based prosthetic simulation technology for part of this lengthy process. The idea of using high-speed dedicated computers in the design and evaluation process of prostheses was first proposed and demonstrated by Mann of M.I.T. for the control design of the upper and lower extremity prostheses known as Boston Arm27, 28) and M.I.T. Knee,29) respectively.

The same idea can be applied to the mobility environment simulation approach.30) The central features of such a design capability must include a method to quantify the motion or movement of an unhampered blind individual walking in a real or mock-up physical environment, and the means of feeding back to the individual in real time, the path information and error from the path by means of a very adaptable and potentially rich psychophysical sensory display code. Such a system would retain the human's *a priori* uncharacterizable ability to interpret and implement an arbitrary code describing obstacle and environment cues. The system would also provide quantifiable information on a human's trajectory both before and after the presentation of the sensory display information. Thus the efficacy of different sensory displays could be compared efficiently and optimal choices made before committing a particular design to the lengthy development process entailed in the development of a field-worthy, practical,

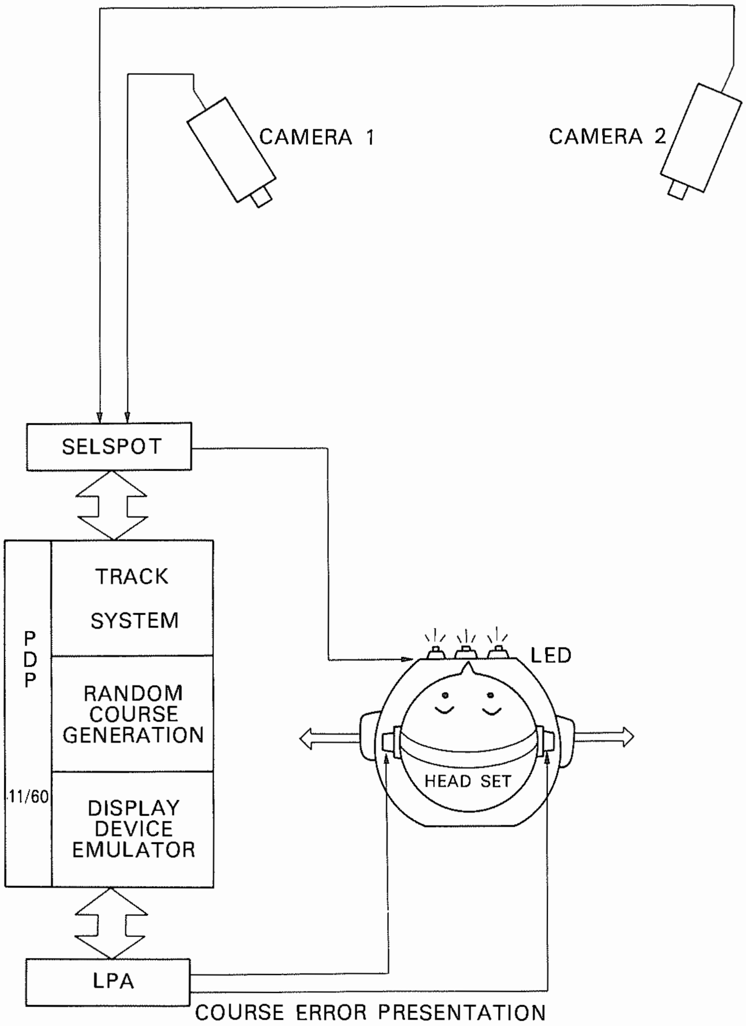

Fig. 2.5.10 Schematic diagram of the emulator system for the real-time evaluation of the display devices for the blind. [after S. Tachi et al.[31)]]

reliable mobility aid for the blind. Furthermore, an aid could be "custom tailored" to the specific attributes of an individual human being.

In cooperation with M.I.T., this computer-based, human-interactive simulation has been studied at our laboratory as well as at M.I.T. to optimize sensory displays for feedback of prosthesis state and environmental parameters to the human.31)

When the device which detects or guides a blind individual has somehow acquired information about the direction of, and width of, the path along which it should lead the blind individual, the next problem is the choice of an appropriate sensory display of the path and its safe margin for presentation to the remaining exterior receptive senses of the blind individual (Fig. 2.5.10).

The method to quantitatively compare alternative displays and thereby determine the optimal display scheme was proposed. The sum of the effective gain and the reciprocal of the time delay were calculated based on the estimated open-loop transfer function of the subjects using each of the displays. The normalized distance between the alternative display schemes was calculated statistically and used as the measure to determine the quantitative superiority of one alternative display scheme relative to another.

This method is proven to be feasible for designing display schemes for mobility aids.31)

2.5.5 Conclusions

The current status and future prospects of rehabilitative robotics in Japan are outlined. The National Large Scale Project on Advanced Robotics, called JUPITER which intends to develop the fundamental technologies necessary for the coming third generation robot, has just started in Japan.

In this eight year project, prosthetic technology and robot technology will be integrated to develop new technology for advanced human-robot systems.

The next ten years will see a new stage of development in rehabilitative engineering and rehabilitative robotics.

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