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A SYNERGISTIC CONTROL FOR BILATERAL REHABILITATION MANIPULATORS

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Abstract

The problem of controlling bilateral rehabilitation manipulators has not received due attention mainly owing to its complexity. In this paper it is shown how this problem can be simplified from the patient viewpoint to the complexity corresponding to unilateral systems by adopting a synergistic control concept. This is very important in rehabilitation where the number of available control sites is strictly limited. An important set of movements was efficiently realized in order to illustrate the control concpet. The coordinate systems necessary for specifying these movements were chosen so that their spatial orientation can be readily assesed by the operator. Problem concerning computation involved, singularities, and kinematical constraints are treated. An experimental evaluation of the concept was performed using stereoscopic simulation technique. The results are presented in the paper. In the conclusion directions for futher related research are poited out.

Introduction

The problems encountered in designing upper-extremity prostheses and orthoses are manifold and usually, difficult to solve. Certainly, one of the most complicated is the control problem. Summarily, the greatest difficulty set before the designer is that of controlling a system with many degrees of freedom (d.o.f.) of an artificial extremity through the limited number of control sites available to the patient. A further obstacle is the fact that such a rehabilitation system should be "patient-oriented". This means that control should be simplified to a

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degree which makes it possible for the patient to readily identify the available repertoire of movements. All ofthis was realized even at the outset of research in artificial manipulation and as a result various solutions were devised /1,2/.

However, little work has gone into investigating possible methods of controlling bilateral manipulator systems (consisting of a right and left manipulator). This is probably due to the fact that as compared to the unilateral case, the bilateral system seems at least twice as complicated. Nevertheless, there is also a need for bilateral prosthetic and orthotic systems. For example, such a rehabilitation system would be applicable to quadriplegic and bilateral amputee cases.

The authors of this paper were interested in the possibility of extending the synergistic control concpet /3,4/ developed for unilateral systems, to bilateral manipulator systems.

Classification of Bilateral Movements

The rehabilitation objective of a manipulator system is to restore the functions of a natural system. In order to obtain a better picture of this objective it is useful to analyse the set of all movements of a bilateral manipulator system. Such an analysis based on the type of manipulation task involved yields the following three general classes of movements of bilateral manipulator systems:

(1) *The class of independent movements,* in which the two manipulators perform their particular tasks independently and concurrently. This class is rarely encountered even in natural systems and is usually restricted to simple manipulation activities.

(2) *The class of complementary movements.* In this case, there is a common manipulation task involved and the individual manipulators "complement" each other in their activities by performing separate functionally coordinated movements. Characteristic for this class of movements is that one manipulator performs an "auxilliary" manipulation while, at the same time, the other performs the "main" manipulation. Typically, one manipulator acts as a vise which holds one object of

manipulation and the other performs various functional operations with some other object (for example, pouring water from a bottle into a glass, placing a bolt through a nut, etc.).

(3) *The class of conjugate movements*, in which both manipulators participate equally in a common manipulation task (for example, carrying a tray, the motion of grasping an object using both manipulators, etc.).

Apparently, since the individual tasks are not related, the first class of movements can be realized by sequentially controlling each individual manipulator using any of the control methods already developed for unilateral systems.

In a like manner, a large subclass of movements belonging to the class of complementary movements can also be realized with sequential control since in a great deal of cases the manipulator performing the auxilliary manipulation is static.

However, this approach cannot be applied to the third class of movements because simultaneous motion of both manipulators is required. But, by making use of the fact that there is a connection between these two motions it is possible to realize movements belonging to this class by a method which can be considered as a generalization of the synergistic control approach.One of the main reasons why synergistic control was selected is because in extreme cases it can be realized with only two input signals which makes it suitable for rehabilitation. In addition, this control method gives extremely functional movements and requires very little training on the part of the patient.

A study of the class of conjugate movements reveals that it can be broken down into three distinct subsets of conjugate movements:

(i) *displacement movements* with the objective of to convey a new state to the object of manipulation;

(ii) *approach movements* with which the whole manipulation system is brought near the object for the purpose of grasping; and

(iii) *reflective movements* with which an object can be picked up or released by the manipulation system.

For a control system to be functional it is necessary to realize all three subsets of movements equally well.

Synergistic Rade Control of Bilateral Manipulation Systems

Basically, the central idea behing synergistic control is a transformation of coordinates. Instead of specifying the motion of individual d.o.f. of the manipulator, the patient specifies parameters of motion (the linear velocity $\underline{V}$ and rotational velocity $\underline{\Omega}$) of the grasping device with respect to a reference coordinate system. This coordinate system is chosen so that each individual component results in a very functional movement. The duty of the control system is to perform the coordinate transformation necessary for resolving such a functional movement into motions of individual d.o.f.

Where bilateral rehabilitation manipulators are concerned, the control problem can be stated as follows: in what way is it possible to define functional movements of the bilateral system so as to require a minimum of conscious effort of the patient? The emphasis here is on the class of conjugate movements since it has been shown how the other two classes of bilateral manipulator movements reduce to unilateral modes.

The objective of conjugate displacement movements is to convey a new state to some manipulation object(s). The state of an object can be changed by translation and rotation of the object (for example, by inforcing a linear velocity $\underline{V}$ and an angular velocity $\underline{\Omega}$). For the patient it is much easier to define six control signals (i.e. the vectors $\underline{V}$ and $\underline{\Omega}$) instead of twelve which is the minimum number of d.o.f. of a non-redundant bilateral system.

However, six control signals are still too many considering that it is next to impossible for a human to generate more than three simultaneous coordinated control signals. A solution is to have the patient generate only one component of $\underline{V}$ or $\underline{\Omega}$ at a time. Each of these components, depending on the manipulation task at hand produses a very functional movement.

The Reference System

Evidently, the basic criterion in choosing a reference coordinate system is the functional value of the component movements. However, there are two additional factors which must be taken into account:

- the patient should be able to easily estimate the motion of the system with respect to the selected system, and
- information concerning the position and orientation of the reference system should be readily available to the control system.

A reference system $0_R x_R y_R z_R$ which meets all these requirements is shown in Figure 1. The origin is placed midpoint on the line connecting the end-points of the furthermost levers of each manipulator. The orientation of the system is determined by the orientation of the right (or left) grasping device, that is, by the system $0_H x_H y_H z_H$. By specifying the components $(V_x)^R$, $(V_y)^R$ and $(V_z)^R$ the patient obtains highly functional movements of the system parallel to the $0_R x_R$, $0_R y_R$ and $0_R z_R$ axes respectively. Of special functional value is the movement resulting from $(V_x)^R$ which is "pointed out" by the reference hand. The components $(\Omega_x)^R$ and $(\Omega_y)^R$ result in angular rotations about the respective axes.

A special feature of this method is the fact that the positioning and orientation of the object are independent of each other. This is practical for many applications (i.e. the well-known "drink test").

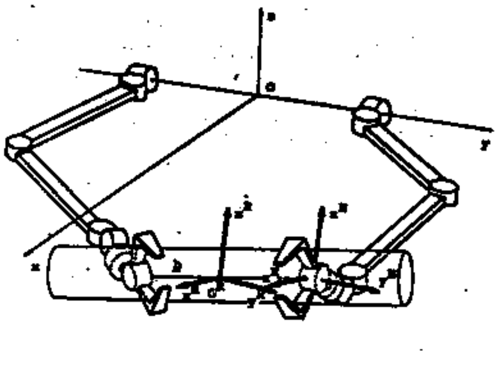

Fig. 1.

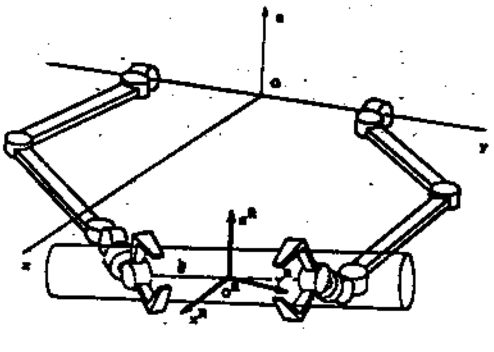

Fig. 2.

Another reference system fulfilling the necessary requirements is shown in Figure 2. This system has the same orientation as the basic system 0xyz. Still another form of synergistic control is obtained if a coordinate system with spherical coordinates is used. A further study of feasible reference systems might yield even more functional movements. This is a potential extension of the control concept described here.

The Manipulator

The bilateral manipulator system consisting of a right and left manipulator which was used in the research is shown in Figure 3. Each manipulator has six d.o.f. which means that there are no redundant d.o.f. All the joints are rotational.

It is characterized by the fact that it has only one joint with a longitudinal axis of rotation per manipulator which makes it suitable for practical realization since this type of joint is the most difficult to construct. The relative angles of rotation in the joints form the two configuration vectors $\underline{\theta}^D = [\theta_1^D, \theta_2^D, \ldots, \theta_6^D]^T$ and $\underline{\theta}^L = [\theta_1^L, \theta_2^L, \ldots, \theta_6^L]^T$ for the right and left manipulators respectively. The angular rotations of the grasping devices are left out since they are not pertinent to this discussion.

The corresponding rate configuration vectors are

$$\underline{\omega}^D = [\omega_1^D, \omega_2^D, \ldots, \omega_6^D]^T$$

$$\underline{\omega}^L = [\omega_1^L, \omega_2^L, \ldots, \omega_6^L]^T$$

where

$$\omega_i^{D(L)} = \frac{d\theta_i^{D(L)}}{dt}, \quad i = 1,2,\ldots,6$$

are the respective angular rates of the joints.

The kinematics of one manipulator (right) of the bilateral system are shown in Figure 4. Let $\hat{x}_i$, $\hat{y}_i$ and $\hat{z}_i$ represent the unit vectors of $0_i x_i$, $0_i y_i$ and $0z_i$ respectively. Then, for the manipulator structure chosen, the angular rate unit vectors are

$$\begin{aligned}\hat{\omega}_i^{D(L)} &= \hat{x}_i^{D(L)},\ i = 6\\ &= \hat{y}_i^{D(L)},\ i = 1,5\\ &= \hat{z}_i^{D(L)},\ i = 2,3,4\end{aligned} \tag{1}$$

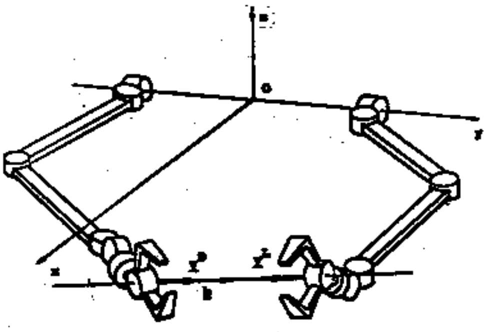

Fig. 3.

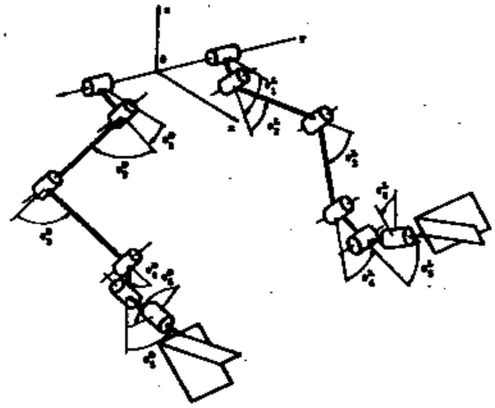

Fig. 4.

Kinematics

The angular velocity which the manipulator imparts to the object is the algebraic sum of all relative rotations in the joints

$$\underline{\Omega} = \sum_{i=1}^{6} \omega_i^D \hat{\omega}_i^D = \sum_{i=1}^{6} \omega_i^L \hat{\omega}_i^L \tag{2}$$

The same holds for the linear velocity $\underline{V}$

$$\underline{V} = \sum_{i=1}^{6} \omega_i^D \hat{\omega}_i^D \times \underline{r}_i^D = \sum_{i=1}^{6} \omega_i^L \hat{\omega}_i^L \times \underline{r}_i^L \tag{3}$$

where the vectors $\underline{r}_i^D = \overrightarrow{0_i^D 0_R}$ and $\underline{r}_i^L = \overrightarrow{0_i^L 0_R}$. These vectors are determined from

$$\begin{aligned}\underline{r}_i^D &= \sum_{k=i}^{6} l_k \hat{l}_k^D + \underline{b}\\ \underline{r}_i^L &= \sum_{k=i}^{6} l_k \hat{l}_k^L - \underline{b}\end{aligned} \tag{4}$$

where $l_k^L = l_k^D = l_k$ is the length of the k-th lever, $\hat{l}_k$ is the unit vector which defines the orientation of the k-th lever and $\underline{b}$ is the vector which determines the position of the reference origin 0_R with respect to 0_6^D and is calculated according to

$$\underline{b} = \frac{1}{2}\left[\sum_{i=1}^{6} l_i(\hat{l}_i^L - \hat{l}_i^D)\right] - \underline{a} \;; \quad \underline{a} = \overrightarrow{00}{}_1^D \tag{5}$$

Finally, on the basis of the above discussion the link between the input vector $\underline{w} = [\underline{V}, \underline{\Omega}]^T$ which is specified by the patient and the output vectors $\underline{\omega}^D$ and $\underline{\omega}^L$ is

$$\begin{aligned} \underline{\omega}^D &= [\underline{J}^D(\underline{\theta}^D)]^{-1}\,\underline{w} \\ \underline{\omega}^L &= [\underline{J}^L(\underline{\theta}^L)]^{-1}\,\underline{w} \end{aligned} \tag{6}$$

where $\underline{J}^D(\underline{\theta}^D)$ and $\underline{J}^L(\underline{\theta}^L)$ have the form

$$\underline{J}(\underline{\theta}) = \begin{bmatrix} (\hat{\omega}_1 \times \underline{r}_1) & (\hat{\omega}_2 \times \underline{r}_2) & \ldots & (\hat{\omega}_6 \times \underline{r}_6) \\ \hat{\omega}_1 & \hat{\omega}_2 & & \hat{\omega}_6 \end{bmatrix} \tag{7}$$

Apparently, there is no formal difference between the conjugate displacement and conjugate approach movements. Therefore, the same reference system can be used and the synergistic transforms are the same. This is very important since it signifies that the control mode which the patient uses to realize the two sets of movements is the same.

There are several ways in which reflective conjugate movements can be realized. The simplest is demonstrated in Figure 5. The two manipulators converge or diverge along a line which connects the two end-points. In that case

$$\begin{aligned} \underline{V}^D &= [V\cdot\hat{b}] \\ \underline{V}^L &= [V\cdot\hat{b}] \\ \underline{\Omega}^D &= \underline{\Omega}^L = 0 \end{aligned} \tag{8}$$

and the patient specifies only one input signal: the algebraic value of V.

A more general approach would be

$$\begin{aligned} \underline{V}^D &= -\underline{V}^L = \underline{V} \\ \underline{\Omega}^D &= \underline{\Omega}^L = 0 \end{aligned} \tag{9}$$

Singularities and Constraints

An important problem concerns situations which occur when, due to various reasons, the required movement cannot be completed. From Equations (6) it can be seen that an inversion of matrices is necessary. Evidently, whenever either of the matrices $\underline{J}^D(\underline{\theta}^D)$ or $\underline{J}^L(\underline{\theta}^L)$ are singular then the required synergy cannot take place.

Due to the anthropomorphic structure of the manipulators it can be considered that

$$l_2, l_3 >> l_1, l_4, l_5, l_6$$

hence,

$$\begin{aligned} \underline{r}_1 &= \underline{r}_2 \\ \underline{r}_4 &= \underline{r}_5 = \underline{r}_6 = \underline{b} \end{aligned} \tag{10}$$

Since $\hat{\omega}_i$ are unit vectors then the determinants of the matrices can be equal to zero only if two or more columns are equal. The necessary condition for columns j and k to be equal is that $\hat{\omega}_j$ and $\hat{\omega}_k$ are equal. If this is fulfilled then the matrix $\underline{J}(\underline{\theta})$ is singular when the corresponding radii vectors $\underline{r}_j$ and $\underline{r}_k$ are equal. The unit vector $\hat{\omega}_1$ cannot be equal to $\hat{\omega}_2, \hat{\omega}_3$ and $\hat{\omega}_4$ since it is always orthogonal to them. When $\theta_3 = \theta_4 - \theta_2$ vectors $\hat{\omega}_1$ and $\hat{\omega}_5$ are equal. However, $\underline{r}_1$ and $\underline{b}$ are not due to the physical constraints in the elbow joint. For the same reason the vectors $(\hat{\omega}_1 \times \underline{r}_1)$ and $(\hat{\omega}_6 \times \underline{r}_6)$ cannot be equal. Furthermore, $\hat{\omega}_2$ is always equal to $\hat{\omega}_3$ and $\hat{\omega}_4$, but, since for all manipulator configurations $\underline{r}_2 \neq \underline{r}_3$ and $\underline{r}_2 \neq \underline{b}$ then the second, third and fourth columncan never be equal to one another. This is true for the third and sixth columns, since $\underline{r}_3 \neq \underline{b}$. The vectors $\hat{\omega}_4$ and $\hat{\omega}_6$ can be equal whenever $\theta_5 = \pm\pi/2$. Since $\underline{r}_4 = \underline{r}_6 = \underline{b}$ then the matrix $\underline{J}(\underline{\theta})$ is singular. Finally, $\hat{\omega}_5$ and $\hat{\omega}_6$ can never be equal which means that the fifth and sixth column cannot be equal.

Therefore, the only singularity occurs when either of the angles θ_5^D or θ_5^L is equal to $\pm\pi/2$. It is easy to eliminate this singularity simply by modifyling the physical contraints on these angles so that

$$-(\frac{\pi}{2} - \varepsilon) \le \theta_5^{R(L)} \le \frac{\pi}{2} - \varepsilon \qquad (11)$$

where ε is a small positive angle.

Whenever the mobility of the manipulator is reduced because one or more of the levers hits a physical constraint it becomes impossible to complete the desired movement. In such cases the best thing is for the system to stop moving completely. Otherwise there would be the possibility for the manipulators to drop the object they are carrying. In addition, this is a signal to the patient that he has hit upon a constraint.

Still another possibility can prevent a movement from being executed. This occurs when any one or more of the computed angular rates $\omega_i^{D(L)}$ $(i = 1,2,\dots,6)$ becomes greater than the physical capabilities of the corresponding driving motors. This problem can be efficiently solved by a proportional reduction of both rate configuration vectors to:

$$\begin{aligned} \underline{\omega}^{D*} &= k\underline{\omega}^{D} \\ \underline{\omega}^{L*} &= k\underline{\omega}^{L} \end{aligned} \qquad (12)$$

where

$$k = \min \left\{ \frac{\omega^{D}_{1\,max}}{|\omega^{D}_{1}|} , \frac{\omega^{D}_{2\,max}}{|\omega^{D}_{2}|} , \dots , \frac{\omega^{L}_{6\,max}}{|\omega^{L}_{6}|} \right.$$

Experimental Evaluation Results

In order to evaluate the synergistic control method for bilateral manipulators an experimaental simulation system was set up. The simulation technique used was real-time stereoscopic simulation which was developed for this purpose /5/.

The experimental system proved very efficient since it enabled quite an extensive evaluation of the control concept.

Three series of experiments were undertaken. In the first of these the efficiency of the bilateral control concept in performing approach and reflective movements as compared to sequential unilateral control was tested. As could be expected, the bilateral control method cut in half the time necessary to perform this task. The second group of experiments served to test the efficiency of the control system in realizing displacement movements. The manipulation task involved the placement of an object from an initial position into another position in space including a change in orientation. The results proved that in changing the position of the object the control method which refers to a reference system defined by the orientation of one hand gave better results, whereas for changes in orientation the opposite was true. Finally, the third series of experiments served to evaluate the capabilities of the method in performing complex manipulation tasks requiring bilateral manipulation. Figure 6 illustrates a typical task.

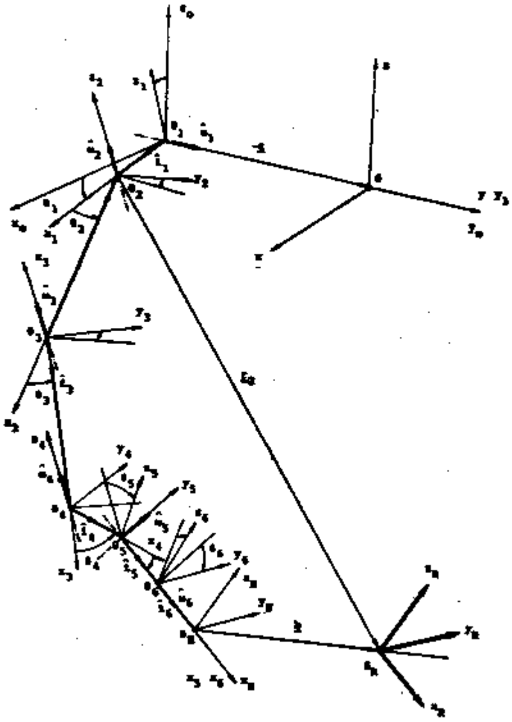

Fig. 5.

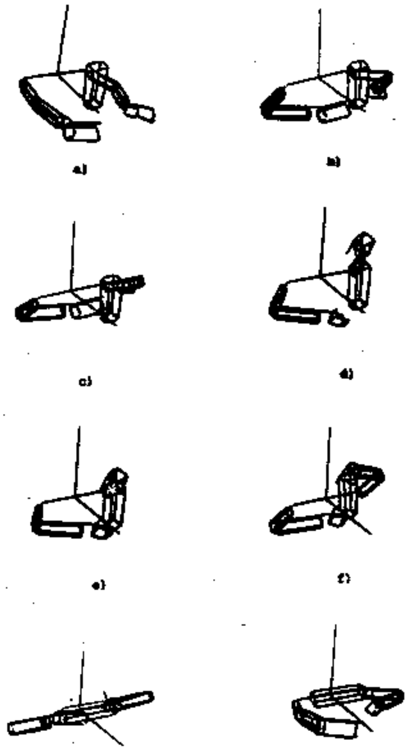

Fig. 6.

Throughout the experiments the operator used only one input. Program selection was accomplished via a digital signal to the control system.

The experimental evaluation proved that:

(1) the synergestic control concept is efficient in realizing the class of conjugate bilateral movements, and
(2) the nature of the control system is such taht the operator can use it efficiently with litle previous training.

Conclusion

The point which is most appealing about synergistic rate control of bilateral manipulation systems is that the number of input control signals required is no greater than the number of signals necessary for controlling a unilateral system. Because it requires very litle training on the part of the operator/patient it seems well suited for rehabilitation purposes. As a result the patient is able to concentrate more on his objective and less on the actual control process.

In the paper many aspects of the control problem are treated, including the choice of the reference coordinate system, analytical representation, and singularities and constraints. Practical solutions to these problems were suggested. The results of the experimental evaluation demonstrated that the synergistic control concept is well suited to the control of bilateral manipulator systems and that combined with the synergistic control algorithms already developed for unilateral systems it forms a practical solution to the problem of rehabilitation manipulation.

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