A FUZZY CONTROLLER FOR A SPECIAL GLOVE TO A HAND WITH DISABILITIES

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Abstract: This paper presents a control method for a medical glove with intelligent actuators for a hand with disabilities. The medical glove has got on outer superior face, an intelligent actuator to every finger, which helps it to bend and to grasp different objects and on outer inferior face a force distributed sensor system. The dynamic model of the outer superior face finger is determined and an approximate model is proposed. The two-level hierarchical control is adopted. The upper level coordinator gathers all the necessary information to resolve the distribution force. Then, the lower-level local control problem is treated as an open-chain hyper-redundant structure control problem. The fuzzy rules are established and a fuzzy controller is proposed.

1 PHYSIOLOGICAL ASPECTS OF HAND FUNCTIONS

The hand functions as an effector organ of the upper extremity for: support, manipulation, prehension. As a *support*, the hand acts in a non-specific manner to brace or stabilise an object and, also, as a simple platform to transfer or accept forces.

The most varied function of the hand is its ability to dynamically manipulate objects. Fingers motions may be repetitive and blunt (typing or scratching) or continuous and fluid with the rate and intensity of motion continuous controlled (writing or sewing). *Prehension* describes the ability of the fingers to grasp for holding, securing and picking up objects. There are many form of prehension: the grip, in which all fingers are used, the pinch, in which primarily the thumb and index fingers are used, the power grip, the precision grip, the power pinch, the precision pinch, hook grip and others.

For hand prosthesis the prehension is the first goal. In this paper we propose a special glove (a hand prosthesis) that realises a great help for the fingers flexion on their grip tasks to a hand with disabilities (the fingers have a great stiffness in their actions) while the other hand is a good hand. We need to know the proper correspondence between fingers actions and the activation of the nerves of the hand upper extremity. The nerves responsible for the hand motor control are: the radial nerve, the median nerve, the ulnar nerve (Neumann, 2002), (Zaharia, 1994). The radial nerve innervates the extrinsic extensor muscles of the fingers and is responsible for the sensation on the dorsal part of the wrist and hand. The median nerve innervates most of the extrinsic flexor muscles of the fingers and is responsible for the sensation on the palmar-lateral part of the hand and the lateral three and one-half fingers. The ulnar nerve innervates the medial half of the flexor digitorum profundus muscle and is responsible for the sensation on the ulnar border of the hand and the ulnar one and one-half fingers. So, we propose the connection of the special glove with the median nerve and the ulnar nerve, because they realise the flexion motion of the hand in prehension. This is necessary, also, for maintaining the indispensable cortical representation of the motor and sensitive hand images.

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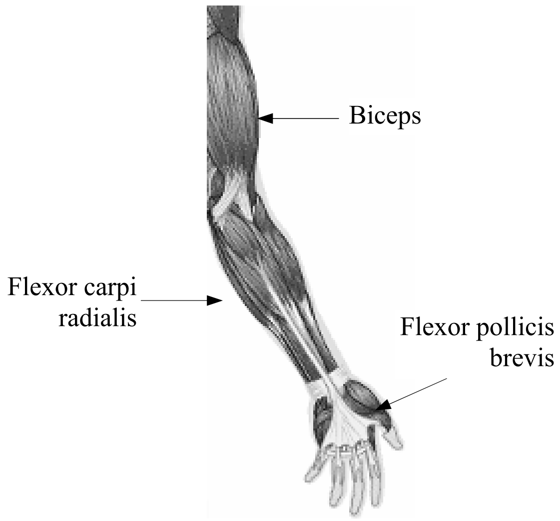

Figure 1: The muscular structure of the hand

2 PHYSICAL STRUCTURE

In Figure 2 is presented the physical structure of the special glove. On the superior faces of the glove fingers are fixed 5 tubes with have their structure presented in Figure 3 (hydraulic or pneumatic actuators) and on the inferior faces (at end of the glove fingers) are fixed strain-gaugeds for force measurement. The chambers of the segment have reinforced rubber walls with fibers on a circular direction. Thus, it is easy to deform it in the axial direction while it resists deformation in the radial direction. The cylinder can be bent in a plan (or in any direction, if it has 3 chambers) by appropriately controlling the pressure in the two (three) chambers (Figure 3). This tube has a hyper-redundant structure with a great number of points of mobility.

3 HIERARCHICAL CONTROL

The problem of controlling coordinating robotic systems with multiple chains in real time is complex. A multiple chain hyper-redundant system is more complicated. A hyper-redundant robotic element is a physical system with a great flexibility, with a distributed mass and torque that can take any arbitrary shape. Technologically, such systems can be obtained by using a cellular structure for each element of

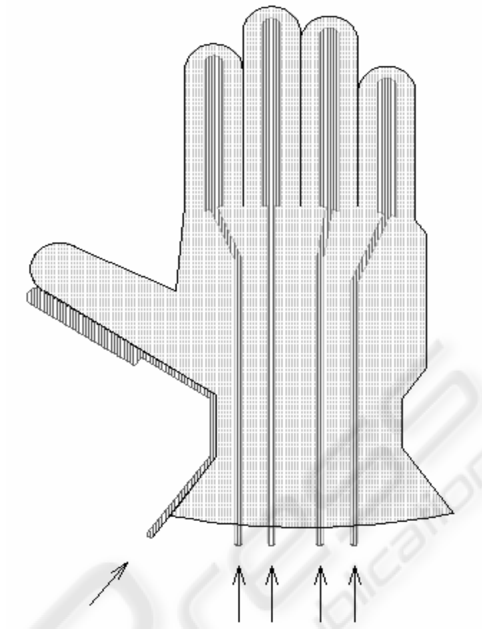

Figure 2: Physical structure of the special glove

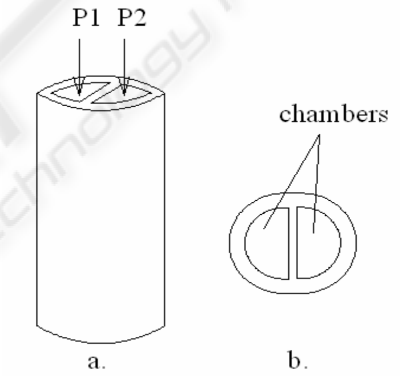

Figure 3: Physical structure of the tube

the tube. The control can be produced using an electro-hydraulic or pneumatic action that determines the contraction or dilatation the peripheral cells. The first problem is the global coordination problem that involves coordination of several hyper-redundant elements in order to assure a desired trajectory of a load. The second problem is the local control problem, which involves the control of the individual elements of the fingers to achieve the desired position. The force distribution is a sub-problem in which the motion is completely specified and the internal forces/torques to effect this motion is to be determined. To resolve this large - scale control problem, a two - level hierarchical control scheme is used (Cheng, 1995). The upper-level sys-

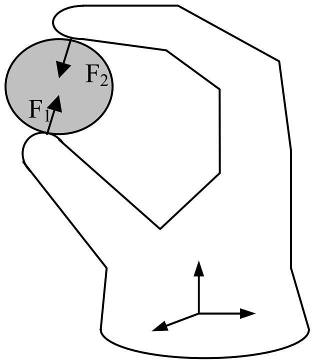

Figure 4: A multiple-chain hyper-redundant system

tem collects all the necessary information and solves the inter-chain coordination problem, the force distribution problem. Then, the problem is decoupled into 5 lower-level sub-systems (5 fingers)

4 MODEL FOR COOPERATIVE HYPER-REDUNDANT GLOVE ELEMENTS

A multiple-chain hyper-redundant system of the glove is presented in Figure 4. With the chains of the system forming closed-kinematics loops, the responses of individual chains are tightly coupled with one another through the reference member (object or load). The complexity of the problem is considerable increased by the presence of the hyper-redundant elements, $\left(TM^j, j = 1 \ldots k\right)$, the systems with, theoretically, a great mobility, which can take any position and orientation in space (Ivanescu, 1984), (Ivanescu, 1986). The dynamic equations for each chain of the system are:

$$\rho_j A^j \int_0^s \left[\sin\left(q^j - q'^j\right)\dot{q}'^{j2} + \cos\left(q^j - q'^j\right)\ddot{q}'^j\right] ds' +$$

$$\rho A g \int_0^s \cos q^j ds' + \tau^j = T^j,\ j = 1,..5 \qquad (1)$$

$$\int_0^{L^j} \tau^j ds = F_x^j \int_0^{L^j} \left(-\sin q^j\right) ds + F_x^j \int_0^{L^j} \cos q^j ds,\ j = 1,..5 \qquad (2)$$

where we assume that each element (TM^j) has a uniform distributed mass, with a linear density ρ^j and a section A^j. We denote by s the spatial variable upon the length of the arm, $s \in [0, L^j]$. We also use the notations: q^j - Lagrange generalized coordinate for TM^j (the absolute angle), $q^j = q^j(s,t)$, $s \in [0,L^j]$, $t \in [0,t_f]$, $q'^j = q^j(s', t)$, $s' \in [0, s]$, $t \in [0, t_f]$, $T^j = T^j(s, t)$ - the distributed torque over the tube; $\tau^j = \tau^j(s, t)$ - the distributed moment to give the desired motion specified on the reference member. All these sizes are expressed in the coordinate frame of the element TM^j. The k integral equations are tightly coupled through the terms τ^j, F_x^j, F_z^j where all of these terms determine the desired motion. We propose a two-level hierarchical control scheme (Cheng, 1995) for this multiple-chain robotic system. The control strategy is to decouple the system into k lower-level subsystems that are coordinated at the upper level. The function of the upper-level coordinator is to gather all the necessary information so as to formulate the corresponding force distribution problem and then to solve this constrained, optimization problem such that optimal solutions for the contact forces F^j are generated. These optimal contact forces are then the set-points for the lower-level subsystems. With F^0- the resultant force vector applied to object expressed in the inertial coordinate frame (0), ${}^0D_j$ - the partial spatial transform from the coordinate frame for the tube TM^j to the inertial coordinate frame (0), we consider the hard point contact with friction and the force balance equations on the object may be written

as: $$F^0 = \sum {}^0D_j F^j \qquad (3)$$

The object dynamic equations are obtained by the

form $$M_0 r = GF^0 \qquad (4)$$

where M_0 is inertial matrix of the object and r defines the object coordinate vector

$$r = (x, z, \varphi)^T \qquad (5)$$

and r(t) represents the desired trajectory of the motion. The inequality constraints which include the friction constraints and the maximum force constraints may be associated to (3):

$$\sum A^j F^j \le B \qquad (6)$$

where A^j is a coefficient matrix of inequality constraints and B is a boundary-value vector of inequality constraints. The problem of the contact forces can be treated as an optimal control problem if we associate to the relations (3) - (6) an optimal index (7):

$$\Psi = \sum C^j F^j \qquad (7)$$

This problem is solved in several papers: (Cheng, 1995), (Mason, 1981), (Zheng, 1988) by the general methods of the optimization or by the specific procedures (Cheng, 1991). After all of the contact forces F^j are determinate, the dynamics of each tube TM^j are decoupled. Now, the equations (1), (2) can be interpreted as same decoupled equations with a given $\tau^j(s)$, $s \in [0, L^j]$ acting on the tube tip.

5 APPROXIMATE MODEL

A discrete and simplified model of (1), (2) can be obtained by using a spatial discretization:

$$s_1, s_2, \ldots s_N \; ; \; s_i - s_{i-1} = \Delta \; |q^j(s_i) - q^j(s_k)| < \varepsilon \qquad (8)$$

where i, k = 1, 2, ... n^j Δ, ε are constants and ε is sufficiently small. We denote $s_I = i\Delta$, $L^j = n^j\Delta$.

$$T^j(s_i) = T_i^j, \; \tau^j(s_i) = \tau_i^j \qquad (9)$$

and considering the tube as a lightweight element, from (1), (2) it results (Ivanescu, 1986):

$$M^J \ddot{q}^J + C^J \dot{q}^J + D^J(q^J)F^J = T^J \qquad (10)$$

where M^J, C^J are $(n^J x n^J)$ contact diagonal matrixes, D is $(n^J x2)$ nonlinear matrix (Ivanescu, 1986, 1995):

$$F^J = col\left(F_x^J, F_z^J\right); \; q^J = col\left(q_1^J \ldots q_{n^J}^J\right);$$

$$T = col\left(T_1^J \ldots T_{n^J}^J\right) \qquad (11)$$

In the equation (10), F^J assures the load transfer on the trajectory. The uncertainty of the load m defines an uncertainty of the force F^J. F^{MJ} is an estimation of the force upper bound and we assume that

$$\left|F^{MJ} - F^J\right|_i \le \rho_i \, ; i = 1,2 \qquad (12)$$

6 CONTROL SYSTEM

The control problem asks for determining the manipulatable torques (control variable) T_I^j such that the trajectory of the overall system (object and fingers) will correspond as closely as possible to the behavior. In order to obtain the control law for a prescribed motion, we shall use the inverse model. A closed-loop control system is used (Figure 5). Let $q_d^j, \dot{q}_d^j, \ddot{q}_d^j$ be the desired parameters of the trajectory, F_d^j the desired force applied at the j - contact point of the object, and, $q^j, \dot{q}^j, \ddot{q}^j$, F^j the same sizes measured on the real system (or estimated), the error of the feedback system is given by: $\Delta q^j = q_d^j - q^j$; $\Delta \dot{q}^j = \dot{q}_d^j - \dot{q}^j$; $\Delta \ddot{q}^j = \ddot{q}_d^j - \ddot{q}^j$; $\Delta F^j = F_d^j - F^j$ The trajectory controller serves as the trajectory perturbation controller which generates the new variations $\delta q^j, \delta \dot{q}^j$, $\delta \ddot{q}^j$, δF^j in order to assure the performances of the motion for the overall system. The control law is proposed as,

$$\delta q^j = K_{11}^j \Delta q^j + K_{12}^j \Delta \dot{q}^j + K_{13}^j \Delta \ddot{q}^j \, ;$$

$$\delta \dot{q}^j = K_{21}^j \Delta q^j + K_{22}^j \Delta \dot{q}^j + K_{23}^j \Delta \ddot{q}^j$$

$$\delta \ddot{q}^j = K_{31}^j \Delta q^j + K_{32}^j \Delta \dot{q}^j + K_{33}^j \Delta \ddot{q}^j \, ; \qquad (13)$$

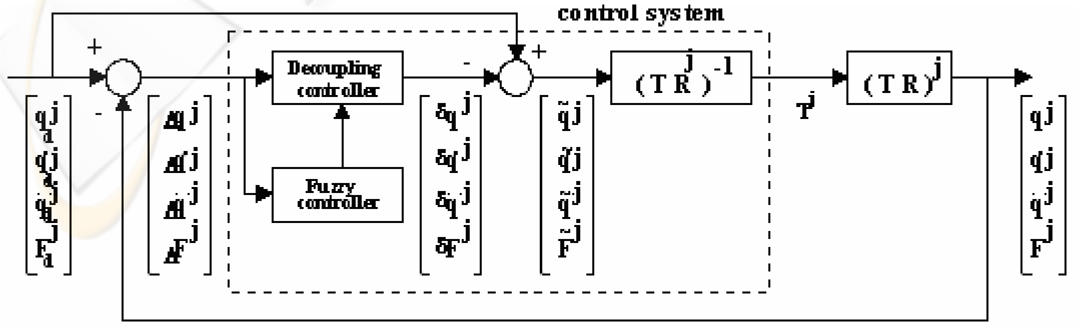

Figure 5: Control system architecture

$$\delta F_x^j = K_{f_{1x}}^j \Delta F_x^j + K_{f_{2x}}^j \Delta \dot{F}_x^j + K_{f_{3x}}^j \Delta \ddot{F}_x^j$$

$$\delta F_z^j = K_{f_{1z}}^j \Delta F_z^j + K_{f_{2z}}^j \Delta \dot{F}_z^j + K_{f_{3z}}^j \Delta \ddot{F}_z^j$$

The control law for the motion and force control requires

$$\begin{bmatrix} 0 & I \\ -P^{-1}R & -P^{-1}Q \end{bmatrix} \text{ to be stable,} \qquad (14)$$

$$\text{and } K_{f2}^{j2} \le 4K_{f3}^j\left(1-K_{f1}^j\right) \qquad (15)$$

where we used the notations

$P^j = (I - K^j_{33} - dK^j_{13})$; $Q^j = (K^j_{32} + d\ K^j_{12})$;
$R^j = d\,(I - K^j_{11}) - K^j_{31}$ (16)

and we considered $K^j_{f3x} = K^j_{f3z} = K^j_{f3}$,
$K^j_{f1x} = K^j_{f1z} = K^j_{f1}; K^j_{f2x} = K^j_{f2z} = K^j_{f2}$;
(17)

The relations (14), (15) define the main conditions imposed to the controller in order to assure the global stability for the motion of the finger and for the force F^j_d at the terminal point of the tube. If the condition (15) is easy to apply, the stability of the matrix (14) is more difficult to use.

We can obtain a simplified procedure if we choose suitable matrices $K^j_{m,n}$ (m, n =1, 2, 3) in the control law (13):

$I - K^j_{33} - d\,K^j_{13} = \alpha I$, α - integer number ;

$K^j_{32} + d\,K^j_{12} = 2\,\Xi^j$;$d\,(I-K^j_{11}) - K^j_{31} = \Omega^j$ (18)

where $\Xi^j = diag\left(\xi_1^j, \xi_2^j, \ldots \xi_n^j\right)$;

$$\Omega^j = diag\left(\omega_1^j, \omega_2^j, \ldots \omega_n^j\right) \qquad (19)$$

The equations (13) become

$$\alpha \cdot \Delta \ddot{q}_i^j - 2\xi_i^j \Delta \dot{q}_i^j + \omega_i^{j2} \Delta q_i^j = 0 \qquad (20)$$

The equations for the control of the tube parameters and for the control of the force offer a simple control for a Direct Sliding Mod Control (DSMC) (Ivanescu, 1995). The DSMC is a control method which operates in two steps. First step assures the motion towards the switching line S_q (or S_F):

$$\Delta \dot{q}_i^j + p_i^j \Delta q_i^j = 0\,;\; \Delta \dot{F}^j + p_{iF}^j \Delta F^j = 0 \qquad (21)$$

by the general stability conditions (Figure 6).

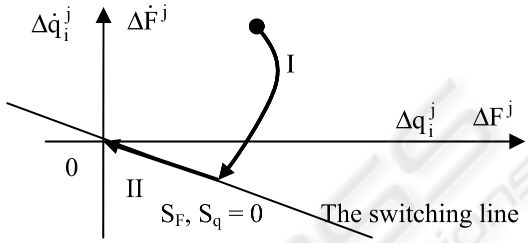

Figure 6: DSMC method

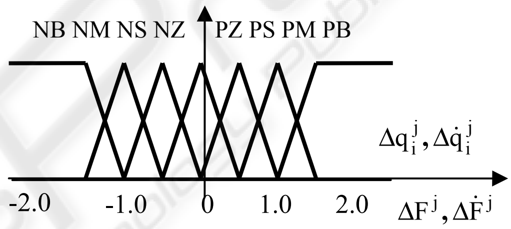

Figure 7: The membership functions for control variables

$$\xi_i^j < \min_S \left[\alpha \omega_i^{j2}(s)\right]^{\frac{1}{2}};$$

$$K_{f2}^j \le 2\left(K_{f3}^j\left(1-K_{f1}^j\right)\right)^{\frac{1}{2}}$$

j = 1, 2 (22)

When the trajectory penetrates S_q (or SF), the damping coefficients ξ_i^j, K_{f2}^j are increased ,

$$\xi_i^j > \max_S \left[\alpha \omega_i^{j2}(s)\right]^{\frac{1}{2}};$$

$$K_{f2}^j > 2\left(K_{f3}^j\left(1-K_{f1}^j\right)\right)^{\frac{1}{2}} \qquad j = 1, 2$$

(23)

The system is moving towards the origin, directly, on the switching line S_q (or S_F).

7 FUZZY CONTROLLER

A fuzzy control is proposed by using the control of the damping coefficient ξ_i^j, K_{f2}^j in (22)-(23). We consider a DSMC strategy with the switching of a control variable on the switching line (21), (Figure 6).

We shall let the errors $\Delta q_i^j, \Delta F^j$ and the error rates $\Delta \dot{q}_i^j, \Delta \dot{F}^j$ be defined by eight linguistic variables, labelled NB, NM, NS, NZ, PZ, PS, PM, PB partitioned on the error spaces $[-\Delta q_m, \Delta q_m]$, $[-F_m, \Delta F_m]$ and the error rate spaces represented here $\left[-\Delta \dot{q}_m, \Delta \dot{q}_m\right], \left[-\Delta \dot{F}_m, \Delta \dot{F}_m\right]$ where all these quantities are normalized at the same interval. The membership functions for these quantities are shown in Figure 7. The fuzzy output variables, the control coefficients ξ_i^j, K_{f2}^j, will use four fuzzy variables on the normalized universe:

$$\xi_i^{*j} = F_i^{*j} = \{\, 0,\ 0.5,\ 1.0,\ 1.5,\ 2.0,\ 2.5 \,\}$$

where the range of the values is chosen such that

$$1 = \frac{\xi_i^{*j}}{\xi_{i\max}^{j}} \left\{ \frac{1}{2} \left[\min\left(\left(\alpha \omega_i^{j2}(s) \right)^{1/2} \right) + \max\left(\left(\alpha \omega_i^{j2}(s) \right)^{1/2} \right) \right] \right\} \quad (24)$$

for the damping coefficient ξ_i^j, and for the force:

$$1 = \frac{F^{*j}}{K_{f2\max}^{j}} 2\left(K_{f3}^{j} \left(1 - K_{f1}^{j} \right) \right)^{\frac{1}{2}} \quad (25)$$

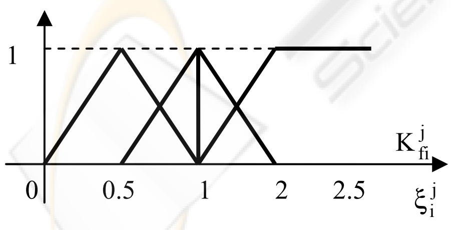

Figure 8: The memberships of the output variables

The memberships of the output variables are represented in Figure 8, where ST1, BT1 define linguistic variable: SMALLER THAN 1 and BIGGER THAN 1, respectively. According to the theoretical results obtained in the previous part of the paper, we can generate the control rules which establish a fuzzy control for a DSMC control (Table 1).

Table 1: The control rules

$\Delta \dot{F}^j$, $\Delta \dot{q}_i^j$ / ΔF^j, Δq_i^j	NB	NM	NS	NZ	PZ	PS	PM	PB
PB	B	BT1	BT1	BT1	S	S	S	S
PM	BT1	B	BT1	BT1	S	S	S	S
PS	BT1	BT1	B	BT1	S	S	S	S
PZ	BT1	BT1	BT1	B	ST1	ST1	ST1	ST1
NZ	ST1	ST1	ST1	ST1	B	BT1	BT1	BT1
NS	S	S	S	S	BT1	B	BT1	BT1
NM	S	S	S	S	BT1	BT1	B	BT1
NB	S	S	S	S	BT1	BT1	BT1	B

The main idea is to assure the normal control towards the switching line and direct control when the trajectory penetrates this line. A standard defuzzification procedure based on the centroid method is then used.

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