AN EVALUATION OF SYNERGIC CONTROL FOR THE REHABILITATION MANIPULATOR

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Introduction

The possibilities of restoring some of the manipulative functions of handicapped patients with the help of an externally powered manipulator have been relized for some time. A considerable amount of effort went into bringing these possibilities closer to practical applications. However, few results have indicated any clinical effectiveness of the rehabilitation manipulator. It seems that up to now there have been no results which demonstrate the effectiveness of the rehabilitation manipulator for the most severe case where the patient has none of the natural upper extremity functions preserved.

Problems encountered in mastering, nonmanually, a rehabilitation manipulator pertain to two categories. One category of problems is caused by the limited number of nonmannual control sites in generating control information as compared to the amount of information needed to position a multiple-degree of freedom manipulator. Other problems are "external" and originate from the discrepancy between the geometry of a manipulator and a "natural" geometry in which the operator conceives and observes manipulator motions.

The ability of the handicapped operator to participate in the processes within control loop system absolutely limits the effectiveness of the manipulation. But it has not been possible to assess these limitations experimentally, since they were masked by external effects. Several coordination and geometry transformation schemes were proposed in order to simplify such external control problems /1/, /2/, /3/. By proposing the concept of external synergy, an attempt was made to offer a solution to the control problem general enough to clearly define the operator´s limitations /4/, /5/, /6/. The main objective of this study was to measure the efficiency of mainpulation obtained under non-

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manual command, and to find how close the boundary efficiency could be approached in actual working conditions.

Synergic Control - An Outline

According to the concept of external synergy control, a computing device, acting concurrently with the operator, helps him to overcome the "geometry" barrier and to master the manipulator. The operator's volitional rate commands are superimposed onto a postural system, maintaining the pose of the manipulator in between volitional interventions.

The class of manipulator systems considered here is restricted by following assumptions:

- the manipulator has anthropomorphic kinematics;
- the manipulation repertoire consists of nonrepetitive (random) movements executed solely with visual feedback.

Basic Coordinated Actions

The manipulation repertoire to be performed under the stated assumptions is defined as a set of movements that could be composed of four basic manipulative actions: REACH, MOVE, ORIENTATE, GRASP-RELEASE.

In REACH and MOVE actions the operator controls the current rate of the manipulator end-point motion. But the rules of coordinating end-point and terminal device motions are different in these two actions, as well as the methods for specifying the rate of end-point motion. In the REACH action the operator specifies the end-point velocity vector by two angles (in an environment-absolute reference system) and by its intensity. During this action the orientation of the longitudinal axes of the terminal device coincide with end-point velocity vector (tangential coordination). In this way the terminal device points toward the object to be grasped, which helps the operator to control the end-point motion. The terminal device "drives" the manipulator in the direction of the object to be grasped along a straight line. Even while still in REACH mode the terminal device is made ready for the ORIENTATE action that can start immediately when the end-point velocity is brought to zero. The motion of the elbow plane (formed by the upper-end and forearm of the manipulator) is coordinated with the end-point motion in order to minimize the space required for performing a movement. The motion of the grasping plane (formed by fingers of the terminal device) is coordinated to end-point motion in order to optimize the grasping.

In the MOVE action the operator specifies the components of the end-point velocity vector (in an environment-absolute reference system). The terminal device motion is coordinated with the end-point motion in order to keep the absolute orientation attained at the begining of the MOVE action (translational coordination). Such coordination is important in object displacement movements. The elbow plane is coordinated here with the end-point in the same way as in the REACH action.

Task-Oriented Elementary Motions

An anthropomorphic manipulator is essentially a system of levers (segments) connected at the joints (having one or more degrees of rotation) and actuated by torques applied to the joints. When the manipulator is controlled through positional servoloops the most obvious choice for the reference coordinates defining the position of the system are the relative angles between segments. Such a system of coordinates is predetermined by the characteristics of the manipulator kinematics and consequently is reffered to as much manipulator (arm) - oriented coordinate system. However, when optimized from the operator's point of view, the choice of coordinates is different. Now the coordinate system has to be independent of the kinematics of a particular manipulator and oriented towards the environment and manipulation tasks. Such a task-oriented system has already been implicitly introduced by specifying the repertoire of movements. All anthropomorphic manipulator placed in a task-oriented system of coordinates is shown in Figure 1.a. Each of the task-oriented coordinates describes one elementary (one-dimensional) motion of the manipulator. Elementary motions are mutually decoupled so that both sequential and simultaneous composition of multi-dimensional motions is possible.

Arm position in an absolute $0\xi\eta\zeta$ system is given by intensity of the end-point radius vector ρ and three angles of rotation of this vector: two angles of rotation ω_A, ϕ_A and one angle of axial rotation ψ_A.Similarly, the position of the terminal device is given by two angles of radial rotation ω_H, ϕ_H, and one angle of axial rotation ψ_H. Angles ω, ϕ, ψ both of the arm and terminal device system from triplets of Euler angles, as shown in Figure 1.b. The end-point velocity vector is given in the same absolute $O\xi\eta\zeta$ system by two angles of radial rotation ω_V, ϕ_V, and intensity.

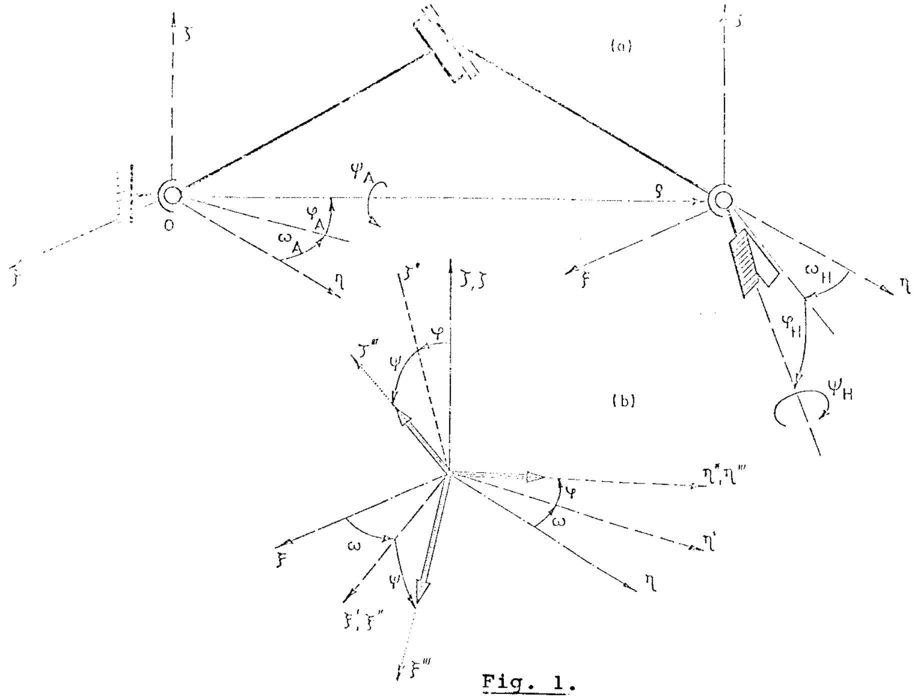

Fig. 1.

Composition of Basic Actions

The process of composing basic action within the context of task-oriented coordinates is summarized in Table 1. Commands coming from the operator are always interpreted as rates of elementary motions. The basic actions of the repertoire could be composed from a set of nine elementary motions, as can be seen from Table 1. This implies that the assistive system should have nine input channels. Input channels must share the available control sites of the operator. Therefore, every command phase in the process of manipulation has to be preceded by a selection phase, in which control sites are associated with some of the input channels. In Table 1, two models of control are described. In the sequential mode the operator generates only one command signal at a time, performing one of nine possible elementary motions. To select elementary motion he wants to perform, the operator has to use separate selection signals. In the parallel-sequen-

Type of Action	ACTION	Composed of Elementary Actions:	Specified by Input Commands -		Coordination
			in Sequential Mode:	in Sequential-Parallel Mode:	
auxilliary	orientating elbow plane	ψ_A	$\mathring{\psi}_A$ (*) (1)	$\mathring{\psi}_A, \mathring{\psi}_H$ (1)	$(\omega_A, \varphi_A, \rho, \omega_H, \varphi_H, \psi_H, p^h) = \text{const}$
	orientating grasping plane	ψ_H	$\mathring{\psi}_H$ (2)		$(\omega_A, \varphi_A, \psi_A, \rho, \omega_H, \varphi_H, p^h) = \text{const}$
actions of terminal device	GRASP-RELEASE	p^h	$(\mathring{p}^l)$ (3)	$\mathring{\omega}_H, \mathring{\varphi}_H, (\mathring{p}^h)$ (2)	$(\omega_A, \varphi_A, \psi_A, \rho, \omega_H, \varphi_H, \psi_H) = \text{const}$
	ORIENTATE	ω_H, φ_H	$\mathring{\omega}_H$ (4) $\mathring{\varphi}_H$ (5)		$(\omega_A, \varphi_A, \psi_A, \rho, \psi_H, p^h) = \text{const}$
end - point actions	REACH	$\omega_H, \varphi_H, \vartheta$	ϑ (6)	$\mathring{\omega}_H, \mathring{\varphi}_H, \vartheta$ (3)	$\omega_H = \omega_v, \varphi_H = \varphi_v; (\psi_A, \psi_H, p^h) = \text{const}$
	MOVE	$\omega_A, \varphi_A, \rho$	$\mathring{\omega}_A$ (7) $\mathring{\varphi}_A$ (8) $\mathring{\rho}$ (9)	$\mathring{\omega}_A, \mathring{\varphi}_A, \mathring{\rho}$ (4)	$(\psi_A, \omega_H, \varphi_H, \psi_H, p^h) = \text{const}$

(*) Simbols with points designate elementary rates

Table 1

tial mode three bipolar command signals have to be generated simultaneously. That way basic actions could be performed by concurrent composition of three elementary motions.

The fact that elementary motions are defined in an absolute task-oriented coordinate system, means that task-oriented coordination results whenever some of the coordinates are kept constant, while others are changing. The elbow plane and the grasping plane are "stabilized", as required by the definition of basic actions, if the angles of axial rotations are kept constant (i.e. inputs $\dot{\psi}_A$, $\dot{\psi}_H$ kept zero). Translational coordination is obtained if the angles of terminal device orientation are kept constant (i.e. inputs $\dot{\omega}_H$, $\dot{\phi}_H$ kept zero). To obtain tangential coordination, however, it is necessary to compute rates of end-point motion $\dot{\omega}_A$, $\dot{\phi}_A$ $\dot{\rho}$ from inputs specifying the terminal device orientation ω_H, ϕ_H and the end-point velocity vector intensity v.

The Structure of Synergic Control

At the highest level of the control structure (Fig. 2) selection signals are interpreted and control sites of the operator associated to proper command inputs of the coordination level. Here the current values of the task-oriented coordinates are computed from the current values of incoming command signals representing elementary rates. On the next level task-oriented coordinates are mapped into manipulator coordinates. The mapping procedure takes into account the kinematic constraints of the actual manipulator. The external synergy system produces at its output reference values for the postural mechanisms.

Evaluation of Synergic Control - Methods and Results

The evaluation programme was performed in a laboratory environment with an experimental assistive system: a demonstration manipulator powered by electric servomechanisms and a digital computer functioning as a synergic controller. The assistive system was designed to have a response time comparable to the response time of a human operator. The maximal angular velocity of the segments of the manipulator was 180°/sec. One computing cycle, in which a sample of a set of input signals is converted into a set of reference values for the servos was programmed to last less than 10 msec.

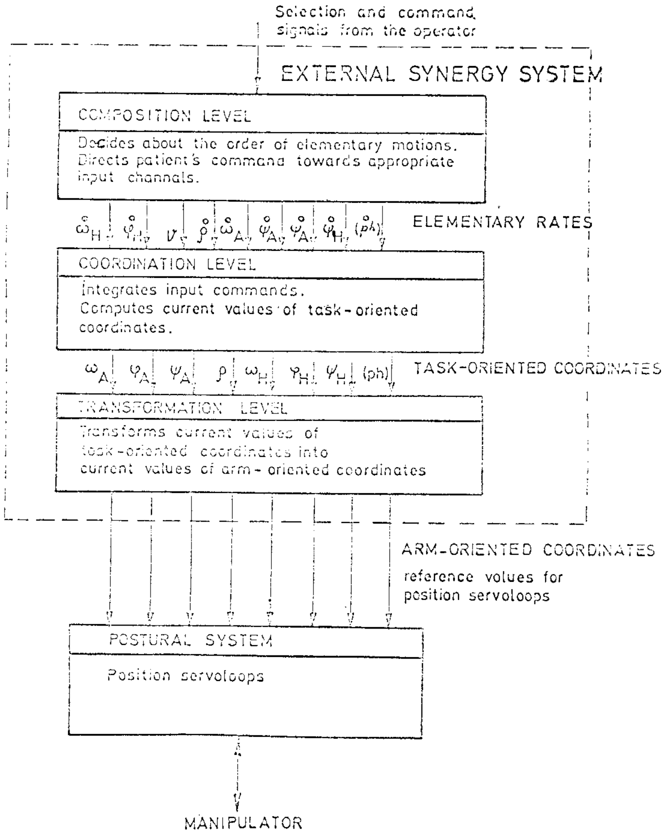

Fig. 2.

Test Movements

The evaluation programme was based on precisely standardized test movements. They were chosen in order to represent the variety of the repertoire of movements with respect to function, complexity and precision. Similar tests have already been used in evaluation of complex rehabilitation devices /4/.

In the Block and Box test blocks are carried from one compartment of a box to another compartment. In the Positioning test it is required to reach for an object and place it onto a special stand. In the Drink test a cup of liquid is to be reached and lifted from a cupboard, brought towards the mouth, a drink taken and the cup placed back to its initial position. The time necessary to perform test movements is measured.

Types of Control that Have Been Studied

Tests performed with synergic control were compared with the tests performed under immediate control (where the operator specifies immediately the angular rates in joints of the manipulator) and tests performed with natural manipulation.

Within the two main types of control considered, synergic and immediate, tests have been repeated both under nonmanual and manual command. In all the four cases test movements were composed sequentially of one-dimensional motions.

Nonmanual selection signals and commands were generated by elevation of the left and right shoulder, each shoulder generating a single polarity signal via a strain-gauge transducer in a quasi-isometric regime (Fig. 3). By time discrimination short signals were isolated from longer signals and used for selection. Pulses generated by fast movements of left or right shoulder forced the unique (bipolar) command channel to cycle (clockwise or counterclockwise) around a "ring" of nine command inputs. The attachment of the operator's command channel to one particular command input was indicated on a display consisting of nine lamps.

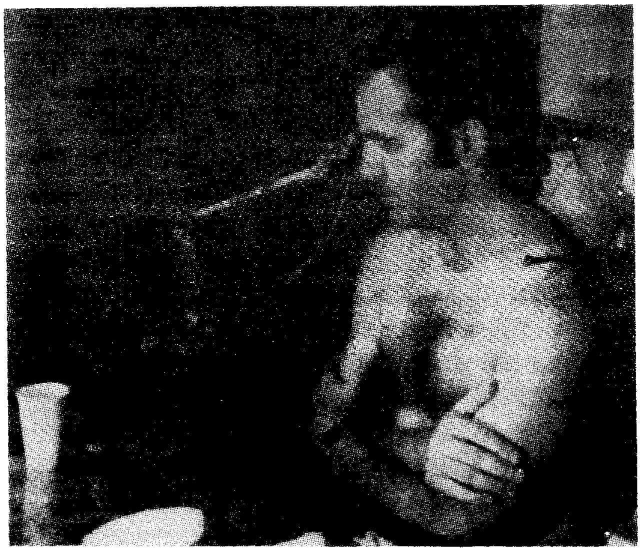

Fig. 3.

When commanding manually the operator used nine separate (one-dimensional, bipolar strain-gauge) transducers in quasi-isometric regime, choosing one at a time.

Under manual command the tests were performed not only in sequential but also in parallel-sequential mode. A joy-stick was used in this case for generating three parallel commands. A switch selector was attached to the joy-stick, enabling selection of one of four provided actions (see Table 1).

Another set of experiments was organized where the real manipulator was replaced by a graphical representation on an electronic display. Controlling the motion of such a simulated manipulator the operator was brought into an ideal external situation. All possible effects of the dynamics of a real manipulator were removed and conditions of observing the motion were ideally stable. The times for carrying out the test movements that could be expected under ideal external conditions, were extrapolated from the results of simulation experiments.

Discussion of the Results

The results of the measurements of the test movements are summarized in Table 2. The figures quoted represent the durations of test movements averaged for a group of 4 normal operators and for samples of 36 repetitions of each test movement, taken after a short period of training. The "Ideal" times obtained from simulation experiments are given in brackets.

Type of control / Test Movement		IMMEDIATE		SYNERGIC			NATURAL MANIPULATION
		SEQUENTIAL		SEQUENTIAL		SEQUENTIAL-PARALLEL	
		NONMANUAL	MANUAL	NONMANUAL	MANUAL	MANUAL	
Blocks & Box test	TIMES IN SECONDS	207	118	38 (25)	28	23	1,1
Positioning test		431	304	65 (40)	45	38	3,7
Drink test		—	—	62 (40)	46	41	3,8

Table 2

Comparing immediate external manipulation and natural manipulation (within the scope of the repertoire of movements that could be performed by immediate manipulation), it follows that immediate manipulation is at least by two orders of magnitude less efficient. However, the results of synergic manipulation are at least one order of magnitude better than the results of immediate manipulation. One important discovery was that in the case of immediate manipulation efficiency decreased rapidly with the increase of the complexity and precision of the movements. It was practically impossible to perform the drink test under immediate control. In the case of synergic control, where tangential and translational coordination were undertaken, the times for the Drink and the Positioning test are in the same range as the time for the Block and Box test, which requires a much lower level of precision and complexity.

The difference in efficiency of manual and nonmanual commands (nonmanual commands are approximately 30% slower) results mostly from the difference in the total time spent on selection. Random selection of one of nine transducers in the manual case is much easier than serial selection in the nonmanual case.

Comparing sequential and sequential-parallel mode, it follows that sequential mode is about 30% faster. The major part of the difference again occurs during the selection rather than during the motion phase.

It was found that synergic nonmanual sequential mode at least 40% of the total time is spent on selection operations. By introduction of a more powerful and more flexible selection mechanism this percentage can be appreciably lowered.

The margin left between real and "ideal" durations of test movements could be further reduced by technical improvements of the manipulator and more extensive training of the operator.

Conclusions

In simulation experiments the operator was performing manipulation under idealized external conditions so that he could maximally exert his abilities in the control process. The results obtaining from simulation experiments show the boundary efficiency that can be expected from synergic manipulation performed solely under visual feedback. Having such an absolute reference and having a standardized test base, it is possible to obtain a comprehensive figure or merit for any real synergic manipulator system.

Evaluation of an experimental synergic manipulation system has shown that

(a) synergic system performs within tolerable time limits (for the complete repertoire of movements) even under nonmanual sequential control (where only one unique selection and command channel was used);

(b) Performance of the synergic system under manual command can be close to the performance of a master-slave manipulator system.

These results indicate that it would be feasible to build a capable, multi-degree of freedom orthotic manipulator with synergic control. Experiments with the evaluation programs have indicated that synergic coordination schemes could be also applied to partial prosthetic and orthotic devices.

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