Robotic assisted trajectory tracking for human arm rehabilitation

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Abstract— The following paper presents an assistive rehabilitation scheme for patients with upper limb impairments such as strokes. Based on the tracking of predefined trajectories either in Cartesian or joint space, the system allows an adjustable degree of variation with respect to the ideal trajectory. The amount of variations allowed is adjusted through the coefficients of an admittance function. It performs the transformation between the opposition forces, from the patient to the robot, and makes it divert, within certain limits, from the original trajectory.

Keywords—*7DOF exoskeleton, admittance, assisted rehabilitation, upper limb rehabilitation.*

I. INTRODUCTION

Stroke is a sudden loss of blood flow to the brain. Most strokes occur by an occlusion (when a blood clot blocks a blood vessel in the brain, interrupting the supply of blood and oxygen to the brain cells in that area) or either a rupture of a major cerebral artery and the resulting bleeding. In both types of stroke, brain cells may die, causing the parts of the body they control to stop functioning [1, 2]. Strokes are a very important health issue in the world. According to the World Health Organization, 15 million people suffer from a stroke throughout the world every year. Out of all of these people, 5 million die directly because of it and another 5 million are left permanently disabled [3]. One of the most common consequences after a stroke is paralysis (the inability of a muscle or group of muscles to move voluntarily) which affects up to 90 percent of stroke survivors. Many stroke survivors experience one sided-paralysis. The most common kind (approximately 80 percent) is hemiparesis, which causes weakness or inability to move one side of the body. Spasticity affects roughly 40 percent of stroke survivors and is characterized by stiff or tight muscles that constraint movements [4]. The main treatment for these cases is rehabilitation: the process of helping an individual achieves the highest level of independence and quality of life possible. When rehabilitation is possible, it implies many hours of highly skilled and extensive physiotherapy procedures. However, the amount of people that can bring this support is not sufficient to carry out with all the patients. The recovery progression can be a lifelong process and while some people recover quickly, others can deal with it for a very long time, even for the rest of their lives. The use of robot assistance in rehabilitation is a very important point of interest.

For the purpose of providing rehabilitation assistance for the upper limb and daily assistance, the ETS - Motion Assistive Exoskeleton Robot for Superior Extremity (ETS-MARSE) is under development [5-7]. Currently it comprises a seven degree of freedom (DOF) exoskeleton, designed to cope with full motion capabilities of the arm's main movements, that are at the shoulder, elbow and wrist levels, combined or individually. So far the work has been developed to the point of passive rehabilitation, which means that the exoskeleton executes movements along predefined trajectories moving the subject's arm with its own movements to help improve the range of movement. This paper describes the first movement towards the next rehabilitation step: assistive rehabilitation, in which the robot takes information from the human-machine interaction, in this case through contact force feedback between the structure and the person's arm and uses it to actively modifying its rehabilitation task. In this step of the research, the robot also has the instruction to follow a predefined rehabilitation exercise; however, the system is measuring the force on the subject that opposes the predetermined movement and allows certain adjustable degrees of variation of the trajectory (or more or fewer degree of help from ETS-MARSE). This encourages the patients to actively participate in the exercise by attempting to follow the path, and motivates them to improve their accomplishments.

This paper is organized as follows. Section II, presents the scheme that will allow the robot to adjust the amount of assistance that will be provided to the patient. In Section III, the experimental setup of the system is described. Section IV summarizes the implementation and the results and finally, Section V presents the conclusions and the future work.

II. TRAJECTORY DEFINITION

In robotics, a trajectory defines a movement of the robot in a multidimensional space. This trajectory has information regarding the position, velocity and acceleration for each degree of freedom in time [8]. To command the robot's movement, the user defines a desired trajectory that includes this information. It is generated usually by means of a trajectory planner.

A. *Trajectory planner*

The base trajectory planner for ETS-MARSE is based on joint space specification. It is performed in real time on the processor designed for that purpose of the system (PXI-8108), described in section III. Initial and final positions for each joint are specified as well as intermediate points, if desired. The transition between trajectory segments is always done with velocity of zero, because they generally indicate changes in the direction of the movement (i.e. to do a flexion and extension of the elbow means to move it from 90º to 170º and then back to 90º.) The trajectory is then calculated by the method of cubic polynomials [8].

In rehabilitation, it is often useful to specify a desired trajectory in the Cartesian space, that is, to specify movements with an immediate sense, as a straight line or for example following a geometrical shape as a triangle, rectangle, etc. For the ETS-MARSE robot, the trajectory can be specified either in the joint space or in Cartesian space (robot workspace); nevertheless, the trajectory tracking is always executed in joint space. Thus, it is necessary that given a position and orientation of the end effector in Cartesian space, find the joint positions of the robot that can accomplish this desired configuration. When the case arises, the method of the pseudo inverse of the Jacobian is used. It is known that the Jacobian matrix of a robot relates the joint velocities with linear and angular velocities of the Cartesian space.

$$\dot{X} = J(q)\dot{q} \tag{1}$$

where $\dot{X} \in \mathbb{R}^6$ is the velocity vector of the end effector, $\dot{q} \in \mathbb{R}^n$ is the joint velocities vector and $J(q) \in \mathbb{R}^{6\,x\,n}$ is the robot Jacobian matrix. However, for the case of a redundant robot like ETS-MARSE (7 DOF), the Jacobian matrix is rectangular. To obtain a solution for the inverse problem of (1), one possible solution is proposed [9]:

$$\dot{q} = J(q)^{+}\dot{X} \tag{2}$$

where $J(q)^{+} = J(q)^{T}(J(q)J(q)^{T})^{-1}$ is the generalized pseudo-inverse. The method can be enriched by adding null space characteristics to the right side of the equation with the term$(J(q)^{+}J(q) - I)\xi$, where $\xi \in \mathbb{R}^n$ is an arbitrary vector that can be used for tasks as obstacle avoidance.

B. *Admmitance modified trajectory planner*

For the assistive rehabilitation that is proposed in this paper, the idea is to modify the predefined trajectory in relation to the subjects' movement limitations. As it is described in Section III, the system measures the force exerted by the user at the level of the end effector of the robot. The first step is to transform this information in something more representative of how the subject's opposition force affects each DOF of the exoskeleton, i.e. joint torque.

Another property of the Jacobian matrix is that as a consequence of the virtual work principle, its transpose assigns Cartesian forces to joint torques. When the Jacobian matrix is expressed with respect to the base frame of the manipulator, the force-moment vector referenced to the same frame can be transformed as:

$$\tau = {}^{0}J^{T\,0}\mathcal{F} \tag{3}$$

where τ is the 7×1 vector of torque actuating in the articulations and $\mathcal{F}$ is a force-moment Cartesian vector of 6×1. The zero leading super indexes specify that they are defined with respect to the base frame. This relation gives us the effect of the user's opposition force in terms of joint torques.

Impedance can be defined as a transfer function between the external force acting on the manipulator and its displacement [10]. Usually this kind of relation takes the form of a mechanical mass-spring-damper system. Knowing the result from (3) and applying the impedance definition in the form of an admittance relation, we have a direct form to modify the desired trajectory.

$$\mathbf{q}_a = \mathbf{q}_d + \tau\left(\frac{1}{K - Cs}\right) \tag{4}$$

where $\mathbf{q}_a$ is the new desired trajectory defined by the admittance, $\mathbf{q}_d$ the original desired trajectory from the trajectory planner and the last right term of the equation in the parenthesis, the chosen admittance function.

III. SYSTEM OVERVIEW

The current architecture of the system is depicted in Fig. 1. The exoskeleton robot arm is an open chain all revolute 7DOF wearable manipulator-like robot; it was designed for its joints to correspond to the principal degree of freedom of the human arm. Those are:

- 3DOF at shoulder level for horizontal flexion/extension, vertical flexion/extension and internal/external rotation,
- 1DOF for elbow flexion/extension,
- 1DOF for forearm pronation/supination, and
- 2DOF at the wrist level for radial/ulnar deviation and flexion/extension.

The exoskeleton structure has a force sensor mounted in the end effector (tip) of the robot, which is at the level of the handle where the patient's hand must be positioned. For

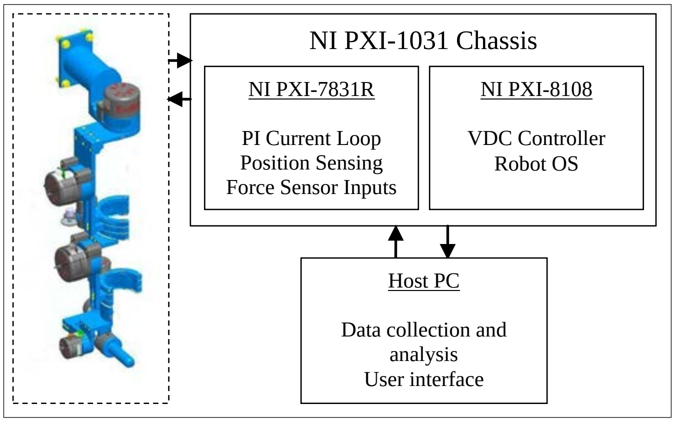

Fig. 1. ETS-MARSE system hardware overview.

illustrative purposes, a schematic of the ETS-MARSE as well as an image showing a person wearing it is presented in Fig. 2. The joints are driven by brushless DC motors, one for each articulation, incorporated with harmonic drives. An output driver that receives a voltage level as its reference control signal controls each motor. Also each motor has a Hall effect sensor, which are used for position feedback of the joints.

These drivers, among security, communication and general circuitry are mounted on a backplane card developed at the ETS. This backplane collects analogic and digital signals and connects through the proper interface cards to an NI PXI-7813R (Remote Input Output card) placed on an NI PXI-1031 chassis. The card has an integrated FPGA in which executes the low level control: A PI controller for the current loop of the motors, the position feedback via the Hall effect sensors monitoring and the collection of the force sensor inputs. Also in the chassis is mounted a PXI-8108 controller. Its embedded dual core processor (Intel® Core™ 2 Duo) executes the high level control: the robot's operating system which is responsible for running the MARSE through its different operation states, and the trajectory tracking controller. In this case we are using the nonlinear control technique known as Virtual Decomposition Control (VDC), a very effective newly control technique [11]. The details about the implementation of the VDC are out of the scope of this paper.

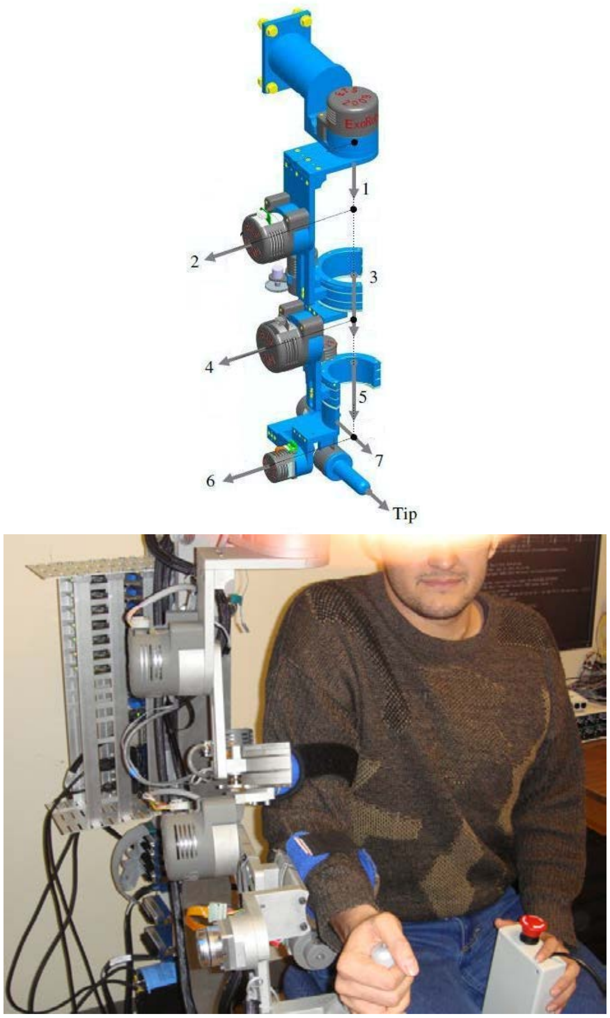

Fig. 2. ETS-MARSE and subject wearing ETS-MARSE.

Finally a PC is connected to the PXI via a local Ethernet network that collects from the PXI the data resulted from the robot execution. This data is used to analyze the performance in trajectory tracking and other useful data for development purposes. Also this computer works as the user interface from which the desired trajectory is selected, including the selection of Cartesian or articular space trajectory. The primitive commands to the robot are sent also from this PC, these are: system on, motors on, reset, initialize, start and abort (also the system have an emergency stop button, since it is a human-machine interface, security is a major concern issue.) The software limits of the joint movements in position and velocity can be setup from this interface. Finally the interface has the option of manual operation of the motors and it can provide feedback of motor position in real time in a user reasonable update rate (very much slower that the position refresh rate used in the controller).

IV. EXPERIMENTAL RESULTS AND SIMULATIONS

As was mentioned in Section III, the experimental setup was performed with the VDC technique that works at an update rate of 1 ms. The experiment described below was executed with a 31 years old healthy male subject with a mass of 83 Kg and 182 cm height. The experiment performed was an elbow extension-flexion movement. It can be seen in Fig. 3. The elbow initiates at a start position of 90º, then goes to 5º, then to 115º and ends at 0º.

If we analyze this movement in the Cartesian space, it can be seen as a portion (110º) of a semi-circle. Because the opposition force to this movement that the subject voluntarily (testing on a healthy subject) exerts toward the robot the trajectory deflects from the predefined one. Fig. 4 shows the effect of this action. It can be seen in red the original desired trajectory, and in blue the new trajectory that is affected by the user interaction. The black line shows the tracking of the controller that can be seen very close of the admittance modified trajectory. The controller performance is not part of the scope of this paper; nevertheless, it was developed to ensure reliable results of the experiments.

In order to test the effects of modifying the parameters of the admittance function, it is considered that two human force inputs to the system cannot be equal. For this reason, to be consistent in the comparison, the force sensor input captured from the experiment shown above, is fed into a simulation. The first result, shown in Fig. 5, preserves the admittance relation of the physical test. Thus it shows the same deflection, but with almost perfect tracking. Then, the admittance function is modified to force the robot to give more assistance to the subject. It can be seen in Fig. 6 that the trajectory will not allow so much drifting from the intended rehabilitation trajectory as in the previous case. Finally we relax the admittance function to provide low assistance, and the results of this trajectory will be a very erratic movement far away from the intended rehabilitation exercise as can be seen in Fig. 7.

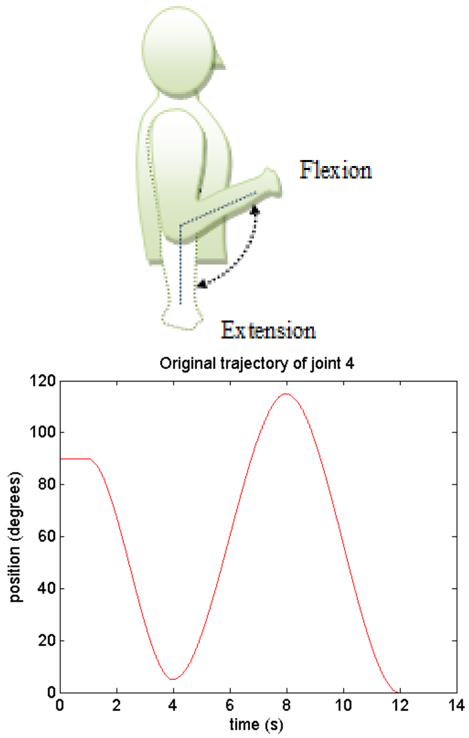

Fig. 3. Test performed: Elbow extension/flexion.

To finish the analysis from the Cartesian point of view, from the results of the experimented performed with the robot (Fig. 4), the trajectories for each Cartesian axis with the force and torque measured with the force sensor are shown in Fig. 8. In the plots of the left, which corresponds to the trajectories in the Cartesian axes, the solid line represents the original trajectory of the movement without any modification; the dotted line represents the trajectory modified by the admittance function that was followed by the human-robot system. It can be seen how the forces and torque, in the center and right columns respectively, affect the desired trajectory.

V. CONCLUSIONS AND FUTURE WORK

As can be seen from the experimental results, the present work can actively help a patient to accomplish a specified trajectory (a rehabilitation exercise). According to the evolution and the needs of the patients, the robot can vary the assistance provided. It is important to say that the robot will not force beyond capabilities of rehabilitation to the patient to fulfill a trajectory, a qualified therapist must adjust the limits according to the requirements. The amount of variation of the trajectory can be quantified as an excellent measurement of progression of the patient. As the next step for active assisted movement, the system will be provided with a virtual environment. It will provide the patients with visual help in the tracking of the movement objectives and will incorporate a variety of exercises in a game-based experience and incorporate powerful tools to track the evolution through the sessions. The next step in this research in force based

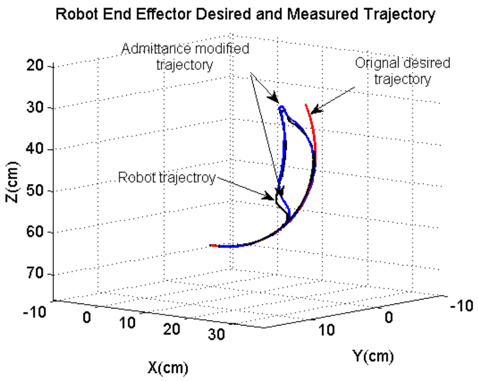

Fig. 4. Elbow flexion-extension results in Cartesian space.

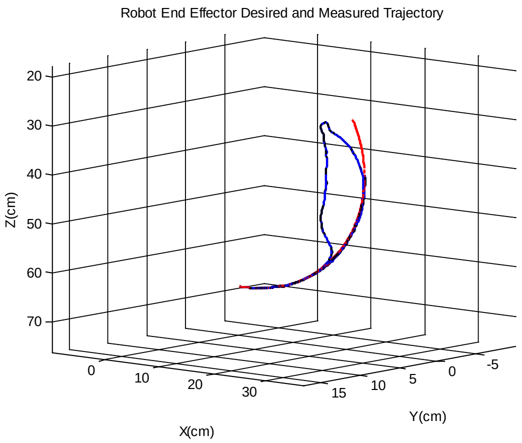

Fig. 5. Simulation of real results

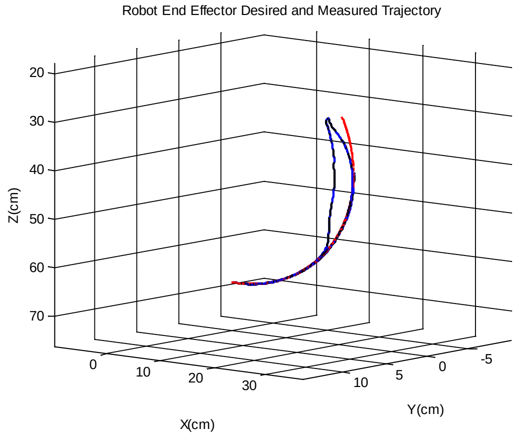

Fig. 6. Simulation with high degree of help.

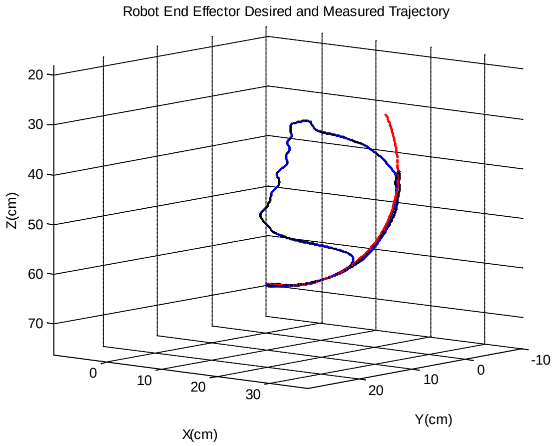

Fig. 7. Simulation with low degree of help.

rehabilitation is to move to active rehabilitation, which means that the patient will have control of his own movements without predefined trajectories, and the robot will help to accomplish that user desired movement.

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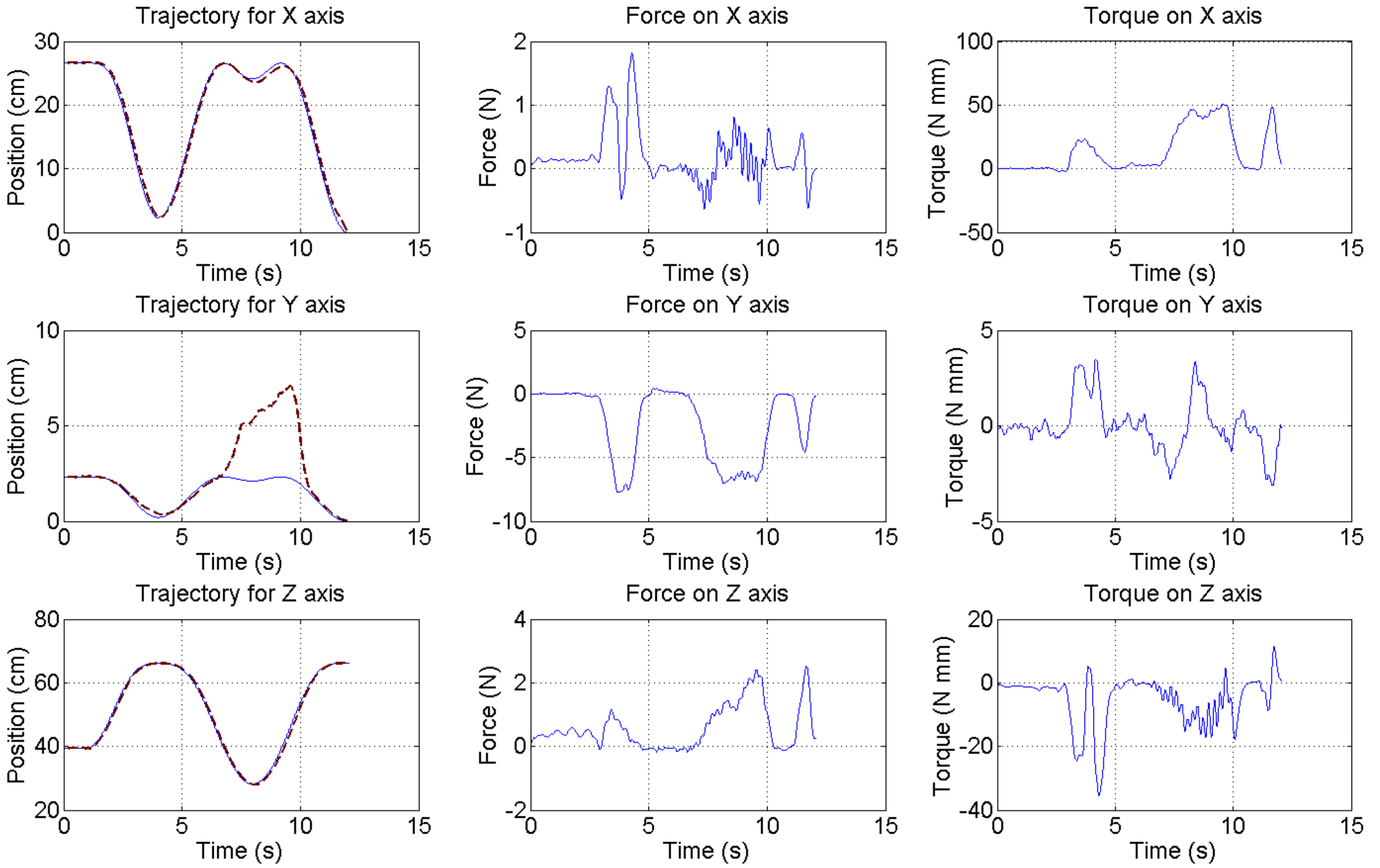

Fig. 8. Cartesian overview of the trajectory and forces and torques of the system.