MEDICAL MANIPULATORS, TECHNICAL AIDS FOR THE SEVERELY HANDICAPPED.

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1. Introduction.

The rehabilitation of severely disabled patients, e.g. tetraplegics with high lesions, has brought up a great number of problems which have not been solved yet. The difficulties in solving these problems stem from the fact, that they all are interconnected and that a solution of one singular problem does not automatically mean a progress in the rehabilitation of these patients. The loss of control over the lower extremities primarily causes all sorts of locomotion problems, but nowadays means can be provided, by which the patient can move around independently at least in a limited area cleared from larger obstacles. This, and the freedom of his upper extremities from bodily harm in most of the cases will be a solid fundament of a successful rehabilitation. The range of possible vocations for these patients is large because besides their intellectual capabilities their skill of the hands can be taken into account. This not only opens them a large field of free and independent occupation but also guaranties general independence in daily life activities.

Severely disabled, however, e.g. patients who have also lost control over the greater part of their upper extremities are completely dependent from the assistance of other people
For several reasons the development of 'medical manipulators', as they were called, turned out to be much more complicated than the corresponding development of manipulators for industrial automation. First of all industrial robots and manipulators were designed for only a few tasks with very many repetitions of the same task in an environment with a strictly organized state of order. Medical manipulators, however, had to be designed for a larger variety of tasks in a more or less random environment, and therefore could not be controlled by rigid programs but required a flexible control completely open to the changing intentions of the disabled operator.

Additionally the design of medical manipulators is confined by two interconnected limitations. Because of the heavily reduced motor functions of the disabled operator that were to be used to control the manipulator only a reduced amount of information would be available for control purposes. Consequently a mechanical device with a rather modest dexterity had to be chosen. The dexterity of this mechanical device in all cases was poor in comparison to the general dexterity of the human hand-arm-system, of course. The tasks of the medical manipulator, however, required a very high dexterity, e.g. the handling of books and files and using a typewriter. This mismatch between rehabilitational requirements and technological possibilities can partly be overcome by submitting the environment of the medical manipulator to a strictly maintained order of objects, as it is normally done in industrial automation.

This briefly summarizes more or less the general experiences made by all the groups in various countries occupied with the design of medical manipulators. A number of systems has been developed in those countries, some of them are still in the process of being developed and nearly every system is in its mechanical part based on one or the other design of a technical or industrial manipulator, a prosthetic device.
in locomotion and daily life activities. Additionally rehabilitation has become far more complicated because it no longer can be based on manual skill and intellectual capabilities but must be based on the latter alone, which generally require much longer times of education. But even the most intelligent severely disabled patient needs a minimum of motor activities for a predominantly intellectual occupation: handling of books and files, and writing, which he cannot perform without human help. So one basic problem of the rehabilitation of these severely disabled patients was and still is whether or not it is possible to provide technical aids which allow them that minimum of independent individual motor activities necessary for a predominantly intellectual occupation or vocation.

On the other hand in the course of the last ten years tremendous progress has been made in the field of industrial automation. Today various types of robots and manipulators reliably replace the human worker at many places where he was submitted to work unfavorable to his health, to dangerous and to tedious work. At the same time efforts have been made in nearly all the technologically developed countries to take advantage of the progress in industrial automation for the design of sophisticated technical aids for the severely handicapped. The basic idea was to provide patients whose functions were reduced to only a few movements of head and shoulders with aiding manipulators controlled by these residual functions. The aim was to achieve at least a part time individual independence of the patient.

The very first realization (1966) of that aim was the so-called 'Rancho Arm', an electrically powered seven degree-of-freedom splint structure. This arm was primarily controlled by the well known tongue switch and was designed to assist the rehabilitation of severely disabled patients. It was connected to the wheelchair. It not only was applied in the field of rehabilitation, but also with many modifications used for various manipulator studies.
or a teleoperator. The report of the 'International Conference on Telemanipulators for Physically Handicapped' held in 1978 in Rocquencourt (France) gives an excellent general account of the state of the art in the field of medical manipulators. Although many different designs have been presented at this conference only a few have been thoroughly tested with patients in practical application. One of the latter ones is the German system sponsored by the German Federal Ministry of Research and Technology and by the Deutsche Forschungsgemeinschaft. Since the author is most familiar with this system it may serve as an illustrative example of the design of medical manipulators and of the experiences that have been made with medical manipulators and severely disabled patients.

2. The design of the mechanical system, the control system, and the adapted environment.

The design of the German medical manipulator system was based as far as possible on the statements of 75 tetraplegics who were questioned about their needs and their expectations. Although many of their proposals were unrealistic a number of remarkable hints were given by these patients. Their statement that a technical aid like the medical manipulator would only be accepted by tetraplegics if it was subjected to the unlimited supremacy of the disabled operator and that no automatic action of the system should be allowed was one of the fundamental design aspects. The whole system was divided into three subsystems: the mechanical system, the control system and the adapted environment. As has been mentioned in the introduction the design of the three subsystems had to be mutually adapted. The following general conception was adopted: To design a simple mechanical system which could be controlled by the minimum of information available from the disabled operator and to construct an environment around the manipulator which was adapted to its limited dexterity and nevertheless allowed as many purposeful actions as possible.
2.1. The mechanical system.

The final result of the development of the mechanical system was an electrically driven rather strong joint manipulator with five degrees-of-freedom. It was designed to transport masses of 5 kg - heavy dictionaries - in its terminal device with a maximum speed of .4 m/sec in any direction with an acceleration of 5 m/sec².

Special care was taken in constructing the terminal device. Because of its compliance a pneumatic actuator was chosen for the prehension device in connection with an additional rubber tipped metal bar, the 'pneumatic finger'. This pneumatic finger was to be used for all those actions which a natural hand normally performs with an extended index finger, because many of the tasks of the medical manipulator involved operations of switches and push buttons. Another major task of the pneumatic finger was turning over single pages in books and files.

2.2. The control system.

The residual motor functions of tetraplegics with high lesions are generally restricted to movements of the head, the lips, the mouth and the tongue. Preliminary control experiments showed that a joy stick controlled by these functions was the most favorable solution for the control input. Analog control was preferred to digital control because analog information was provided by the disabled operator, and rate control was preferred to position control because it seemed more advantageous to let the disabled operator determine the velocity of the manipulator's movements according to his individual capabilities.

At a very early stage of the development of the control system it turned out that end point control or coordinated control of the manipulator joints was unavoidable. The movements of the manipulator end point were described in a cylindrical coordinate system (R,z,\(\phi\)), the shoulder joint being the
Fig. 1: Joy stick displacements and coordinated motions of the manipulator end point.

origin of the coordinate system. The three velocity input commands \((\dot{R}, \dot{z}, \dot{\phi})\) from the joy stick were transformed into three angular velocities of the manipulator joints:

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\mathbf{\dot{v}}(\dot{R}, \dot{z}, \dot{\phi}) \rightarrow \mathbf{\dot{v}}(\dot{\alpha}, \dot{\beta}, \dot{\phi}) = \mathbf{\dot{v}}
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and the transformation was carried out by a microprocessor.

The displacements of the joy stick for mouth control were allocated obviously to the corresponding motions of the manipulator end point (Fig. 1). The up-down displacement of the joy stick caused the up-down motion of the manipulator end point (z-direction), the in-out displacement caused the in-out motion (R-direction) and the right-left displacement caused the rotation about the vertical axis (\(\phi\)-direction).

Two of the three displacements of the joy stick can be switched over to the terminal device control, to the rotation
and the extension/flexion of the prehension device, while the in-out displacement is preserved to allow small corrections of the horizontal position if necessary before prehension. Prehension is controlled by blow and suction through the mouth piece of the joy stick (Fig.1). An additional switch was introduced to bring the pneumatic finger into working position.

2.3. The adapted environment.

Because of its modest dexterity the medical manipulator alone would not be able to replace the human upper extremities to an acceptable extent as has been stated above. But by giving the environment of the medical manipulator a characteristic structure adapted to the modest dexterity of the mechanical system a greater number of purposefull actions was made possible. Care had to be taken, however, that the structure was not perturbated after being set up. An environment having such a characteristic structure was called an adapted environment. The word 'environment' in this context describes all the movable and unmovable objects within the range of the medical manipulator.

Precise prescriptions can normally be given for the structure of the environment of an industrial manipulator, e.g. for a simple pick-and-place system. Because of the greater variety of tasks this is not possible for the medical manipulator. Its final structure of the adapted environment will always be a result of experience and mutual adaptation of tasks for the manipulator and order of objects. But some general outlines can be given: The disabled operator's position must be the centre of the whole system. The disabled operator must be able to overlook the complete range of the manipulator. The adapted environment must be equipped with boundaries to prevent objects from inadvertently getting out of the range of the manipulator.
The tasks of the medical manipulator can be classified into three major groups: taking up, transport, and manipulation of objects, e.g. a dictionary is picked up at its deposition, is transported into the range of visibility for the disabled operator, opened and pages are turned over. In order to make the adapted environment easy to survey it turned out to be appropriate to subdivide it into three regions corresponding to the three major tasks: storage, transport, and manipulation region. The storage region should have easy access, the transportation region was to be kept free from obstacles as far as possible, and the manipulation region should be well in view of the disabled operator. The structure of the adapted environment is also determined by the position of additional equipment which is prepared for being handled by the medical manipulator.

The final version of the adapted environment had the following structure: the disabled operator was sitting at a working table with a motor driven adjustable table top. The joy stick for control input and a remote key board of reduced size for the type writer were mounted to the table easily accessible for the disabled operator. The manipulator was standing opposite to the disabled operator, motor driven rotating shelves were arranged on both sides of the border of the manipulator's range. Additional equipment, a tape recorder, a push button telephon, a typewriter, storage baskets and arrays of switches were deposited well in the range of the manipulator. Two specimen of the final version of the complete system were set up at the end of the technical development.

Among others the following actions could be executed: Operating of switches for the rotating shelves and other electrically powered equipment, e.g. tape recorder. Changing tapes in the tape recorder. Dialing numbers on the press button telephon (special design) with the pneumatic finger.
Taking files out of the storage baskets.
Feeding paper into the type writer.
Turning pages in blocks with the claw and one by one with the pneumatic finger.

3. Applications, observations and experiences.

Many experiments with tetraplegics were carried out in the course of the development of the different subsystems. The aim was to discover whether a specific detail of the design served its purpose or not, and to make improvements as early as possible. Introductory experiments with tetraplegics were carried out on the first version of the complete system in order to get a general impression how the manipulator and the adapted environment worked, and how the execution time of single actions could be decreased. As a result of these repeated evaluations the mechanical system, the control system, and the adapted environment were redesigned several times before a final version could be put together. Tetraplegics were very willing to take part in the experiments and to cooperate for the evaluation.

In another series of experiments with the first version of the complete system selected courses of actions were introduced to tetraplegics, practised with them for a certain time and then tested to get an impression of the learning behavior of the disabled operators and the improvements gained by learning selected motion patterns with the manipulator. The function of the manipulator, the control as well as the structure of the adapted environment was explained to the test subjects by an occupational therapist familiar with the system. Tasks of different degrees of difficulty were selected and the execution times for these tasks were measured after a few trials. Then these selected actions were practised two hours per day for a period of ten days. Complex tasks were practised longer than simple tasks. At the end of the learning phase execution times were measured again. The general result was that execution times could be reduced to roughly the half of what they had
been without practice. Individual differences, however, were large. Turning of one single page in a book lasted for ten seconds! Observations of the supervising occupational therapist as well as suggestions of the tetraplegics were used to further improve the structure of the adapted environment. Later on these experiments were repeated with the final version of the complete system which was working with increased velocity and was more sensitive to control displacements of the joy stick.

Now the test subjects were generally taking longer times to perform a single task in the beginning of the experiments, but after a learning period of 4 hours considerable progress had been made. The tetraplegics felt challenged by the higher velocity of the system and preferred the more sensitive control, although initially it was more difficult to handle. The impressions of the tetraplegics were generally confirmed by the results. The execution times were reduced to less than the half of what they had been at the beginning of the learning phase, but again individual differences were large. Again tetraplegics were willing to take part in the experiments and to cooperate.

In a final series of experiments with the medical manipulator and its adapted environment extensive long time tests were planned with the final version of the set up. With these experiments it was expected to make experiences about the appropriateness of the system for a daily use over a long time. But although all the technical and organizational conditions were met the expected regular use of the system by a larger number of severely disabled did not come. From many tetraplegics who had been summoned to take part in the experiments only two were willing to cooperate. One of them gave up after a short time because of various reasons. He apparently was overstressed by the simultaneous demands of his rehabilitation program and the practice with the medical manipulator. He only used the system rarely and preferred to be assisted by the personnel of the rehabilitation centre he was living in.
Completely different experiences have been made with a disabled student. He had an extraordinarily strong motivation to be independent and made extensive use of the manipulator and the adapted environment during the preparation for his examinations. The adapted environment was modified for his personal needs. It must be admitted, however, that the patient was able to perform the most time consuming actions of the manipulator by his own residual motor functions, like turning pages in a book, etc. He primarily used the manipulator for transportation tasks which he could not perform because of his disability. He was very interested to have the medical manipulator at his disposal for the future time, too.

After that all attempts to find tetraplegics or other severely disabled patients willing to use the medical manipulator for an unlimited time were unsuccessful. A great number of these patients was summoned but in spite of all the efforts of the responsible attendants the system from now on was only used sporadically. How could that be explained?

The technical development of the medical manipulator had been terminated with acceptable results. Tests with severely disabled patients during the development showed that the system was working appropriate under the conditions determined in the course of the research program. The tests also indicated that the medical manipulator would be accepted by the patients as a technical aid. Nevertheless, when the program was finished and completely installed working places were available, no patients could be found willing to use them permanently.

The medical manipulator and its adapted environment allows actions which many severely disabled patients cannot perform without this device. It serves their independence but on the other hand requires a large amount of effort for the control of the feasible motion patterns. A severely handicapped should be glad to make use of the manipulator to occupy himself inde-
pendently at least for several hours a day. But still the disabled patients did not want to accept this offer. Two aspects must be considered in this context, a technical aspect and a rehabilitational aspect.

Objections against the system which can be removed by technical means can generally be raised because of the clumsiness and the long duration of the single actions executed by the manipulator. From a technical point of view this type of a medical manipulator with its adapted environment may be an acceptable but not the optimal solution of the problem to provide the severely disabled with a technical aid for individually independent actions. In comparison to the motion patterns of human upper extremities the system is not flexible enough, clumsy and for simple daily life activities not dexterous enough. Because of the small amount of input information available from the residual motor functions of the severely disabled narrow limits were set for the design of the manipulator and its control which could only be removed a little by the introduction of the adapted environment.

Technological improvements of the system, however, are feasible. It is a generally accepted point of view of nearly all the groups working on similar projects that the supplementation of the control system of the medical manipulator with an adaptive learning system would considerably facilitate the control of many actions in the adapted environment. Additional improvements may be deduced from an empirical development of the adapted environment. Moreover local tasks requiring increased precision control could be supported by the installation of local sensors at selected positions providing information for the control system about the momentary state of the manipulator. Automatically controlled motions of the manipulator which have been excluded because they were rejected by the majority of tetraplegics questioned at the very beginning of the technical design could be reintroduced tentatively to decrease the execution time of some frequent but time
consuming motion patterns. Frequently used information from heavy books and dictionaries could be reproduced by an electronically controlled microfilm reader instead of turning pages with the pneumatic finger of the medical manipulator. These and other technical inadequacies of the present set up could indeed be one reason for the rejection of the system, which by its nature is forced to make normally simple actions time consuming and complicated.

All these arguments are concerning the technical development of the medical manipulator and its adapted environment. One further problem in the supply of severely disabled patients with complicated technical aids is cost. It is a disappointing experience of many severely disabled patients that a complicated and therefore expensive technical aid will not be given to them because of the high cost, although it is generally acknowledged that they really need it. The medical manipulator with its adapted environment still in the tryout phase in the experience of the severely disabled is one of those technical aids which most probably will not be given to them because of the high cost. Why should they bother to learn the handling of the manipulator if it is obvious that they most probably will not have it for permanent use? Perhaps this is an explanation, too, for the minor interest of the disabled in taking part in the long time experiments with the manipulator.

But the rehabilitational aspect must be considered, too. The medical manipulator offers to the severely disabled the opportunity to perform the most important motion patterns for an essentially intellectual occupation. Manual occupation is prevented by their motor disability and no manipulator based on the present state of technology will be able to provide enough dexterity for an essentially manual occupation. Therefore any rehabilitation program for these patients either has to rely on an existing intellectual education or has to include it into the program. There is no question that not too many
of the severely disabled patients already have an intellectual education. This perhaps is another explanation for the dislike of the severely disabled to make use of the possibilities of the medical manipulator.

Medical manipulators and other sophisticated technical aids are designed and constructed by engineers. It is an excellent practice to give disabled patients and occupational therapists a share in the development, as has been done in this research program. But nevertheless, if a general technical device solves an acknowledged problem or solves it better or cheaper, the engineer normally can rely on the fact that there will be a demand, too. It is a very impressive result of this research program that a technical aid is not automatically accepted simply because it meets apparent needs of the disabled. Moreover, this research program suggests that it might be more advisable to imbed medical manipulators and other sophisticated technical aids in a complete vocational rehabilitation program.

4. Improvements of the control system.

As has been mentionned above an adaptive learning system would appreciably improve the control system of the medical manipulator. If the manipulator is used permanently for a greater number of tasks because of the repetition of these tasks certain motion patterns will be developed which are characteristic for the specific use of the adapted environment. Nothing of the control effort for the single tasks, however, is preserved and any repetition of the task again requires the same control effort. But the control effort could be reduced if it was possible to preserve a part of it, or, with other words, if the manipulator would move with always the same precision and velocity although commands of varying precision were given from the control input.

The Deutsche Forschungsgemeinschaft presently is sponsoring a research program to design an adaptive learning system
for the control of the medical manipulator. The adaptive
learning system will be based on statistical learning of
motion patterns characterized by the local velocity vector
of the trajectory of the manipulator end point. If a task is
repeated in the adapted environment many times, all the
corresponding trajectories of the manipulator end point will
lie inside a tube-like hollow body which can be described
by a mean value and a standard deviation of the local velocity
vector. The working space of the manipulator is subdivided
into a number of appropriate space elements, and mean value
and standard deviation of the local velocity vector are
attributed to that space element the trajectory is passing
with a given motion pattern. From the standard deviation a
decision criterion can be derived to make the following
decisions: (1) If the momentary velocity vector is within a
given interval depending on the standard deviation control
is taken over by the learning system. (2) If the momentary
velocity vector is not within the given interval control
is left to the disabled operator. A computer simulated study
in two dimensions has shown that a statistical learning system
of the suggested structure is feasible. The learning program
is now extended to three dimensions.

In our opinion this type of computer based learning is
especially appropriate for the medical manipulator because
the individual skill of the disabled operator is measured by
the standard deviation. By making the memory of the learning
system exchangeable the same manipulator and adapted environ-
ment can be used by several disabled patients having different
controlling skill and different motion patterns. On the other
hand the decision criterion can only work if the disabled
operator feeds in a control signal at the joystick. This
preserves the required absolute supremacy of the disabled
operator, who will never know whether it is he who controls
the motion of the medical manipulator or the adaptive learning
system.
This development is expected to be finished in the next year. We hope to be able then to answer some of the questions still open today.

Literatur.
Colloques IRIA.
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