FUZZY LOGIC BASED HYBRID IMPEDANCE/FORCE CONTROL FOR UPPER LIMBS ROBOTIZED REHABILITATION

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Abstract: In our previous study [1], a hybrid control law, using a weighted sum of force and impedance, was proposed to implement on a robotized arm the Active-Assisted rehabilitation mode. The weighting of the force and impedance components is calculated by a classical formula which only depends on error position. In this paper we propose to determine this weighting by fuzzy logic, using not only error position but also velocity error. Results show that fuzzy logic weighting allows a safer and smoother man/machine interaction.

Introduction

Training and rehabilitation systems are automated devices that are used to: i) perform various types of movements at constant speed (isokinetic), fixed position (isometric), constant load (isotonic); ii) and measure the muscular forces of the target joints (shoulder, knee, wrist…). The use of these systems is becoming popular in the clinical and sport centres. However, the realizable movements are limited to circular motions, because the corresponding machines generally comprise a single rotation axis. Moreover, the fundamental movements of the shoulder are not rigorously circular [2], and they require the 3 degrees of freedom of space. For example, the movements of abduction/adduction in the frontal plane and flexion/extension in the sagittal plane induce a displacement of the shoulder's rotation axis of approximately 8 cm for an articular amplitude of 100° [3]. Moreover, the physiological movements are not strictly restricted within the plane which defines them. Therefore, during the execution of these movements, the circular trajectories of classical systems force the user to resort to non desired muscular compensations at the elbow, shoulder and trunk. These muscular compensations could distort the muscular evaluation, entailing traumatic rehabilitation and inefficient training.

In order to solve these problems and to increase the range of the realizable motions, we developed a prototype of a robotized arm with 3 degrees of freedom, allowing the execution of physiological movements (Figure 1). The development of this robotized arm benefits from our previous experience related to the specification and the design of rehabilitation and training machines for the lower limbs [4][5].

The use of 3 articulations makes it possible to compensate the misalignment between the rotation axis of the user's shoulder and the rotation axis of the robotized arm. Thus, it becomes possible to carry out the movements of abduction/adduction in the frontal plane and of flexion/extension in the sagittal and scapular planes, while limiting the undesirable muscular compensations. This confers many possibilities to the system in terms of accuracy and efficiency of evaluation and rehabilitation.

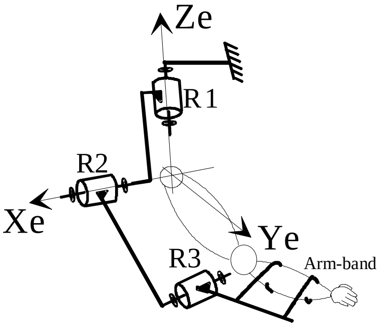

Figure 1: Robotized arm with 3 degrees of freedom

The majority of the prototype robots developed for the rehabilitation of the upper limbs [6][7][8][9][10] use traditional rehabilitation techniques, based on passive or active mobilization. In passive mobilization, the subject is not the actor of the movement and his/her arm is lifted by an external force, while the muscles remain completely relaxed. In active mobilization, the subject carries out a voluntary movement through muscular contraction. The robot must provide the necessary assistance if the subject is not capable of correctly performing the movement. Therefore, the robot should be able to quantify and adjust the degree of assistance necessary to succeed the various stages of rehabilitation. This mode of rehabilitation, known as *Active-Assisted* mode [2], requires a rather complex man-machine interaction. To guarantee the safety aspects of this interaction, robots like MIT-MANUS [11] were designed. This robot, which is highly back-driveable (i.e., it has a low intrinsic endpoint mechanical impedance) and whose low inertia is almost isotropic, is particularly dedicated to the rehabilitation of the cerebral vascular victims. But one of the major disadvantages of these robots, arising from the non-utilization of active force feedback in their control, is the impossibility of varying the apparent inertia felt by the subject to suit the requirements of a gradual rehabilitation. To avoid this inconvenience, the developed prototype (Figure 1) is not back-driveable and its inertia is not isotropic. Thus, it becomes possible to use an active force feedback to vary the apparent inertia [12][13].

In this paper, we first present the control architecture of the 3-dof system. Then we describe the synthesis of the control law for the *Active-Assisted* mode of rehabilitation. Control is based on a weighted sum of force and impedance. A new fuzzy method for the weighting are proposed and is compared to the previous one by simulations of our 3-dof robot.

Materials and Methods

The architecture of the system (Figure 2) consists of a mechanical part, a human-machine interface (HMI) and a software development environment. The mechanical part comprises the 3-dof robotized arm with 3 motors-reducers and an effort sensor to measure the forces applied by the user at the removable robot end-effector (arm-band or handle). A numerical 3 axes servo-controller is used to control the positions, speeds or torques of the 3 motors, according to training or rehabilitation requirements. The control laws are synthesised using dSPACE and Matlab/Simulink environment, and then compiled and implemented on a DSP board.

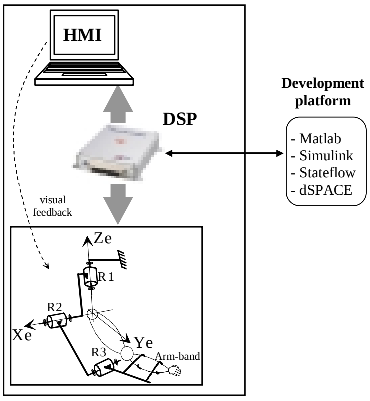

Figure 2: Architecture of the system

The human-machine interface allows users to choose a training exercise from a pre-established data base and to select the required parameters. To facilitate the correct execution of the exercise, a screen is used to provide visual information about the measured forces and the execution of the real movement trajectory compared to the desired one.

The hierarchical control structure (Figure 3) is inspired from the generic framework, proposed in [2] for the specification and design of any training and rehabilitation machine. This hierarchal structure comprises two parts: a sequential controller divided into 3 levels and a continuous switching control block corresponding to the control laws which are selected to carry out a training session. The module corresponding to a Rehabilitation session (Figure 3) is used to co-ordinate the rehabilitation (or training) modes and the consecutive phases forming the session. A phase is given by a succession of training series separated by a period of muscular relaxation. Each series comprises a number of repetitions of a particular *forward* trajectory pattern followed by a particular *backward* trajectory pattern, which are selected as a function of the training type required for the current phase. This information is to be given by a physiotherapist. The modules of level 3 represent the states and the switching control sequences required to perform a given movement pattern.

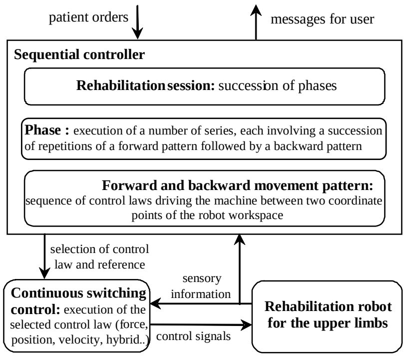

Figure 3: Hierarchical control structure

Many modules, corresponding to movement patterns, were developed to drive the upper limb(s) between two coordinate points of the robot workspace. Each of these modules invokes one or more control laws (position, velocity, force, impedance) as well as a predefined trajectory. The next section presents the control design for the *Active-Assisted* mode, which implements two concurrent control laws: force and impedance.

For economic reasons, the majority of force/position control schemes implemented in industrial robots do not compensate the nonlinearities of the dynamic model of the robot. They are generally based on a PID controller with gravity compensation to guarantee good static performances. However, during training and rehabilitation session, both static and dynamic performance requirements must be guaranteed. Therefore, he robot controller must fully compensate the nonlinearities of the dynamic model. A robot model constrained by the environment can be given by:

$$\Gamma = A(q)\,\ddot{q} + n(q,\dot{q}) + J^T F \qquad (1)$$

where q represents the angle positions vector, Γ the torque vector, A the matrix of inertia, n the vectorial sum of the centrifugal and Coriolis torques, gravitation torques and viscous frictions torques, J the jacobian matrix, F the vector of contact forces and torques supported by the robot end-effector.

If all the elements of the dynamic system are supposed to be measurable, the control law given by:

$$\Gamma = A(q)\, y + n(q, \dot q) + J^T F \tag{2}$$

leads (A being a positive definite matrix), with a global feedback linearization of the system (1), to the linear and decoupled system $\ddot q = y$. The choice of the new input vector y depends on the required control (position, force, impedance…).

This well-known inverse dynamics control, ensures a good tracking of the trajectory if the parameters of the dynamic model are known with sufficient accuracy. Despite the complexity of this control law is complex, in terms of architecture and calculation, its implementation is feasible thanks to the advent of increasingly fast microprocessors.

The first requirement of the *Active-Assisted* mode is to let the robot end-effector behave like a simple inert mass. The goal of the control law is thus to assign the following dynamics to the end-effector:

$$M_d\, \ddot x = F + M_d\, g \tag{3}$$

where M_d is the matrix of desired inertia, F is the vector of the contact forces and torques supported by the robot end-effector, g is the vector of gravity acceleration and x is the position vector in the operational space.

The resulting control scheme is similar to a force controller as (3) can be written as follows:

$$F_r - F = -M_d\, \ddot x \tag{4}$$
$$\text{where} \quad F_r = -M_d\, g$$

The measured force, F, is compared with the reference value, F_r, to determine the dynamics of the movement. The integration of relation (3) into the inverse dynamics control, confers to the robot a similar behaviour to that of an ideal weight machine, with the additional advantage of the ability to execute complex movements, without frictions [2].

To avoid a large movement deviation from the desired trajectory, we use the impedance control [14], usually employed in the man-robot interactions for its advantages in term of safety. In our case, the dynamics of the movement only depends on the subject and not on desired velocities and accelerations, and the impedance model is given by:

$$F = K\left(x - x_d\right) + B\dot x + M\ddot x \tag{5}$$

This relation provides the desired impedance to the robot end-effector. When contact forces arise, the real position x will deviate from the desired position x_d to satisfy (5) and, hence, to establish a compromise between force and position according to the matrices of stiffness K, damping B and inertia M. Relations (3) and (5) can be combined within the framework of the inverse dynamics control as follows:

$$\begin{aligned}
\ddot x_F &= \alpha\left(M_d^{-1}F + g\right)\\
\ddot x_I &= (I-\alpha)\, M^{-1}\left[K\left(x_d - x\right) - B\dot x + F\right]\\
\ddot x &= \ddot x_F + \ddot x_I\\
y = \ddot q &= J^{-1}(\ddot x - \dot J\, \dot q)
\end{aligned} \tag{6}$$

$$\begin{aligned}
&\text{where} \quad x = L(q) \quad \text{direct geometric model}\\
&\text{and} \quad \dot x = J(q)\dot q \quad \text{direct kinematic model}
\end{aligned}$$

$$\text{For the 3-dof robot: } \alpha = \begin{bmatrix} \alpha_1 & 0 & 0\\ 0 & \alpha_2 & 0\\ 0 & 0 & \alpha_3 \end{bmatrix}$$

The resulting hybrid-structure controller is based on the weighted sum of force and impedance control. α allows fixing the respective weight of the contributions of force and impedance.

In our previous study [1], this weighting (α , I - α) was calculated by a classical formula which only depends on error position:

$$\alpha_i = \frac{\tilde x_{i\max} - \left|\tilde x_i\right|}{\tilde x_{i\max}} \qquad \tilde x_{i\max} > 0 \tag{7}$$

where $\tilde x_{i\max}$ is the upper limit of the position error in the considered direction. This method exhibits satisfactory results in simulation. According to the requirements, when the position error is small, the contribution of force prevails and, reciprocally, when the position error is significant, the impedance control prevails. But only postion error is used.

Next we propose to determine this weighting by fuzzy logic, using not only position error $\tilde x_i$ but also velocity error $\dot{\tilde x}_i$ as input variables. Sugeno’s inference method is used in this system [15]. This method is computationally efficient and very popular for control problems. The fuzzy sets of input variables are : negative (N), zero (Z) and positive (P). The output variable is α_i, the weighting along direction i. The Sugeno fuzzy model takes the form:

Rule j: IF $\tilde x_i$ is A AND $\dot{\tilde x}_i$ is B THEN $z_j = c$

z_j is the output membership function of the rule j. Because a zero-order Sugeno model is used, z_j is equal to a constant c. In order to determine the final output α_i , z_j is weighted by w_j, the firing strength of the rule j:

$$\alpha_i = \frac{\sum_{j=1}^{N} w_j z_j}{\sum_{j=1}^{N} w_j} \tag{8}$$

In our case, six rules, based on Active-Assisted rehabilitation mode objectives, are defined:

IF $\tilde{x}_i$ is N AND $\dot{\tilde{x}}_i$ is NOT P THEN $z_1 = 0$
IF $\tilde{x}_i$ is N AND $\dot{\tilde{x}}_i$ is P THEN $z_2 = 0.5$
IF $\tilde{x}_i$ is Z AND $\dot{\tilde{x}}_i$ is NOT Z THEN $z_3 = 0.5$
IF $\tilde{x}_i$ is Z AND $\dot{\tilde{x}}_i$ is Z THEN $z_4 = 1$
IF $\tilde{x}_i$ is P AND $\dot{\tilde{x}}_i$ is N THEN $z_5 = 0.5$
IF $\tilde{x}_i$ is P AND $\dot{\tilde{x}}_i$ is NOT N THEN $z_6 = 0$

The three triangular membership functions for position error and velocity error are shown in Figure 4.

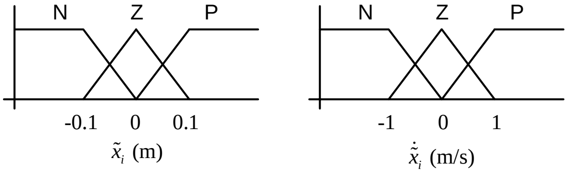

Figure 4: Membership functions

The control scheme (Figure 5) requires compensating of nonlinear terms, inversing the jacobian matrix, measuring forces at the end effector, and measuring angular positions and velocities. Compared with an impedance control alone, the proposed hybrid force/impedance control allows a better satisfaction of requirements imposed by the *Active-Assisted* mode.

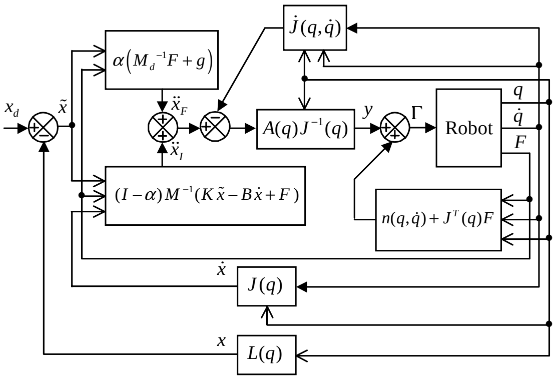

Figure 5: Control scheme

When the position error tends towards zero, the robot behaves indeed like an ideal weight machine. The parameter $\tilde{x}_{i\max}$ defines the subject's workspace in the considered direction. The larger this parameter is, the lower is the assistance provided by the robot. If this parameter is identical in all directions ($x_{i\max} = x_{\max} \quad \forall i$), the workspace at instant t is reduced to a sphere centred on the desired position $x_d(t)$ nearest to the real position $x(t)$ (Figure 6). The proposed controller forces the subject to remain in this space which, gradually, forms a safety space. To maintain the subject in this workspace, the position error is required to satisfy the following condition:

$$|\tilde{x}_i(t)| < \tilde{x}_{i\max} \qquad (9)$$

The satisfaction of this inequality depends obviously on the control parameters m_i, k_i and b_i, but also on the capacity of the subject to carry out the desired task. By considering (6), it is advantageous to choose the matrix M equals to M_d to ensure a good compromise between the contributions of force and impedance and to render the inertia felt by the subject equal to desired inertia irrespective of the position error. The choice of the control parameters k_i and b_i is more delicate, because the control must be sufficiently compliant to guarantee the subject's safety while ensuring a good trajectory correction. In [1] we proposed a method to determine the parameters k_i and b_i which fulfil this requirement.

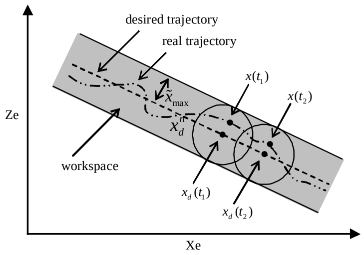

Figure 6: Workspace in the sagittal plane (Xe, Ze)

For obvious safety reasons, the suggested control should be tested exhaustively before experimentation. Indeed, we propose in the following section, simulations which compare the two weighting methods and illustrate the potentialities of the controller in terms of dynamics performance and medical interest. In order to validate the control hierarchy and a part of the control architecture, the control laws were compiled and loaded in the DSP board.

Results and Discussion

To simplify the presentation, we will consider the movement of flexion/extension in the sagittal plane, whose desired trajectory brings into play only two of the robot's three degrees of freedom. We will neglect small displacements in the horizontal direction when the movement is carried out in a natural way.

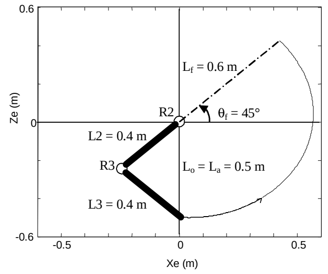

Figure 7: Initial robot's position and desired trajectory

The initial position of the robot as well as the trajectory taking into account displacements of the shoulder (glenohumeral) joint [3] are depicted in Figure 7. The origin of the reference mark, chosen in the sagittal plane (Xe,Ze) to describe this trajectory, coincides with the estimated initial position of the gleno-humeral rotation centre of the subject. This origin is at the intersection of the two axis of rotation of the robot's shoulder (Figure 1). The axis Ze is directed to the top, in opposite direction to the gravity acceleration. From the initial position, the subject's arm, of length $L_a = 50\ cm$, is directed downwards, $\theta_0 = -90°$. In the final position, $\theta_f = 45°$, the length L between the origin of the reference mark and the wrist of the robot is: $L_f = 60\ cm$. Thus, we suppose that the rotation axis misalignment of the subject's shoulder relatively to the rotation axis of the robot's shoulder, R2, entails a *10 cm* increase of the length L for this motion range of *135°*. L2 and L3 are both fixed at *40 cm*. Thus, any proximity with the singular position of the robot (tended arm) is impossible since the sum of these two lengths largely exceed the length of the subject's arm.

If one neglects the effect of the sampling ($Te = 1\ ms$), the robot's dynamic model is completely compensated. The desired isotropic mass is fixed at *1 kg* and the acceleration of gravity at $9{,}81\ m.s^{-2}$. For all directions, we consider that the subject cannot exert forces higher than $f_{i\ max} = 100\ N$. To simulate his/her behaviour, we suppose that the subject exerts a force of *1 N* in the direction of the anticipated position error $x_d^{n+1} - x(t)$ and entirely compensates the gravity force:

$$F(t) = \frac{1}{\left\| x_d^{n+1} - x(t) \right\|}\left(x_d^{n+1} - x(t) \right) - Mg \qquad (10)$$

In order to study the control reactions with respect to abrupt force variations induced by an abnormal behaviour of the subject (injury, weakness, tiredness…), we add a sinusoidal disturbance (with a frequency of *3 Hz* frequency and amplitude of *20 N* in the vertical direction) to relation (10). The forces simulated in the 2 directions of the sagittal plane are given by:

$$f_{Xe}(t) = f_1(t) = \frac{1}{\left\| x_d^{n+1} - x(t) \right\|}\left(x_{d1}^{n+1} - x_1(t) \right)$$

$$f_{Ze}(t) = f_3(t) = \frac{1}{\left\| x_d^{n+1} - x(t) \right\|}\left(x_{d3}^{n+1} - x_3(t) \right) - m_d g_3 + 20\sin(6\pi t)$$

$$\text{with:}\quad m_d = m = 1\,kg \quad \text{and} \quad g_3 = -9.81\,m.s^{-2}$$

Figure 8 depicts the simulation results for the two weighting methods. Subject workspace is fixed at 5 *cm*. The other control parameters are selected according to the method proposed in [1] and are given by:

$$M = M_d \qquad B\left[Nm^{-1}s\right] = 98.I \qquad K\left[Nm^{-1}\right] = 1000.I$$

For both weighting methods, the movement is completely achieved inside the assigned subject workspace. But we notice that the tracking of the desired trajectory is better with the fuzzy weighting method. The average norm of weighting matrix α informs us about the average rate of force control preponderance versus impedance control. This index is of medical interest within the framework of a gradual rehabilitation since it provides a quantification of the quality of movement execution. A higher percentage (about 85 % for fuzzy method and 71 % for non-fuzzy one) indicates a better accuracy of movement execution and a lower assistance provided by the robot.

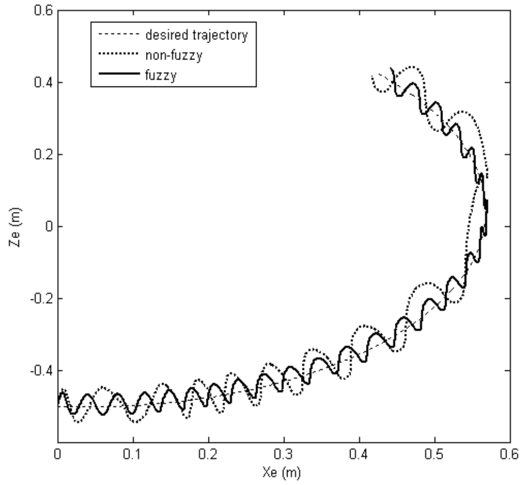

Figure 8: flexion/extension movement

An other simulation was conducted to test dynamic and static performances of the proposed control scheme and to compare the two weighting methods. We simulated the release and grab of the handle in vertical direction (Figure 9). Subject workspace is fixed at 10 *cm*. The release occurs at $t = 0\ s$ and the grab at $t = 1\ s$.

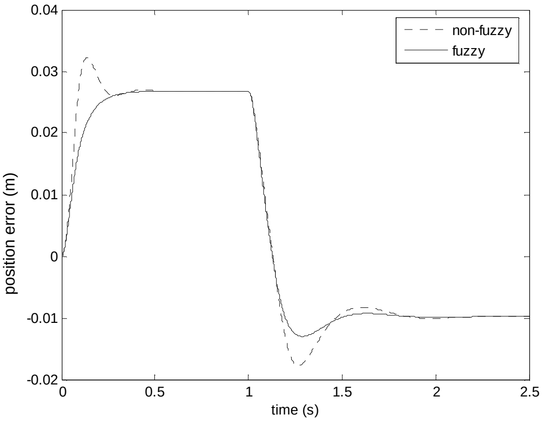

Figure 9: Release and grab of the handle

Results show limited static errors which are the same for both methods. This because the zero membership function (Z) of position error (Figure 4) was designed such that its limits are those of the subject workspace. Notice that these static errors are easy to cancel because force control is dominating for this weak position errors. Dynamic error are different according to the weighting method used. Fuzzy method presents much less oscillations than non-fuzzy one with a dynamics hardly slower. Thus, fuzzy method allows a safer human/machine coupling.

Conclusions

This paper has presented the architecture and the control hierarchy of a 3 degrees-of-freedom robot destined for the rehabilitation of the upper limbs. This structure is inspired from a generic framework for the specification and design of any training and rehabilitation machine. For robotized neuromuscular rehabilitation in *Active-Assisted* mode, we proposed an original hybrid controller, based on a weighted sum of force and impedance contributions. This control, specially adapted to non back-driveable robots, uses an active force feedback and confers to the robot the behaviour of an ideal weight machine, without frictions, when position error is quasi null. The fuzzy weighting method presents better dynamic performances than the previous one. Moreover fuzzy logic is well adapted to a safe human/machine coupling because it reproduces human reasoning. Simulation results have shown that the controller is satisfactory in terms of dynamic performances and safety.

In our next studies we will optimize the fuzzy method by taking into account not only position and velocity error signals but also force signal. Then, the overall control scheme will be experimented on our 3-dof robot.

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