ROBOTS: COMING OF AGE

PROCEEDINGS OF

THE INTERNATIONAL SYMPOSIUM AND EXPOSITION ON ROBOTS

Sydney, Australia
6–10 November 1988

designated the 19th ISIR by the
International Federation of Robotics

edited by R. A. JARVIS

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All inquiries should be made to the Australian Robot Association, G.P.O. Box 1527, Sydney NSW 2001, Australia.

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ADVANCED REHABILITATIVE ROBOTS

P. Dario, M. Bergamasco, A. Sabatini, A. Bicchi, G. Buttazzo

Scuola Superiore S. Anna, Pisa

and

Centro "E. Piaggio", University of Pisa, Pisa, Italy

ABSTRACT

The interest for investigating possible applications of advanced robots to the solution of a number of different biomedical problems is growing worldwide. Rehabilitation, prosthetics, orthotic telemanipulation, stereotactic surgery and medical laboratory automation are some of the areas in which robot technology is expected to be increasingly used in the next future. In this paper some general problems related to the use of robots for the rehabilitation of severely disabled patients are discussed, and the current state of implementation of this type of robots is summarized.

New and attractive applications of robot technology would also be possible in the rehabilitation field if manipulators capable of physically interacting with the patient were available. To this purpose we have investigated some basic issues associated with the development of an advanced robot system equipped with a dexterous end effector and with different types of sensors, and designed to eventually incorporate a substantial degree of intelligence. These problems are discussed with reference to a prototype robot finger system, and to its use for detecting pulse rate and waveform at the wrist artery, and for sensing hard nodules in a mock breast.

1. INTRODUCTION

The medical assistance to severely disabled and elderly people is becoming a socially significant problem. In fact, the number of severely impaired people (i.e. individuals who have little direct control over their personal space) in the United States is estimated at seven percent of the total population (1), while there are at least 500,000 bedridden patients who require almost continuous assistance in Japan (2). Unfortunately, this population is expected to increase along with the diffusion of somewhat dangerous activities (personal mobility, outdoor activity, sports, etc.) and with the steady increase of the average life duration. In contrast, the costs of the paramedical personnel for the assistance to the disabled, and the difficulty to find such qualified personnel, also increase steadily. These considerations, together with the wish of alleviating the psychological dependence of the disabled and of restoring his/her ability to carry out some everyday activities autonomously (in a single word: to "rehabilitate" him/her), motivate an increasing research interest towards the use of robotic techniques in this field.

It is interesting to observe that the development of robotic manipulators for rehabilitative purposes has proceeded, especially during early research on robotics, almost in parallel with the development of industrial robots. Actually, the precursor of the modern industrial robot, the telemanipulator, was also used, in its orthotic version, as an aid for the disabled (3). Research on rehabilitative robotics has received new impetus by the progresses of industrial robotics and by the related ubiquitous use of computer control. In fact, most telemanipulators did not utilize computers at all, or used them just for augmenting to some extent the performance of the manipulator, whose control, however, remained under the direct supervision of the disabled.

Unfortunately, the very same fact that most of the present robots have been conceived and developed for industrial applications determines their limitations as true rehabilitative aids. In fact the characteristics that are most appreciated in an industrial robot, e.g. structural rigidity, speed of operation, accuracy and repeatability, are not necessarily so important in a robot intended for operating in unstructured environments ("advanced robot") as the ability to comply with variable situations in such environment would be. This situation explains why two different approaches are being followed at present in rehabilitative robotics research: some groups are trying to utilize the already existing and reliable industrial robots by structuring as extensively as possible the working environment; some other groups feel that only a dedicated robot can answer satisfactorily the peculiar needs of rehabilitation. Both approaches have pros and cons: the use of an industrial manipulator provides an acceptable and immediately usable (although partial) solution in those particular situations, such as the assistance to quadriplegic patients, in which no other practical means is available to restore some degree of personal independence to the disabled; on the other hand, the development of new and dedicated robots is likely to generate more flexible solutions to the problem of the assistance to the disabled, but probably in a relatively far future.

The first part of this paper discusses some of the considerations which motivate the choice of a robotic approach to the problem of environmental control for the disabled, and outlines some representative examples of robotic rehabilitative aids. The second part of the paper addresses the issue of designing dedicated rehabilitative robots. We believe that the ability to manage the physical interaction with the working environment and with the patient him/herself through manipulation is an essential feature of a true rehabilitative robot: therefore we devoted particular attention to this aspect and to its conceptual and practical implications for the design of a robot system. As an example of implementation of some of these ideas, the design and fabrication of a prototype robot system developed in our laboratory is described, and its use in the execution of simple sensor-based palpatory procedures on body parts is discussed.

2. ROBOTIC AIDS AND ENVIRONMENTAL CONTROL

The term "environmental control" has been used in the rehabilitation field to mean the ability of a disabled individual to control his/her environment (1). Although in general all sensory and motor capabilities are necessary to an individual in order to achieve complete environmental control, in this paper we shall mostly refer to the handicaps deriving from the partial or total loss of upper limbs functionality, and to the consequent reduced or null manipulation capability. This type of impairment, especially when associated to the functional loss of the lower limbs (as in quadriplegy) is the most critical obstacle for an individual to carry out a number of everyday's activities ranging from personal hygiene to working tasks. In this extreme (but unfortunately not so rare) condition, the subject receives a flow of information from the environment through the intact senses of sight, hearing and smell, but he/she is not able to actively operate and modify the environmental conditions. Based on this observation the phylosophy of the robotic approach to rehabilitation is to interpose the robot manipulator between the patient and the environment. Hence, as a robot can be regarded as the interface between a computer and the environment, so a rehabilitative robot aid can be viewed as an "intelligent" and "able" interface between the nervous central system of a severely disabled subject and the environment.

Two distinct approaches can be followed in the design of environmental control systems for the severely disabled: one involves the development of a collection of special-purpose devices which allow the patient to feed him/herself, turn pages of a book, open doors, etc. The second approach is based on the assumption that the disabled user is best served by a single, general-purpose system, rather than a set of dedicated devices. Actually this assumption is behind the design philosophy of the rehabilitative robot. A single robot, owing to the intrinsic "flexibility" provided by the combination of its articulated mechanical structure and of computer reprogrammability, can assist, for instance, a disabled user in different tasks such as activities of daily living (e.g. food preparation and personal hygiene), medical therapy (e.g. physical therapy and some forms of diagnostic testing), personal and vocational tasks, recreation, etc.

The ultimate ability of a robot system to execute the above mentioned tasks depends on its degree of autonomy, i.e. on its capability of detecting and appropriately reacting to environmental variations. Since present robots are not very adaptive (or, almost equivalently, "intelligent"), a rehabilitative "personal" robot must operate under the direct supervision of the user. This committment may represent a mental burden intolerable for a severely disabled patient. Such consideration is a major motivation for further research efforts aimed at incorporating as much "intelligence" as possible in the robot system, in order to alleviate the user's involvent in the direct control of the robot aid and to ultimately reduce his/her committment to that of formulating synthetic commands. Thus, besides posing extremely demanding specifications on the performance of the robot system, the development of an intelligent robot "assistant" for rehabilitation also requires particular attention to the problems of man-machine interaction.

3. THE STATE OF THE ART: EXAMPLES OF ROBOTIC MANIPULATION AIDS

The concept of a computerized orthotic telemanipulator (i.e. an exoskeletal structure that supports and moves the user's arm and that is usually driven by an external power source) has been implemented by researchers at Case Institute of Technology, Cleveland, U.S.A., in the early '60s (4). The Case system, a four-degree-of-freedom, externally powered exoskeleton carried the paralyzed user's arm through a variety of manipulation sequences, under the control of the user him/herself who directed a head-mounted light beam at photoreceptors located on selected objects. The technology employed and the concept of computer-augmented manipulation of the Case system were already very sophisticated, and the Case group invested also significant research efforts and clinical trials, just like the designers of the "Rancho Los Amigos Golden Arm" a few years later (5). However, the inherent limitations of this type of orthosis, that attempts to animate a paralyzed human arm having no residual motor and sensory functions, could not be overcome.

In the late '60s and early '70s, work began with manipulators that were not attached to the user's limb, and thus had complete functional autonomy. The first group to explore this solution by utilizing an industrial manipulator and a highly structured work environment was the one at the University of Heidelberg, West Germany (6). The approach based on a robot manipulator separated from the user and controlled by him/her has then evolved significantly so as to include generalized computer control, automatic routines, improved man-machine communication means and even some simple sensory functions (7)(8)(9).

Japanese investigators have also been active in the field of medical robotics in general and of rehabilitative robotics in particular. At the Mechanical Engineering Laboratory of MITI, for example, and with the collaboration of the University of Tokyo, a robot system has been developed comprising a powerful mobile robot ("MELKONG") intended for executing heavy manipulations of bedridden patients both in hospitals and private houses (10). Japan is also participating, in partnership with the U.S.A., Canada and U.K. (which leads the project) to an important initiative promoted by the O.E.C.D. (Organization for Economic Co-operation & Development) in the area of advanced robots for health care. In this contex the U.K. Department of Trade & Industry has organized a study on robotics in diagnosis, surgery, rehabilitation, nursing and drug handling, whose conclusions have identified the development of robots for the assistance to the disabled or elderly as a key area of application for robotics in medicine, with a significant market expected for it (11).

Although in the U.S.A. some other groups have been active or have recently initiated new programs in the field of rehabilitative robotics (for instance, at Carnegie Mellon University, Pittsburgh, PA) (12), the project on rehabilitative robotics being carried out for about ten years at the Rehabilitation Research and Development Service at the Veterans Administration Medical Center in Palo Alto, CA, jointly with Stanford University, and directed by Larry Leifer, can be regarded as an excellent example of thorough consideration of the real needs of the disabled, skill in practical implementation and extensive clinical testing of some fundamental concepts of rehabilitative robotics (13).

The Stanford researchers have pursued a very pragmatic approach based on the explicit statement that trying to restore the manipulation capabilities of a disabled by imitating the anatomy of the lost limb rather that its functions is misleading. According to the Stanford researchers, in fact, the wish of replicating the anatomical features of the lost upper limb impose, at present, too severe technological constraints to the design of a robotic aid, ultimately limiting the functional performances of the system. The most significant achievement of the Stanford group is probably a robotic aid workstation for enabling a quadriplegic to accomplish some everyday eating and hygiene tasks. The system, developed by a team of engineers, therapists and users, incorporates a human-scale industrial manipulator (Unimation PUMA), microprocessor-based voice command and synthesized voice response units, a two fingered gripper with simple sensors and mixed mode hierarchical control software running in a number of independent microcomputers. Tests carried out on more than one hundred quadriplegic users have indicated that the psychological acceptability of the robotic aid is satisfactory, and that it can make a valuable and effective contribution to the rehabilitation of severely disabled individuals.

4. A SCENARIO FOR AN INTELLIGENT REHABILITATIVE ROBOTIC AID

As already pointed out, a rehabilitative robotic aid should incorporate some degree of intelligence in order to reduce the mental load of the user. In practice, it would be highly desirable that the robot system were capable of understanding and executing such synthetic commands as, for example, "give me a glass of water" or "serve me a ripe pear", and so on. Among the many complex problems implied in the design of an intelligent interface between the user and the robot system able to manage the above tasks, our research interest has been drawn by the specific problem of investigating how tactile sensing can be used for executing tasks requiring sophisticated manipulation capabilities.

One of the implications of the ability to interpret synthetic orders is obviously the existence of an adequate model of the environment, or the ability of the system to generate it if not available. A fundamental contribution to a thorough definition of the "world model" for the robotic aid derives from tactile exploration. In fact, the sense of touch can be used: a) to integrate other sensory modalities (vision, proximity, hearing, smell, etc.) in order to generate information (what is the shape of the bottle and of the glass? what is a "ripe" pear?) useful to create a model of the environment; b) to assist the system in the identification of the actual status of the environment when the robot is required to execute some tasks; and c) to drive sensor-based manipulation during these tasks.

Based on this premise, we elected to investigate artificial tactile perception as a means to provide a fundamental skill to a future truly advanced rehabilitative robotic aid. In particular, the ability to physically interact with the human body would be quite important for an advanced robotic aid in order to execute some simple diagnostic or therapeutic procedures on the user, for instance by palpation. Such ability would also be attractive for some other applications of broader potential interest in the field of biomedical robotics, for instance for automated diagnosis (14).

In order to investigate this problem we conceived an idealized general scenario, such as the one sketched in Fig.1, in which, for ease of investigation, manipulative and sensory functions are separated and attributed to a PUMA arm and to a single anthropomorphic finger, respectively.

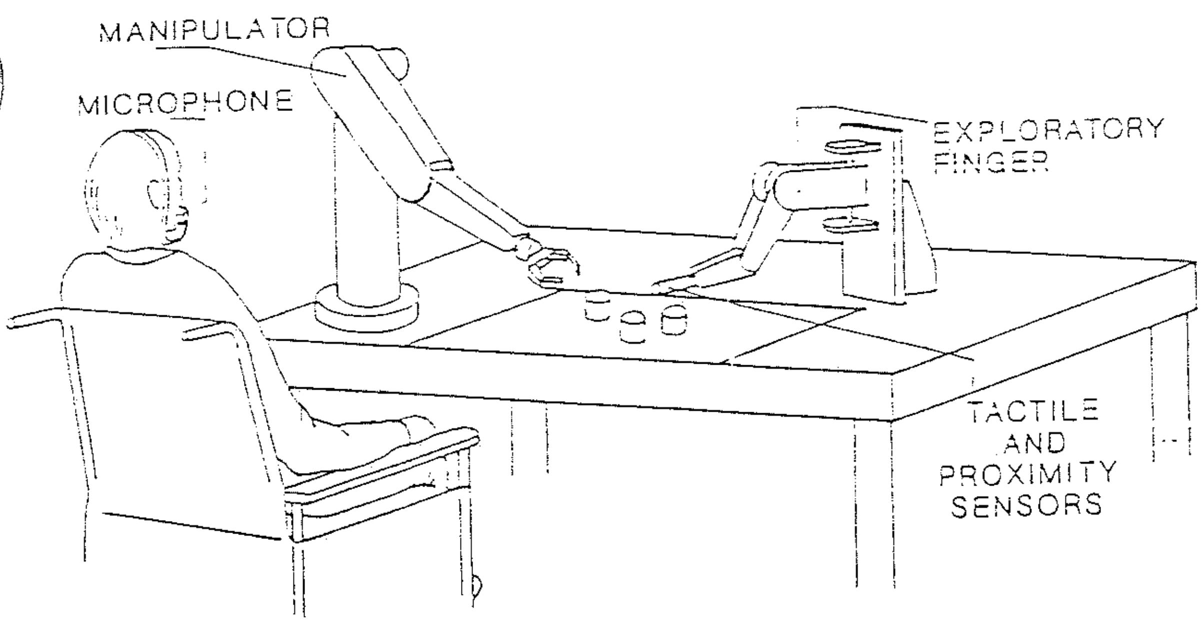

Fig. 1: Scheme of a possible robot workstation for disabled assistance

In the following, some peculiar features of the robotic finger system are discussed. We intend to incorporate these features also in the fingers and in the control architecture of a future articulated hand, which will be eventually mounted on the wrist of the PUMA arm. A few experimental results demonstrating the ability of the system to carry out delicate palpatory procedures aimed at sensing some different body features are also reported.

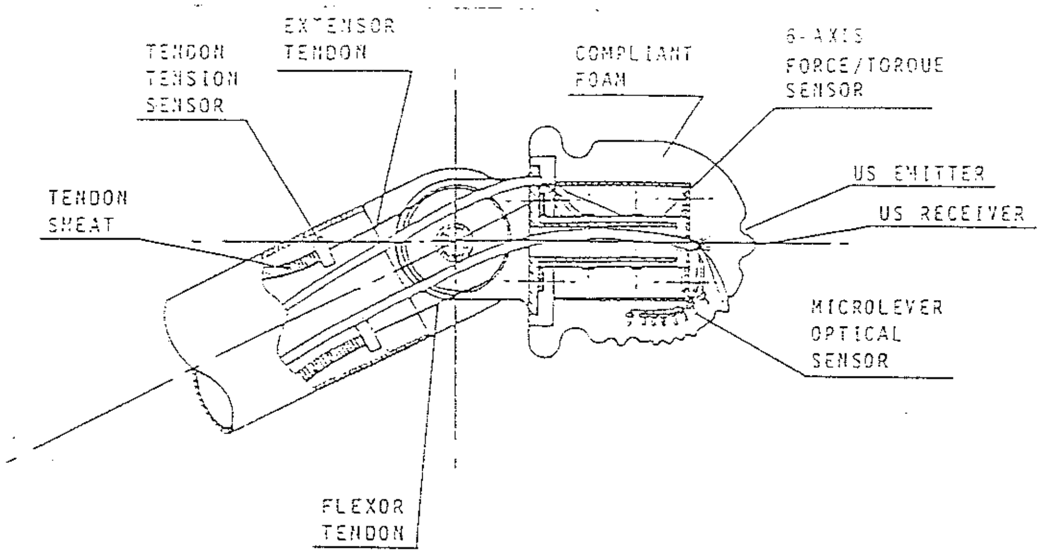

Fig. 2: Cross section of the fingertip showing the strain gauge-based force sensor, the optoelectronic tactile sensor and the US range sensor.

5. THE ROBOT FINGER

The exploratory finger is composed of four rigid links connected by hinge joints. Compared with a previous version of the finger we described in other papers (15)(16) (and that we have actually used in some of the experiments described in this paper) some important modifications are being studied for the sensors and the actuators in order to optimize finger performances during the delicate sensory-motor procedures we intend to investigate. A preliminary description of this multisensor fingertip has been presented in (17).

A sketch of the fingertip, showing the three different types of sensors it incorporates, is reported in Fig. 2.

The structure of the fingertip has been designed to include a resultant force/torque sensor at the base, an array of optoelectronic tactile sensors at the cover, and an external undulated array of piezoelectric polymer ultrasonic (US) range transducers conforming to the tactile sensor underneath.

A seeming dilemma that we have tried to solve is that between the need for accurate force sensing and the interest for local information on contact features. The solution we propose is to assign these two sensing roles to distinct devices (18): the force/torque sensor is purposely designed to accomplish the sensing functions required for finger low level compliant motion control, while the tactile sensor array has the primary function of sensing local object features mainly for perceptual purposes. The US range sensor also contributes to the finger ability to comply with variable environmental conditions by providing not only relatively long-range information on the presence of objects, but also middle- and short-range data usable to reconstruct some geometrical object features. Thus, the range sensing array allows to control the approach motion to an object as well as to extract "pretactile" non contact information on the object through appropriate exploratory movements.

Let us now briefly consider the functioning of each individual sensor.

In general, a force sensor is a device which measures, in a particular coordinate frame, the six components of the "generalized force" vector (i.e. three pure force and three torques) that is exerted through the sensor itself during contact. This task is usually carried out by measuring the deformations that the applied load originates in a suitable mechanical part of the sensor. So far, most force sensors have been developed to fit the wrist of a robot arm; thus, specifications concerning size, weight, robustness, etc., differ considerably from those required for a fingertip force sensor. A fingertip force sensor has been recently developed to be incorporated in the finger of the Stanford/JPL hand (19). Although this sensor turned out to be rather efficient, it is rather complex and delicate; a simpler structure may be desirable in order to integrate the force sensor with other sensors in the same fingertip.

We devised an extremely simple, miniaturized sensor configuration in which the deformations of a thin walled cylinder originated by the contact force are transduced by the minimal number (i.e. six) of strain gauges (20). In the theoretical analysis that supports the design of this optimized force sensor, particular attention has been devoted to render the linear system of equations that relate strain measurements to the unknown components of the external load as well conditioned as possible.

It is also worth observing that a force sensor mounted in the fingertips of a robotic hand can be useful not only to detect the six components of the resultant contact force vector (thus being immediately useful for the force-servo loop control), but also, provided that some reasonable hypotheses are verified, to calculate the point of application and the direction of the resultant force vector (thus providing information usable also for perceptual tasks) (21). We have verified experimentally that a simple and cheap foil strain gauge-based force sensor located at the base of a spherical fingertip having 26 mm diameter can detect forces as small as 0.1 N with an accuracy of 2%; the sensor also allows to calculate the location of the point of application of the resultant contact force with an error smaller than 1 mm in a force range of 0.1 - 30 N.

One of the above mentioned hypotheses is that only pure forces (no torques) are exerted through the fingertip contact area. ~~Such point contact is somewhat unrealistic in the~~ frequent case of very compliant finger pads (a convenient solution for achieving better grasping stability). Furthermore, fine manipulation and palpation may require extracting very detailed information on local contact, both in terms of force sensitivity and of spatial resolution. Skin-like tactile sensors distributed on the fingertip pad and capable of resolving the local distribution of contact forces may effectively integrate the force sensor for the control of delicate manipulation as well as provide specific information on geometrical and other physical features of the objects belonging to the work environment.

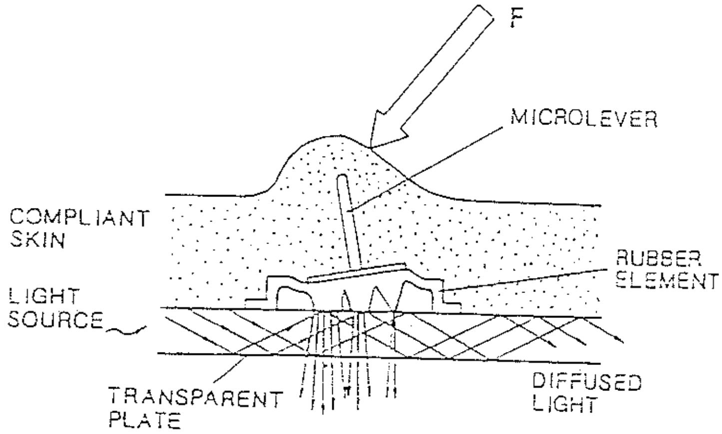

Fig. 3: Principle of transduction of the optoelectronic tactile sensor

We have investigated an approach to the design of a conformal fingertip tactile sensor based on an optical transduction principle that involves the frustration of total internal light reflection. This principle can be illustrated referring to Fig. 3.

The light emitted by a constant intensity optical source is guided into a transparent plate, shaped as the fingertip pad, by total internal reflection at the air-plate interface. If a rubber element located at the top surface of the transparent plate is pressed on it by the external load, the rubber-plate contact surface varies, thus influencing the local light reflection conditions. The light diffuses out of that area, in an amount proportional to the dimensions of the contact area and hence to the local indentation of the rubber.

By improving on previous examples of tactile sensing devices based on the total internal light reflection technique, we have designed a fingertip-shaped tactile sensor that incorporates an array of microlevers capable of detecting locally both normal and tangential actions. The array of microlevers is embedded in an undulated urethane layer forming the compliant cover of the fingertip. As shown in Fig. 3, each microlever is rigidly connected to a base incorporating three conical rubber elements. When the microlever tilts upon application of an external load, the three cones press on the plate originating a distribution of diffused light intensities that can be either collected by individual optical fibers and read by an array of photodetectors, or detected directly by a CCD located inside the fingertip with the interposition of a suitable lens system. During preliminary tests, each sensing element exhibited a force sensitivity of 0.01 N, with non linearity and hystheresis (combined) better than 3.6 % F.S.O., a measurable force range of 0-1 N and a bandwidth of 25 Hz. More details on this sensor have been given in (22).

As preliminarily investigated by Schoenwald and Martin (23), it is possible to use polyvinylidene fluoride (PVF2)-based curved transducers to emit and receive US waves. We have elaborated this idea and designed an array of curved, alternatively concave and convex, transducers using a 25 micron thin film of the piezoelectric polymer PVF2. Each concave

(Tartarini Sonia)

element emits a focused US beam, while each convex element forms a wide acceptance angle US receiver. The easy conformability of the PVF2 film allows to vary the shape (hemispherical or hemicylindrical) of each element, its dimensions and the pitch of the array.

The PVF2 array has been designed so as to cover, as illustrated in Fig. 2, the undulated pattern of tactile sensing elements underneath, which is arranged in a variable pitch pattern. This is intended for obtaining a central high sensor density area that implements the concept of a "tactile fovea", i.e. an area where most sophisticated sensory functions, both in terms of spatial resolution and of different sensed variables, are concentrated.

The US transducers located in the foveal area have a small radius (about 1-1.5 mm), that is they emit an US beam focused at a short distance (usually 10-30 mm). This feature fits the aim of concentrating fine (i.e. high resolution and short range) exploratory capabilities in the foveal region of the fingertip. Additional US transducers are disposed on the residual surface of the fingertip with an increasing distance separating their centers and a larger radius (about 3-4 mm), thus focusing at larger distance (50-120 mm) from the fingertip. Preliminary experimental results on this US array have been presented in (17).

An interesting new feature is also being added to the finger: an ad hoc designed shape memory alloy (SMA)-based motor devised for providing direct drive actuation to the finger joints. Direct drive would be particularly beneficial in order to improve the control accuracy of fine manipulation tasks: in fact, it eliminates the need for long tendons and complex routings inside the fingers of the end effector (presently adopted in most advanced articulated hands), thus reducing the negative effects of friction and elastic deformations inevitably associated with tendon actuation.

The design philosophy and the operating principle of this SMA actuator have been discussed in detail in (24). The SMA actuating module, depicted in Fig. 4, includes two counteracting units, (1) and (2), each incorporating SMA coil-type springs.

A thermoelectric heat pump (3) is sandwiched between the two SMA units. The SMA elements contained in each module are connected mechanically in parallel and electrically in series, in order to increase both electric resistance (thus facilitating electric heating) and actuating force. Each module actuates a joint through short flexible tendons, whose tension is monitored by strain gauge-based devices. Joint rotation is measured by a position transducer. The temperature of each SMA unit is monitored by a thin, fast thermocouple located close to the SMA coils. The SMA module operates as follows: starting from the initial position one unit ("agonistic") is electrically heated above the austenite transition temperature, while the elements of the counteracting unit ("antagonistic") are cooled below the same temperature. The agonistic unit is heated by controlling three different heat sources: a) the electric current flowing through the SMA coils; b) the external thermoelectric device (A), which pumps heat from the environment into the unit; and c) the internal thermoelectric device (3) which pumps heat from the antagonistic unit (2).

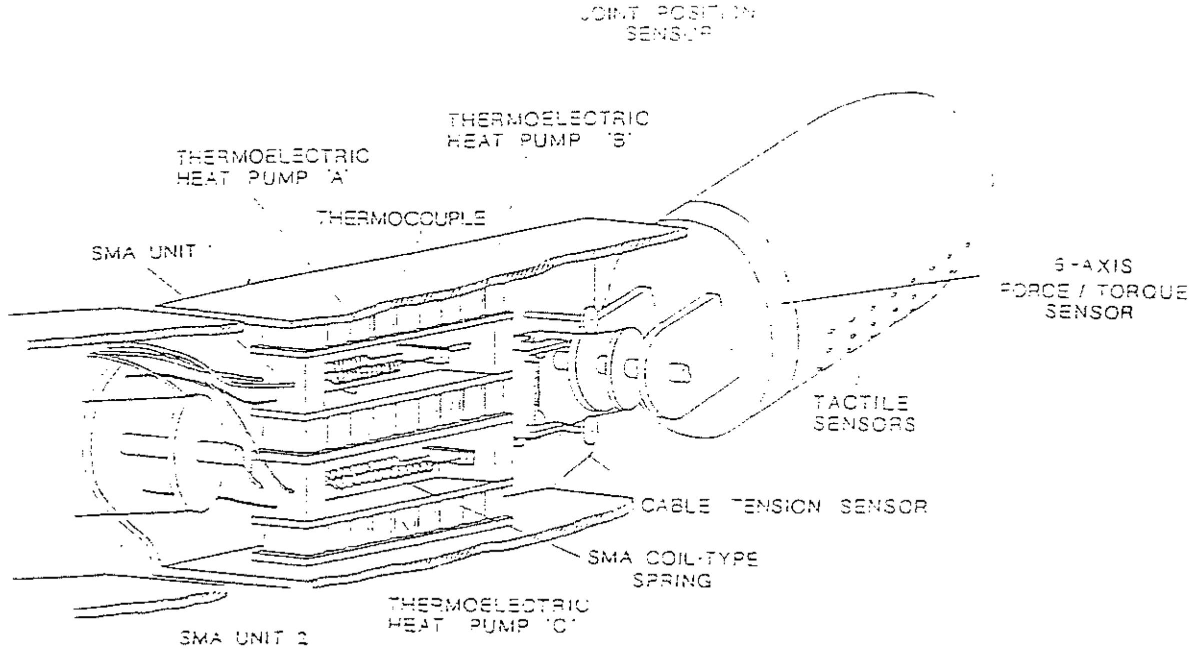

Fig. 4: The SMA actuating module incorporated in a link of the articulated sensorized finger.

Analogously, the antagonistic unit is cooled by (B) and (C). When a unit is heated, the SMA coils belonging to that unit tend to contract towards the shape memorized during a previous annealing process. The force resulting from the phase transition occurring in the SMA is used in part for actuating the joint and in part (about 10%) for elongating the antagonistic SMA elements. A rather sophisticated control system has been devised and is being implemented for controlling the SMA module.

Preliminary experimental results indicated that, provided that the SMA temperature does not exceed a limit value, the actuator can exert a variable force at costant strain, a fundamental property for an actuator to carry out effectively fine manipulation tasks. During isotonic (i.e. constant force) tests, a module incorporating three SMA coils , each having a diameter of 1.45 mm, a memorized length of 63 mm, and made out of 0.45 mm diameter Titanium Nickel alloy wire, lifted a load of 10 N for a stroke of 10 mm. The total weight of the module is less than 50 g and the frequency response 0.11 Hz (quite low, but improvable; sufficient, anyway, for the usually slow fine manipulation tasks).

6. EXPERIMENTAL PROCEDURES

As the new finger is still in its developmental stage, we elected to use an existing version of the finger for carrying out some experiments aimed at investigating tactile exploratory paradigms useful, as explained before, both directly and indirectly for rehabilitation purposes. We summarize here the characteristics of the system architecture that are relevant to the specific application considered in the present work.

The robot system consists of three blocks: 1) a high level "expert" system, at the top of the control hierarchy (this "expert", which decides the overall diagnostic strategy consisting of sequences of tactile exploratory "subroutines" coordinated at the intermediate control level, might be the same disabled user; the "expert" should also be capable of processing and interpreting the data provided by the finger sensors); 2) a middle-level block that controls the execution of tactile subroutines; and 3) a low level block comprising the hardware components: the finger with sensors, motors and drivers, preprocessing electronic units, and other sensing devices (for instance, a TV camera).

In the version used for the following experiments the finger, that is intended to imitate functionally the index finger of the hand, has four rigid links individually actuated by dc servomotors via Bowden cables. The finger also incorporates position, velocity and torque sensors at each joint, as well as piezoelectric polymer-based tactile sensors at the fingertip.

The fingerpad-shaped tactile sensor comprises a "bilaminate" sensing layer, made out of two 40 micron thick PVF2 films, on which an array of 7 circular sensing sites (diameter 1.5 mm, center to center spacing 2.5 mm) has been obtained. The sensing layer is backed by a 1.5 mm thick silicone rubber layer, that provides some compliance to the contact surface and increases the strain sensitivity of the piezoelectric film sensor by allowing it to operate like a flexible membrane. Every exploratory strategy includes positioning first the fingerpad on the body part to examine; then, both contact force and finger position are finely adjusted in order to optimize the detection of the desired body feature through the tactile sensing element located directly on that area. The tactile sensing elements, which respond primarily to strain, are able to detect not only tiny surface features, like roughness, but also other object characteristics such as elastic or thermal properties extremely useful to create an accurate model of the environment. In the context of the present paper, however, the tactile sensor is considered as a membrane sensor responding only to the combination of normal and tangential strain acting at its surface.

A number of different tactile subroutines can be executed. For instance, it is possible a) to control the motion of the finger towards an object and to anticipate two potentially dangerous situations (hot or sharp objects) by exploiting the high pyro- and piezoelectric sensitivity of the epidermal sensor; b) to follow the surface of an object and to infer its 3D shape; c) to sense surface roughness, and to probe d) the elastic and e) thermal properties of the materials the objects are made out (25).

We have elected to investigate here the possibility of using our tactile system to carry out procedures of potential rehabilitative interest, such as sensing by palpation arterial pulse and hard inclusions (i.e. nodules) embedded in a softer tissue.

The subroutine "PULSE" is a sequence of sensory-motor acts, that has been devised to command the robot finger to search, by palpation, the radial artery pulse at the patient's wrist. During the execution of PULSE the finger is pressed

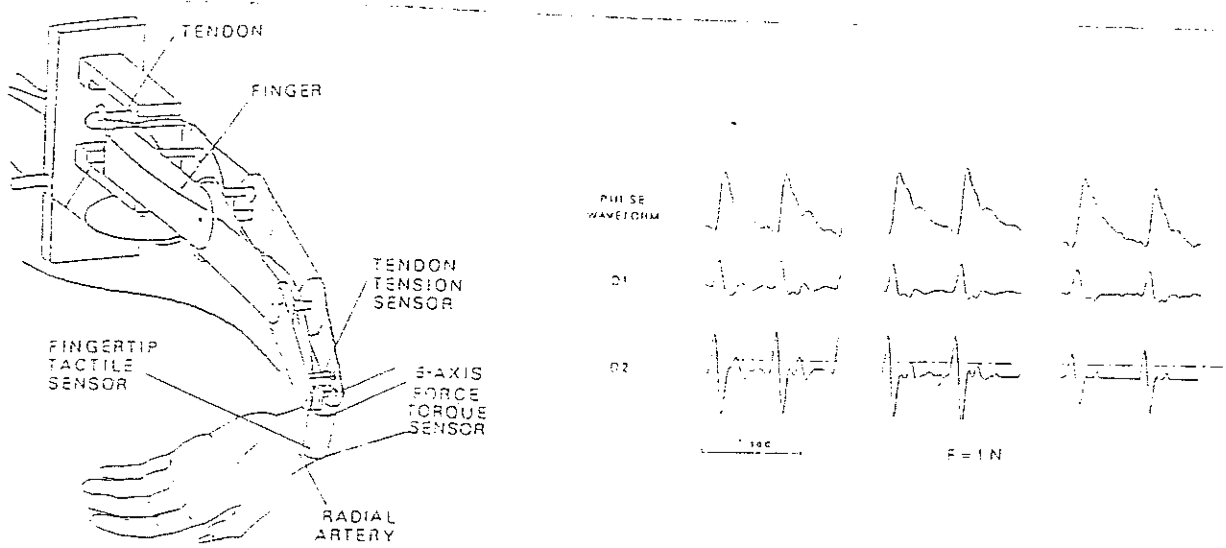

Fig. 5: Sketch of the robot setup for sensing the arterial pulse (left). The pulse waveform recorded at the same wrist location, with the calculated first (D1) and second (D2) time derivatives, allowing to detect the dicrotic notch, are also shown (right).

against the patient's wrist with an adjustable contact force (measured by the joint-torque sensors), while exploratory movements are commanded in order to optimize the pulse waveform signal detected by the tactile sensor (see fig.5 left).

The waveform is perceived as optimal when: a) pulse amplitude is the largest, and b) the dicrotic notch is clearly detectable. The first condition is related to the position of the finger on the wrist, while the second depends (for the same finger position) on the pressure exerted by the finger on the artery. At present, the search for optimal pulse waveform is carried out through a two-step procedure, in which finger movements and force adjustments are commanded sequentially. An example of pulse waveform detected by the PVF2 sensor when the fingertip exerts a contact force of 1 N on the wrist of a healthy patient is shown in Fig.5 right.

The subroutine "PALPATION" is intended for controlling the robot finger to sense hardened regions in soft environment, as shown schematically in Fig.6, left.

A sort of anthropomorphic phantom breast was prepared with two layers of high density urethane rubber (Young's Modulus Y = 10 MPa, in the small deformation range). A few spherical inclusions, having the same diameter (10 mm), but made out of different materials (high density styrofoam, with Y = 2.5 10 MPa; polyethylene, with Y = 1.5 10 MPa, and stainless steel, with Y = 2.1 10 MPa), were embedded between the two rubber sheets (each 10 mm thick). The phantom was posed in the working area of the robot finger, and the finger was then commanded, through the subroutine "PALPATION", to press the phantom on and

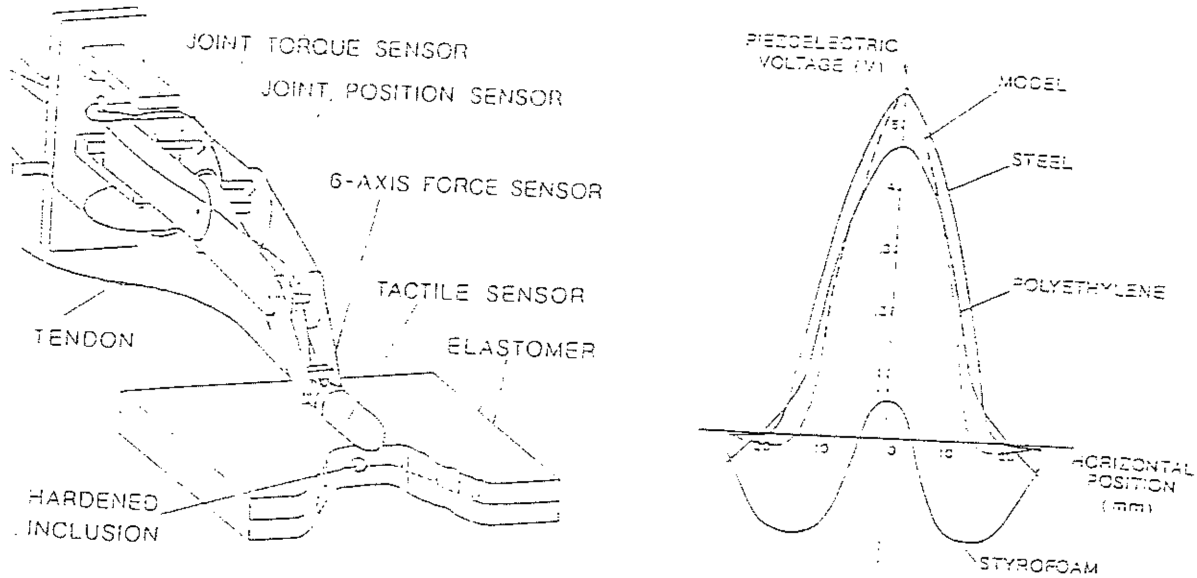

Fig. 6: The anthropomorphic finger sensing a hardened inclusion in a soft environment by palpation (left). The finger sensor output for different spherical inclusions (diameter = 1 cm, depth = 1 cm) is also shown (right).

around the areas in which the spheres were embedded. The typical imparted force law was sinusoidal, with frequency 1 Hz, offset force 2 N, peak-to-peak force 1 N. After each palpation test, the finger moved a 1 mm step laterally. The peak-to-peak amplitude of the signal detected by the tactile sensor element in contact with the phantom breast was recorded during each palpation procedure. These values were used to draw the diagrams of Fig.6, right, which show a clear peak in correspondence with the center of the spherical inclusion, and a marked dependence of the signal on the material of which the inclusion is made out.

7. CONCLUSIONS

The approach proposed in this paper, although supported at present only by very preliminary theorethical analysis and experimental results, seems promising for a number of reasons.

First, the problem we are investigating is susceptible of being extended to cover a variety of aspects related to the robotic assistance to the disabled. In fact robot technology will have a significant impact on health care only after that the hardware and software tools required for a robot to be capable of controlling the contact force it exerts on the patient body are available. In this context, the ability of palpating soft biological tissues is a sort of basic skill that every real "biomedical" robot should possess.

A second comment relates to the design of the robot finger and of the multilevel control architecture devised for commanding finger motion and for processing sensory signals. Originally proposed for investigating basic sensory-motor modalities of tactile exploration, the hardware and software components of the robot system demonstrated to be very flexible: in fact, besides the two exploratory procedures based on palpation that we have illustrated in this paper, other sensory-motor sequences are being considered both for diagnosis and for therapy.

Many problems remain to be solved. Some of them are technological, and relate mostly to the reliability of the mechanical structure of the finger, and to the performance of the tactile sensors. Hopefully, both aspects will be improved in the new version of the finger. Other difficulties derive from the complexity of the overall control architecture, even if most of the sensory-motor processes we are considering are intrinsically slow, and hence not really demanding in terms of real-time operation.

A final observation relates to the use of this approach to a real rehabilitative robotic aid. We believe that, despite its complexity, the attempt of investigating the type of problems outlined in this paper is worth being carried out if a general solution is to be obtained for a robotic aid.

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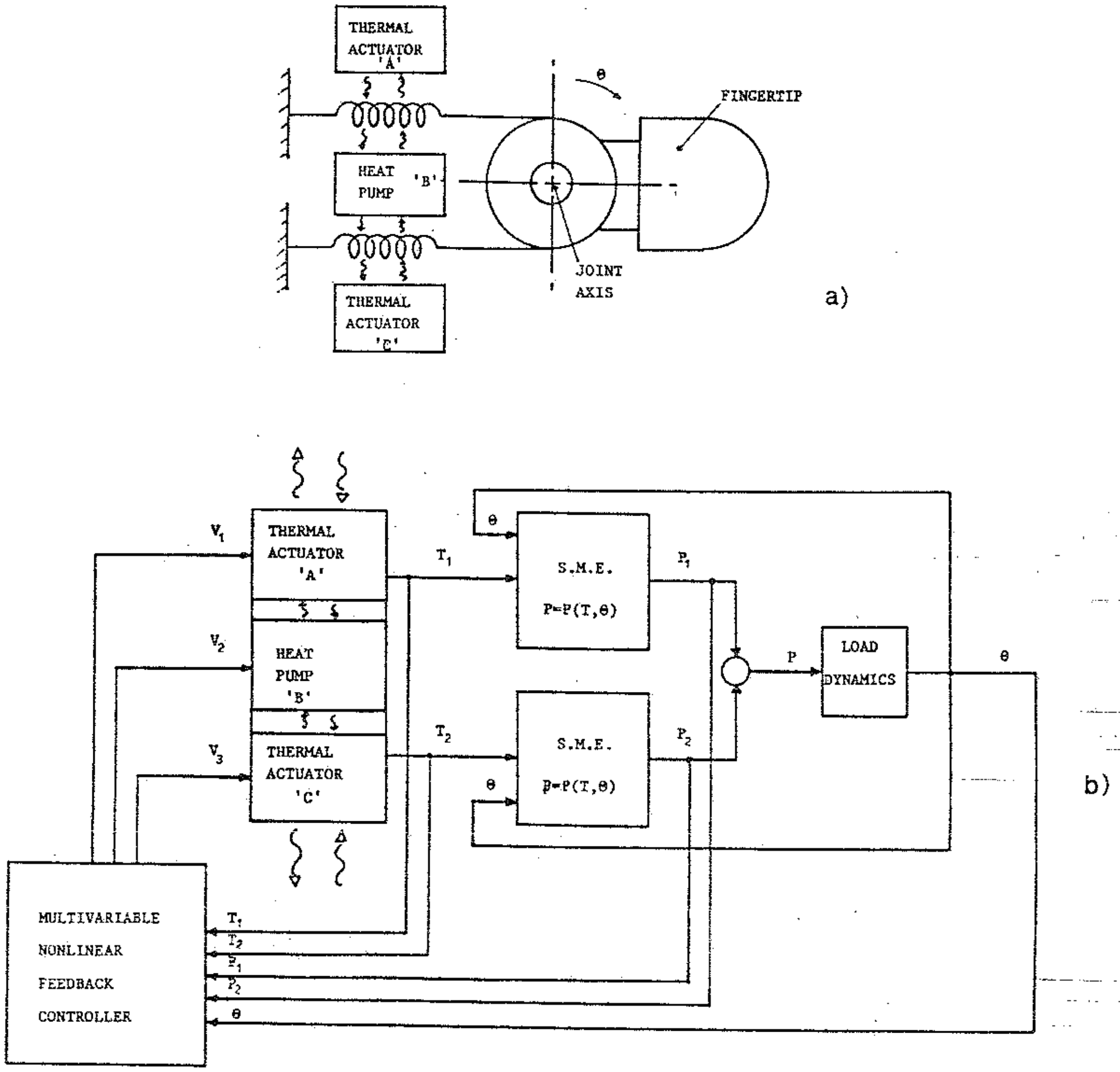

Figure 3. Scheme of a push-pull SMA actuator (a), and block diagram of a possible closed-loop control architecture (b).

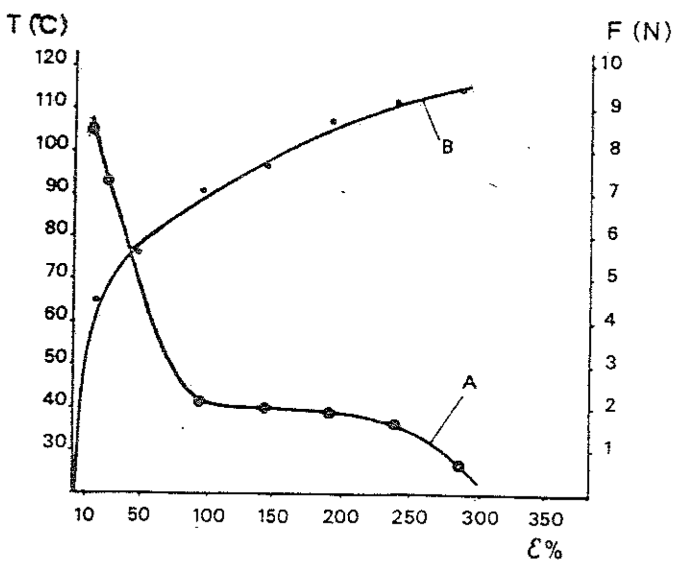

Figure 4. Results of isometric tests.

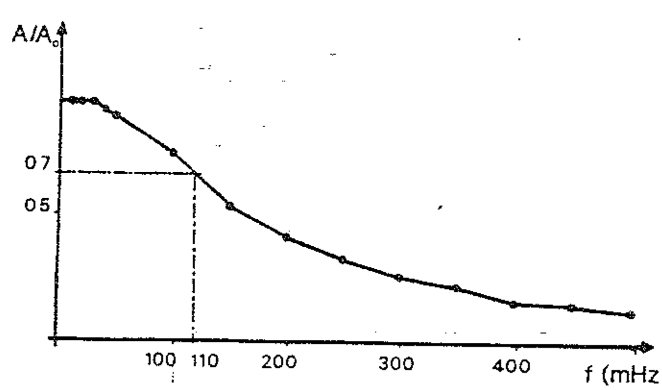

Figure 5. Amplitude vs. frequency plot.