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ON A WAY TO CONTROL ARTIFICIAL UPPER LIMBS BY USING THE "INFRARED GUIDE BEAM CONTROL SYSTEM"

U. Brudermann

Introduction

As reported in (2) total upper limb prostheses need at least six degrees of freedom; therefore the problem arises how to control all of them simultaneously. Four degrees of freedom can be controlled by shoulders' locomotion and following (1), (2), (3) two degrees of freedom can be handled by the "Infrared Guide Beam Control System" using the principle of follower control: By attaching the guide beam transmitter to a spectacle frame with the beam approximately showing into the normal direction of the visual range, the hand fixed receiver is able to realize the deviatoric angle within the capture range of the guide beam respectively to its magnitude and its orientation. The signals thus derived control the drives to make the deviation vanish.

Besides the expansion of the restrictive possibilities of shoulder control the advantages of the application of this control system are that the basic requirement of visual tracking is applied and, moreover, that there is no contradiction to the principle of the "Extension of the Physiological Proprioception" (4).

Selecting the two infrared controlled joint axes there are either two active shoulder movements to be controlled or there is only one active degree of the shoulder available whereas the other one remains pasive. In this case this one and the active elbow joint are to be controlled. Both possibilities have in common that the controllability is only guaranteed if no change in sign of the components' coordination occurs between the gradients of the receiver signal and the hand movement.

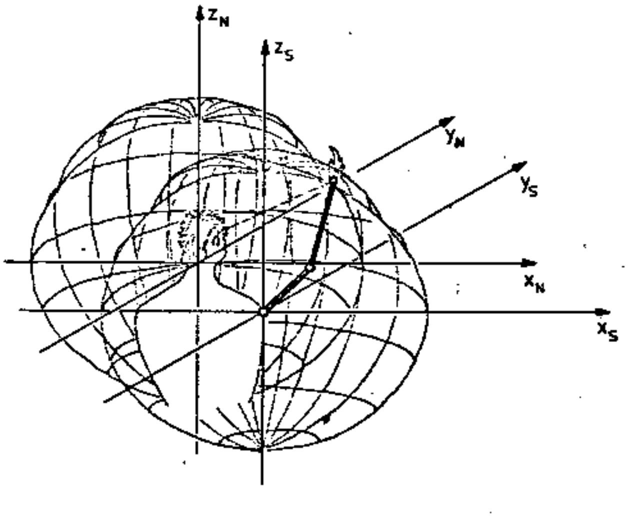

Fig. 1: Coordinate Systems of Arm's and Guide Beam's Movement, Controlling Two

This requirement is only satisfied if the coordinate planes caused by varying the joints to be controlled can be pe-

Controlling two active shoulder joint axes this can be achieved by coordinating each, the elevation and the azimuth of the guide beam's and the arm's movement limiting the admissable and possible hand moving space in a proper way (fig.1).

If one degree of freedom of the shoulder and the elbow joint are to be controlled it is not possible, however, to answer by pure intuition whether the uniqueness of the penetration point exists, and whether the components' coordination is uniquely defined. To investigate these connexions a convenient model, its mathematical formulation, and the simulation of the jointal peculiarities are developed.

Methods and Procedures

The position vector of the hand $\varphi_i = \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}$

is represented in the coordinate system i. For i=15 the origin is put into the center of the transmitter, its y-axis coinciding with the direction of the guide beam. The directions of the z- and x-axis are given by the projections of the components of the hand movement into the x-,z-plane. With

α_1 = angular position of the elbow joint,

α_2 = angular position of the active shoulder joint,

α_3 = angular position of the passive shoulder joint,

and from the statements made above:

$$x_{15} = z_{15} = 0 \quad , \tag{1}$$

$$\frac{\partial z_{15}}{\partial \alpha_2} = \frac{\partial x_{15}}{\partial \alpha_1} = 0 \quad , \tag{2}$$

$$\frac{\partial z_{15}}{\partial \alpha_1} > 0 \quad , \quad \frac{\partial x_{15}}{\partial \alpha_2} > 0 \; . \tag{3}$$

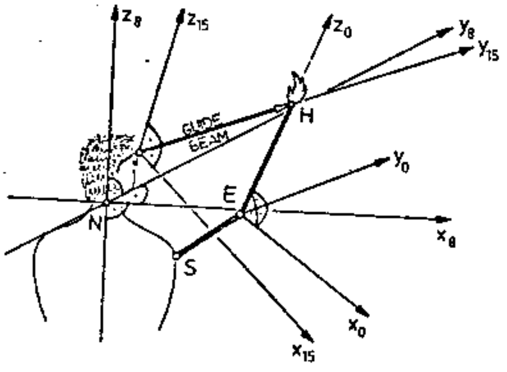

Fig. 2: Isometric View of the Paraphlegic Handicapped in Several Selected Coordinate Systems

The coordinates result from a stepwise transformation of the hand position vector φ_0 from the system i=0 to the system i=15 (fig.2). Of the first mentioned one the origin is positioned in the elbow joint with its z-axis pointing at the hand. Thus:

$$\varphi_0 = \begin{pmatrix} 0 \\ 0 \\ k_1 \end{pmatrix} \quad ,$$

$$\ell_8 = (\ell_o \cdot R_1 \cdot R_2 + \begin{pmatrix} 0 \\ 0 \\ k_2 \end{pmatrix}) \cdot R_4 \cdot R_5 \cdot R_6 \cdot R_7 + \begin{pmatrix} k_3 \\ -k_4 \\ -k_5 \end{pmatrix} \quad ,$$

$$\ell_{15} = (\ell_8 \cdot R_9 \cdot R_{10} \cdot R_{11} + \begin{pmatrix} -k_6 \\ -k_7 \\ -k_8 \end{pmatrix}) \cdot R_{13a} \cdot R_{13b} \cdot R_{14} \cdot R_{15} \quad ,$$

whereas the individual skeletal dimensions of the upper extremities are

k_1 = length of the forearm,

k_2 = length of the upper arm,

$\left.\begin{array}{r} k_3 = \\ -k_4 = \\ -k_5 = \end{array}\right\}$ coordinates of the neck point in the system i=8,

$\left.\begin{array}{r} k_6 = \\ k_7 = \\ k_8 = \end{array}\right\}$ initial coordinates of the transmitter position in the system i=8.

With i=1,2,4,5,6,9,10,13a,13b :

$$R_i = \begin{pmatrix} \cos\gamma_i & -\sin\gamma_i \cdot \cos\vartheta_i & -\sin\gamma_i \cdot \sin\vartheta_i \\ \sin\gamma_i & \cos\gamma_i \cdot \cos\vartheta_i & \cos\gamma_i \cdot \sin\vartheta_i \\ 0 & -\sin\vartheta_i & \cos\vartheta_i \end{pmatrix} \quad ;$$

with i=7,11,14 :

$$R_i = \begin{pmatrix} \cos\varphi_i & 0 & -\sin\varphi_i \\ 0 & 1 & 0 \\ \sin\varphi_i & 0 & \cos\varphi_i \end{pmatrix} \quad ;$$

$$R_{15} = \begin{pmatrix} \cos^{-1}\varrho_i & 0 & 0 \\ 0 & 1 & 0 \\ -\tan\varrho_i & 0 & 1 \end{pmatrix} \quad .$$

The γ_i, ϑ_i, φ_i, and ϱ_i are enlisted in table 1. The position of the head is idealized by the three head angles

$\varkappa_1$ = pitch angle,

$\varkappa_2$ = angle of horizontal rotation,

$\varkappa_3$ = angle of sideward inclination.

Adjusting the angular deviation between the guide beam and the normal direction of the visual range making the guide beam pointing at the hand when $\alpha_{1,2,3} = \varkappa_{1,2,3} = 0$ the kinematic system is completely determined in dependence of the parameter set a_j $(j=1,\dots,10)$ and the individual magnitudes k_k $(k=1,\dots,8)$ for this initial position of the arm, whereas

$$c_1 = -a_5$$

to enable the arm to be completely stretchable,

$$c_2 = \frac{z_8-k_8}{y_8-k_7} \qquad \text{and} \qquad c_3 = \frac{x_{13a}}{y_{13a}}$$

to point the guide beam at the hand in the initial position,

$$c_4 = \frac{\partial x_{13b}}{\partial \alpha_1} / \frac{\partial z_{13b}}{\partial \alpha_1} \qquad \text{and} \qquad c_5 = \frac{\partial z_{14}}{\partial \alpha_2} / \frac{\partial x_{14}}{\partial \alpha_2}$$

to hold equations (2) and (3). The partial derivatives can be determined by the stepwise application of the compound rule of three.

By variation of the $\alpha_{1,2,3}$ the angles $\varkappa_1$ and $\varkappa_2$ can be evaluated from equation (1) so far as a real solution exists, i. e. so far as $DQ \geq RQ$. With

$$\begin{aligned}
R1Q &= y_8^2 + z_8^2 , \\
R2Q &= y_8^2 + x_8^2 , \\
RQ &= x_8^2 + y_8^2 + z_8^2 , \\
RSQ &= k_6^2 + k_7^2 + k_8^2 , \\
T1 &= \tan c_2 , \\
T2 &= \tan c_3/\cos c_2 , \\
B1 &= k_7 \cdot T1 - k_8 , \\
B2 &= k_7 \cdot T2 - k_6 , \\
B3 &= k_6 \cdot T1 - k_8 \cdot T2 , \\
A &= T1^2 + 1 + T2^2 , \\
A3 &= T1 \cdot B1 + T2 \cdot B2 , \\
DQ &= (B1^2 + B2^2 + B3^2)/A
\end{aligned}$$

follows

$$\begin{aligned}
YPS &= (A3 + (+SQRT(A3^2 + A(RQ - B1^2 - B2^2))))/A , \\
ZET &= YPS \cdot T1 - B1 , \\
YKS &= YPS \cdot T2 - B2 .
\end{aligned}$$

Table 1:(a = Free Parameters)

i	γ_i	ϑ_i	φ_i	ϱ_i
1	$a_1+\alpha_1$	a_5		
2	a_4	c_1		
4	$a_2+\alpha_2$	a_6		
5	$a_3+\alpha_3$	a_7		
6	a_8	a_9		
7			a_{10}	
9	0	$\varkappa_1$		
10	$\varkappa_2$	0		
11			$\varkappa_3$	
13a	0	c_2		
13b	c_3	0		
14			c_4	
15				c_5

If $R1Q \geq ZET^2$, follows with $YPSS1 = +SQRT(R1^2 - ZET^2)$

$$\mathcal{X}_1 = \arctan\frac{z_8}{y_8} - \arctan\frac{ZET}{YPSS1} \qquad \text{and}$$

$$\mathcal{X}_2 = \arctan\frac{x_8}{YPSS1} - \arctan\frac{YKS}{YPS} \ .$$

If $R1Q < ZET^2$, follows with $YPSS2 = +SQRT(R2^2 - YKS^2)$

$$\mathcal{X}_2 = \arctan\frac{x_8}{y_8} - \arctan\frac{YKS}{YPSS2} \qquad \text{and}$$

$$\mathcal{X}_1 = \arctan\frac{z_8}{YPSS2} - \arctan\frac{ZET}{YPS} \ ,$$

causing a change in sequence of the transformation chain from R_9, R_{10} into R_{10}, R_9.
(The ambiguity of the arctan-function must be considered!)
$\mathcal{X}_3$ is assumed to be zero.

The assignment of the jointal axes to the components of the gradient of the receiver signal is defined by equations (1), (2), and (3) in the initial position of the arm. So the controllability is guaranteed for any $\alpha_{1,2,3} \neq 0$, iff equations (3) hold as well.

The quality of the parameter set is determined by the controllable volume of the region in which the hand position is located as a function of $\alpha_{1,2,3}$. This volume as well its partitial derivatives with respect to the parameters cannot be explicitely evaluated in order to find its maximum in the parameter space. As this region has to be a connected subspace a special scanning function was developed which scans the region hank-like throughout its edges beginning at the inner point $\alpha_{1,2,3} = 0$ as shown in fig. 3. The length of its edges is normalized being 180° for each IQMAX. The scanning has to be carried out for each investigated point in the parameter space.

This non-linear optimization of the ten parameters a_i is to be achieved at an accuracy of one degree. The method of steepest ascent or similiar tools can-

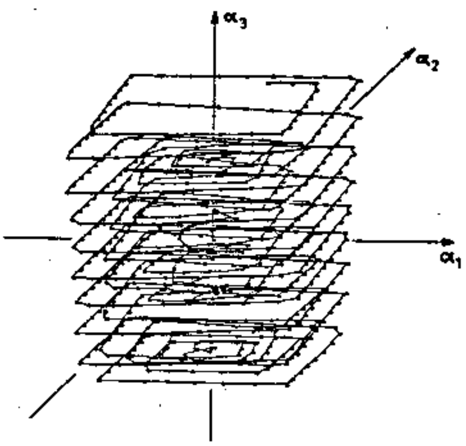

Fig. 3: Isometric View of the Scanning Function Representing the First IQMAX=700 Points in the α-Space

not be applied and scanning the space consequently 360^{10} parameter sets should have to be investigated. Hence it seemed to be convenient to use the "Evolution Strategy" (5), (6) which imitates the biologic evolution based on mutation and selection. Keeping up a promising success probability by varying continuously the individual spread of each parameter the optimum search gets an objective being considerably increased.

A basic requirement in this theory is the knowledge of the supplementary conditions and the objective function. The restrictions are given by the demand for controllability in the initial position, and the quality of the parameter set is measured by the controllable volume V_a of the α-space replacing the real region of the controllable hand locomotion, and the magnitude of the influence on the distance between the transmitter and the receiver, i.e. the distance between the nearest and the farest y_{15}-value YDL in the controllable space:

$$\mathrm{YDL} = \mathrm{const}\cdot\sin(1/2\cdot\sqrt[3]{V_a}) \quad ; \quad V_a \leq \pi^3 \ .$$

As this distance increases monotonically with V_a, it can be used as the objective function.

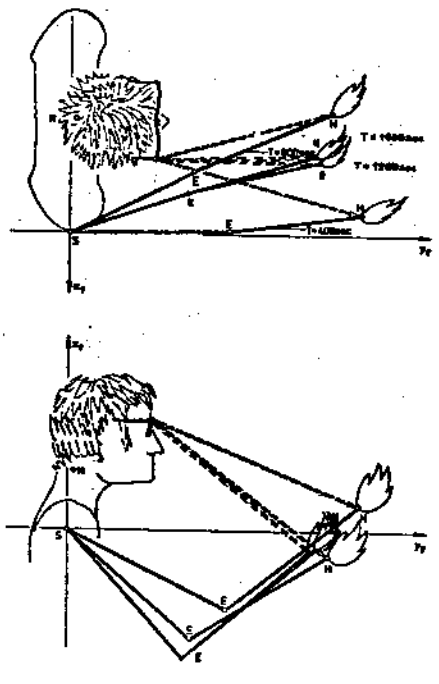

Fig. 4: Optimized Prostheses (T=Execution Time, CDC-Cyber 76) in Top and Right Side View Represented in the Initial Position

Preliminary Results

The first results determined by four runs of 400sec execution time (CDC-Cyber 76) are listed in table 2. These results, so far, are encouraging. The evolved initial arm positions, as shown in fig.4, are physiological at least, and coincide with possible anatomic ones. The maximum range between transmitter and receiver approaches the maximum possible value of the double length of the forearm (560mm). The maximum angular range per joint exceeds the value of 120° ensuring an increased mobility and controllability.

Discussion

In order to accelerate the optimum search during the first execution runs the α-space was scanned by a number of points IQMAX=100. Reaching 37 per cent of IQMAX the controllable region is mainly positioned in the lower part of the α-space, as shown in fig. 5

Table 2: Results of the Optimization Procedures

	Begin	1. Run	2. Run	3. Run	4. Run
T (sec)	0	400	800	1200	1600
a_1 (°)	-90	-66	-68	-84	-84
a_2 (°)	0	-36	-46	-36	-36
a_3 (°)	0	51	52	55	56
a_4 (°)	0	62	43	42	40
a_5 (°)	-90	-96	-93	-93	-94
a_6 (°)	-90	-103	-90	-93	-93
a_7 (°)	-90	-108	-115	-116	-119
a_8 (°)	0	-71	-85	-92	-94
a_9 (°)	-90	-79	-64	-56	-54
a_{10}(°)	0	-55	-58	-56	-56
Q (°)	0	124	127	127	127
YDL(mm)	0	422	461	476	480
IPS	1	11333	23263	35141	48813
ZE	0.000	0.741	0.810	0.835	0.842

With: T = Execution Time on a CDC-Cyber 76,
a_j = Optimized Parameters,
Q = Controllable Angular Range of $\alpha_{1,2,3}$,
YDL = Maximum Distance Between Controllable Hand Positions,
IPS = Total Number of Investigated Parameter Sets,
ZE = Normalized Value of the Objective Function.

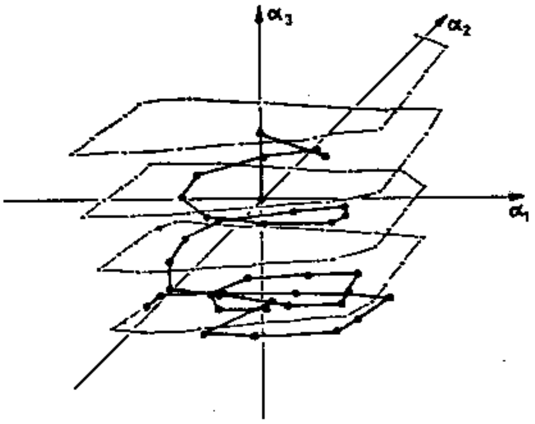

Fig. 5: The First 37 Points of IQMAX = 100

and the upper region remains nearly uncontrollable. Centering V_a in the α-space by increasing IQMAX causes the proportional increasing of the execution time as well. Thus it is intended to alterate the scanning function by multiplying IQMAX using an equally distributed set of it only. An appropriate shape is achieved if the first 700 points approximately are plotted (fig.3). Normalizing this value with respect to the approximately reachable 37 per cent the total number of steps can be assumed to IQMAX = 2000. Using each 20. of them, the first 37 investigated points are better positioned - as shown in fig. 6 - without considerably increasing the execution time.

The involved derivatives of the optimal parameter set thus found than can be determined more precisely using a closer winding of the scanning function. Finally it is intended to represent all possible movements emphasizing the effectiveness and the suitability of the developed device.

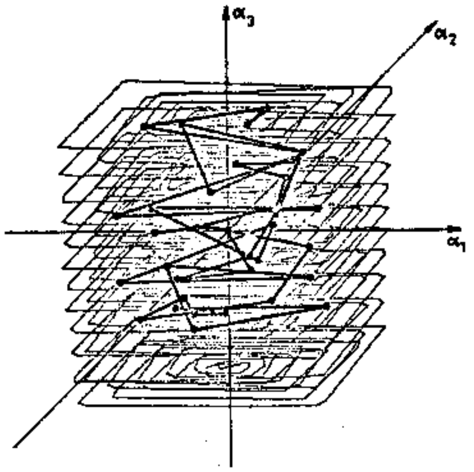

Fig. 6: The First 37 Investigated Points of IQMAX=2000, Using Each 20. of Them

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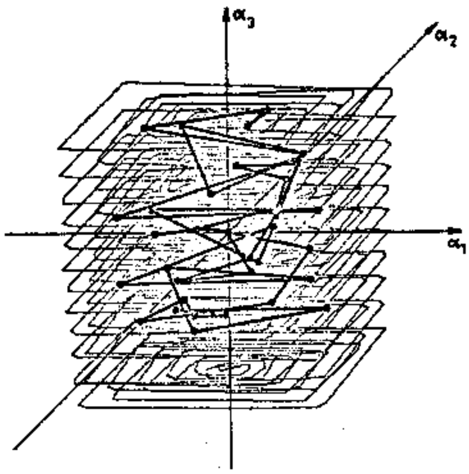

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