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Kinematical and dynamical modeling of a multipurpose upper limbs rehabilitation robot

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ABSTRACT

Knowing accurate model of a system is always beneficial to design a robust and safe control while allowing reduction of sensors-related cost as the system outputs are predictable using the model. In this context, this paper addresses the kinematical and dynamical model identification of the multipurpose rehabilitation robot, Universal Haptic Pantograph (UHP), and present experimental validations of the identified models. The UHP is a Pantograph based innovative robot actuated by two SEAs (Series Elastic Actuator), aiming at training impaired upper limbs after a stroke. This novel robot, thanks to its lockable/unlockable joints, can change its mechanical structure so that it enables stroke patient to perform different training exercises of the shoulder, elbow and wrist. This work focuses on the ARM mode, which is a training mode used to rehabilitate elbow and shoulder. The kinematical model of UHP is identified based on the loop vector equations, while the dynamical model is derived based on the Lagrangian formulation. To demonstrate the accuracy of the models, several experimental tests were performed. The results reveal that the mean position error between estimated values with the model and actual measured values stays in 3 mm (less than 2% of the maximum motion range). Moreover, the error between estimated and measured interaction force is smaller than 10% of maximum force range. So, the developed models can be adopted to estimate motion and force of UHP as well as control it without the need of additional sensors such as a force sensor, resulting in the reduction of total robot cost.

1. Introduction

According to the World Health Organization (WHO), every year, more than 15 million strokes or cerebrovascular accidents are diagnosed and two thirds among them survive but have to live with the sequels of stroke. Nowadays, more than 33 million people in the world are affected by stroke sequels [1,2]. Up to date, various research results on stroke have demonstrated that, thanks to brain plasticity, stroke patients may recover most of their skills executing adequate rehabilitation exercises [3]. However, in classical rehabilitation programs, stroke patients require constant supervision by the therapist, which increases the economic cost of the therapy, and leads to the reduction of rehabilitation times, impeding continuous and long-term rehabilitation interventions [4].

Hence, over the last couple of decades, several rehabilitation robotic devices for stroke patients, particularly for upper limbs rehabilitation, have been developed [5,6] and demonstrated at both academical and clinical settings. The robots are believed to be a good alternative to traditional rehabilitation therapies due to several advantages of the robot-mediated therapy [7]: 1) robots emulate and replicate the movements produced by a physiotherapist, executing longer duration, higher frequency and better accuracy treatments; 2) with the objective of evaluating the progress of the patient as well as adapting the exercises to their needs, the device can act as a measurement tool that quantifies forces and/or movements; 3) using a graphical interface, a virtual reality environment can be built, facilitating patient involvement in the rehabilitation process.

The rehabilitation robotic devices can be classified into two groups: end-effector type and wearable type (exoskeleton). The MIT-Manus [8], MIME [9], GENTLE/s [10], REHAROB [11] belong to the end-effector type while Armin [12], L-Exos [13], RUPERT [14] or Limpact [15] fall into the wearable type. Differently from other robotics areas where the usual position control strategies are used with great success, rehabilitation robots should take into account the interaction between the patient and the robot, and use it so as to safely apply assistive force to the patient during trainings. This indicates that it is necessary to implement advanced control algorithms that combine motion and force measurements [16]. In the literature, several approaches such as force control [17], computed torque control [18], algorithms using EMG signals [19] or

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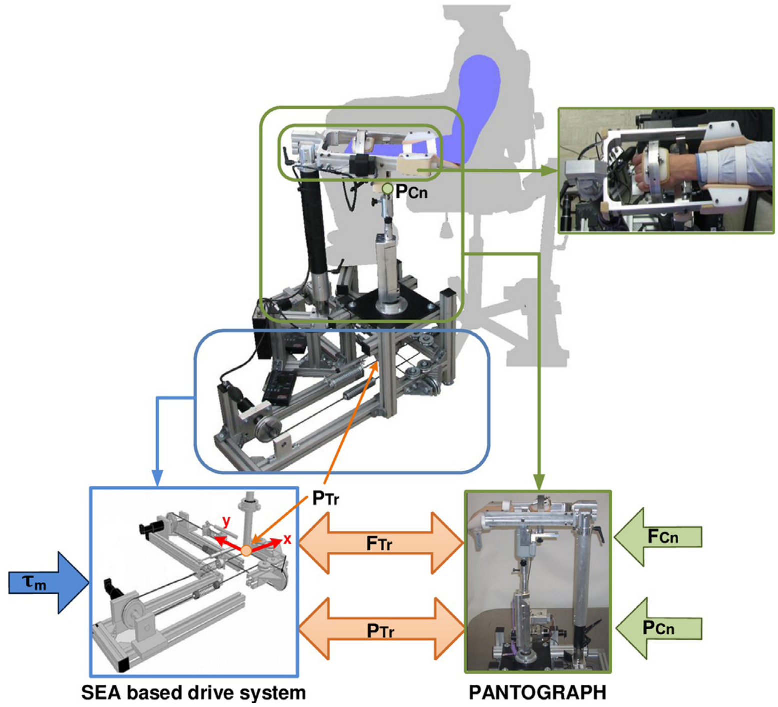

Fig. 1. Universal Haptic Pantograph (UHP).

neurofuzzy control [20] have been proposed to control the patient-robot interaction. Among the proposed approaches, impedance control introduced by Hogan in 1984 [21], and its complimentary method, admittance control, have been the most common [22,23].

In order to implement these advanced controllers, an appropriate kinematical and dynamical model of the robot is required. This model determines the human-robot interaction forces and its motion, and force transmission between the actuators and the interaction point [24,25]. Moreover, in order to implement the control law, the actual position and force exerted to the patient need to be not only motorized but also sensorized continuously. However, direct force measurement requires force sensors that add mechanical and electrical complexity to the mechanical structure. In addition, these sensors are normally very expensive compared to other components such as motor [26], resulting in unaffordable price of robots. Such unaffordability is one of main barriers that impede wide use of the rehabilitation robots.

Accurate models of the robot can be used to implement estimators of both position and force as an alternative of direct measurement using the sensors in order to reduce the cost of the robot. Normally, these estimators use the easily measurable variables and elements information provided by manufactures (e.g. actuator specifications) to estimate the motion and forces of the robots [27,28].

Therefore, a proper and accurate mathematical model of the robot not only facilitates the design of the advanced control strategies but also possibly realizes affordable robotic solutions for rehabilitation area. In this context, this study presents the kinematical and dynamical modeling approach and the resultant models of a multipurpose upper limb rehabilitation robot, referred to as the Universal Haptic Pantograph (UHP) [29]. The UHP is a Pantograph based innovative device actuated by two SEAs (Series Elastic Actuator) whose main characteristic is the reconfigurability of its mechanical structure using lockable/unlockable joints. This feature allows to adapt the structure to the rehabilitation needs of different parts of the upper limb [30].

The article is organized as follows. In Section 2 the UHP rehabilitation robot and the adopted modeling approach are presented. In Section 3, as a first subsystem of UHP, the SEA based drive system and its kinematical and dynamical models are identified. Section 4 describes the identification procedure of the kinematical and dynamical models of the Pantograph which is a subsystem directly contacting users upper limbs. In Section 5, several experimental case studies are presented in order to validate the models. Finally, the most important ideas and conclusions appear in Section 6.

2. Universal Haptic Pantograph and the modeling approach

The Universal Haptic Pantograph (UHP) (Fig. 1) is a rehabilitation robot developed to train impaired upper limbs after a stroke [29]. One of the most important benefits of the UHP is its reconfigurability, which allows to modify its mechanical structure thanks to its lockable / unlockable joints. In this way, for each mechanical configuration, the UHP can execute different types of exercises that focus on certain parts of the upper limb: the shoulder, elbow and wrist [30].

This work focuses in one of the most complete modes, the ARM mode. This mode is used to rehabilitate elbow and shoulder by means of 2 degrees of freedom (DOF) motions that allow arm extension in forward, backward, leftward and rightward directions.

In order to provide this movement, a Pantograph-based structure is used to interact with the patient. The Pantograph is actuated by two perpendicular SEAs (Series Elastic Actuator) in order to generate forces in x and y directions as shown in 'SEA based drive system' block in Fig. 1.

The motion of the UHP results from the forces ($\mathbf{F_{Cn}}$) exerted by the user in the contact point ($\mathbf{P_{Cn}}$) and the torques ($\boldsymbol{\tau}_\mathbf{m}$) exerted by the motors through the SEA based drive system. The two subsystems are connected in the transmission point ($\mathbf{P_{Tr}}$) such that the torque ($\boldsymbol{\tau}_\mathbf{m}$) exerted by the actuators of the drive system and the force ($\mathbf{F_{Cn}}$) and motion ($\mathbf{P_{Cn}}$) applied to the Pantograph by the patient are transmitted bilaterally in the form of force ($\mathbf{F_{Tr}}$) and motion ($\mathbf{P_{Tr}}$) (Fig. 1).

As mentioned previously, a proper mathematical model of the robot is required to implement the robot-patient force interaction controller. Since the model demands position measurements of the drive system for the estimation of the torque ($\boldsymbol{\tau}_\mathbf{m}$), the force ($\mathbf{F_{Cn}}$) and motion ($\mathbf{P_{Cn}}$) shown in Fig. 2, the UHP prototype includes two optical encoders and two linear potentiometers to measure the actuators rotation angle ($\mathbf{q_m}$) and the lengths of SEAs upper springs (n_{S_A} and n_{S_B}), respectively.