Preliminary Study on the Admittance Control of a Hand Rehabilitation System

Mertcan KOÇAK[1], Okan AYAR[2]
[1]Mechatronics Engineering, [2]Mechanical Engineering
İzmir Katip Çelebi University
İzmir, Turkey
[1]mertcan.kocak@ikc.edu.tr, [2]okan.ayar.35@gmail.com

Erkin GEZGİN[3]
[3]Mechatronics Engineering
İzmir Katip Çelebi University
İzmir, Turkey
[3]erkin.gezgin@ikc.edu.tr

***Özetçe* — Nörolojik bozukluklar sinir komutlarını yok ederek insan yaşamını olumsuz yönde etkilerler. Bu durumlarda, nöral plastisite oluşturulabilmesi ve etkilenen motor fonksiyonlarının yeniden kazanılabilmesi için rehabilitasyon prosedürlerinin hızlıca uygulanması gerekmektedir. Buna karşın, mevcut fizyoterapistlerin sayısının sınırlı olması ve rehabilitasyon süreçlerinde tedavi kalitesini etklileyen ağır bir iş yüküne ihtiyaç duyulmasından dolayı, kaza sonrası hızlı müdahale olasılıkları azalmaktadır. Bu bağlamda literatürdeki rehabilitasyon robotiğine yönelik tasarım ve kontrol çalışmaları çok sayıda tedavi ihtiyacının karşılanabilmesi amacıyla hızla artmaya başlamıştır. Buradan yola çıkarak, mevcut çalışmada, hali hazırda geliştirilmekte olan tek serbestlik dereceli bir el rehabilitasyon robotuna admitans kontrol algoritmasının uygulanabilmesi amaçlanmaktadır. Bildiri kapsamında gerçekleştirilen ön çalışmanın sonunda ilerideki çalışmalara yön gösterecek umut verici sonuçlar elde edilmiştir.**

Anahtar Kelimeler — Rehabilitasyon; Tıbbi Robotik; Robotik Rehabilitasyon; Admitans Konrol.

***Abstract* — Neurological disorders influence human life by destructing neural commands. In such cases, rehabilitation procedures should be applied to the patients immediately in order to create neural plasticity and regain affected motor functions. On the other hand as the number of available physical therapists is limited and rehabilitation procedures requires heavy cumbersome work that affects overall quality of the treatments, immediate interventions are limited after the accidents. As a result, studies towards rehabilitation robotics in related literature that includes both design and control strategies have started to increase rapidly in order to compensate high numbers of treatment needs. In light of this, current study tries to implement admittance control algorithm to a one degree of freedom hand rehabilitation robot that is currently under development. At the end of the preliminary study, promising results were achieved and represented.**

Keywords — Rehabilitation; Medical Robotics; Robotic Rehabilitation; Admittance control.

I. INTRODUCTION

For several reasons such as accidents or some diseases like stroke, neurological disorders may occur. These incidents destruct neural commands and affect motor functions. When such situation occurs, patients should undergo series of physical rehabilitation procedures as soon as possible and carry out necessary exercises repeatedly in order to create neural plasticity. However, classical rehabilitation has some limitations such as the limited availability of physiotherapists, exhausting treatment periods and lack of data collection during the treatment in order to observe and interpret patient development. Thus number of scientific studies on robotic rehabilitation [1-5] has been increased currently to compensate limitations in the rehabilitation treatments as well as increase their overall quality. Thanks to these studies, rehabilitation robots are also continuously being developed commercially today. These robots mostly focus on lower extremity, upper extremity and other important individual parts of the human body such as fingers and hands. Generally, these devices are combined with virtual environment in order to create cognitive effects and convert treatment sessions to a fun play for patients due to the importance of the emotions that have important role in recovering period.

Throughout the literature indirect force torque control strategies are commonly used for rehabilitation robotics. In Dede's Master's thesis [6], existing position/force algorithms were discussed briefly and they were compared with each other along with simulations. Hlaing et al. [7] designed a one degree of freedom assisting device for physical human-robot interaction with admittance control. In their experiments, the first step was the tuning of PID parameters for the pure position control part in the inner control loop of the system. Later authors worked on admittance control setup as an outer loop and compared the performance of different virtual gains. Seraji [8] proposed two adaptive PID and PI force compensator as admittance control in the problem of controlling a manipulator in contact with environment having an unknown stiffness. Keemink et al. [9] presented seven design guidelines for achieving high-performance admittance controlled devices that can render low inertia, while aspiring coupled stability and proper disturbance rejection.

Considering the control strategies in related literature, this study aims to implement admittance control to a one degree of freedom hand rehabilitation robot. Existing rehabilitation system setup includes a nonbackdrivable transmission system actuated by a brushless Maxon motor. Actuator is coupled with a shaft to shaft torque sensor attached between the transmission output and the end effector input in order to monitor torque

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data acquired from the patient hand during the treatment that imitates grasping motion. Using the signal acquired via the torque sensor, admittance control algorithm was utilized as an outer control loop that converts patients torque input to a desired angular velocity estimation. Following this, estimated angular velocity was used in the velocity control mode of motor driver as an inner control loop input. Throughout the procedure current of the electric motor was measured by the Hall effect sensor and it was multiplied by the torque constant of the actuator to calculate real time motor torque. In order to extract correct torque values that represent patients grasping intention, torque sensor readings and calculated torque values were used in conjunction. Acquired results were verified on the rehabilitation system at the end of the study.

II. Rehabilitation Procedures

Robot assisted rehabilitation procedures are mainly considered in three steps during treatments. Procedural approach starts with the actuator of the system that is driven without any patient intention in order to create plasticity in patient's brain after a series of treatment sessions. This helps patient to regain lost muscle activity at the target extremity. In this part, predefined characteristics for the rehabilitation exercises are considered.

After reorganization to compensate injuries at the patient brain is achieved by the help of the first step, the system is started to be used as a support manipulator. In this part, rehabilitation system awaits for patient to activate desired motion with small muscle activity. This small intention is sensed by the implemented sensor (in the case of current study: torque sensor) and amplified with a virtual admittance gain in order to drive the system with actuator as if target patient drives on his/her own. This aims to support patient fully in the will of executing desired activity repeatedly, which is quite important for recovery phase.

Finally, after the patient mostly regains desired muscle activities, the system is started to resist patient's motion intention in order to enhance muscle strengths. In this part, when a muscle activity is sensed by the sensor, the controller sends a signal to actuator to generate a predefined counter force, which makes the system harder to be driven.

III. System Setup

A. Hand rehabilitation system

In this paper, hand rehabilitation system in development designed by Gezgin et al. [1] was used as a test plant. End effector of the system where the patient hand is attached (Figure 1a) during treatments is a single degree of freedom six bar mechanism that was designed to mimic natural hand grasping motion for stroke patients. In authors' study, in order to design linkage system with a proper end effector path, motion capture system was used by the authors to acquire natural path of the fingers during grasping.

Utilized rehabilitation system includes a Maxon brushless DC actuator (250 W, 5000 rpm, 331 mNm) with a built in low backlash planetary gearbox (43:1), encoder, Hall effect sensor and FUTEK TRS300 20 Nm shaft to shaft rotary torque sensor between transmission output and end effector input.

Figure. 1. a) Hand attached to the end effector of the system, b) Overall robotic rehabilitation setup [1].

Without changing the direction of the actuator, structural design of the system allows continuous motion to achieve grasping motion. Overall construction of the system can be seen in Figure 1b.

B. Torque sensor calibration

In this work, FUTEK TRS300 20 Nm shaft to shaft rotary torque sensor was used as the main feedback in the control loop along with an amplifier module FUTEK CSG110, which is capable of giving analog output between -10/+10 V with the resolution of 0.5 V/Nm. This analog signal was measured by Humusoft MF624 PCI card, which was installed onto a PC. All of the acquired sensor data were digitalized and observed with Desktop Real Time Toolbox of Simulink. Prior to the implementation, torque sensor was calibrated to be used properly.

During dedicated calibration procedure, one of two shafts of the rotary torque sensor was fixed. For the remaining one, a single link with a 12 cm length was designed and manufactured with a rapid prototyper in order to generate a known torque value at the sensors rotation axis by hanging an object with a known mass to the link tip.

Figure. 2. a) Torque sensor calibration linkage, b) Admittance control test setup.

At horizontal position of the linkage, which can be seen in Figure 2a, an object with a mass of 2 kg was hanged to the tip of the link and torque value of 2.35 Nm was created on the system. Since it is a linear torque sensor with 0.5 V/Nm resolution, the voltage needs to be measured from the sensor should be approximately 1.18 V. At stable state, by turning the span knob on the amplifier module, measured value was adjusted to match the linearly calculated voltage value. After the arrangement, object and the link was removed from the system. At this point, as the expected value measured from the sensor should be 0 V, zero knob on the amplifier was adjusted until the zero value was read from the output of the sensor. At the end of the procedure calibration of the torque sensor was verified with different objects.

C. Manipulation with MATLAB Simulink

As mentioned before, in this work Maxon brushless DC motor with built in gearbox, encoder and Hall effect sensor was used as the actuator of the system. It was controlled by its specific hardware driver EPOS2 developed by the same brand. EPOS2 driver system allows users to communicate with personal computers via serial communication. Utilizing EPOS2 communication command libraries from Eugenio [10], the system was driven real time with Simulink, thus all the control algorithms were simply applied in Simulink environment. In order to include current and velocity feedback of the Maxon motor in the control loop on Simulink, small code modifications were also carried out inside the libraries.

D. System implementation

Prior to the system implementation of preliminary admittance control, hand rehabilitation system was modified. For the ease of experiments, torque sensor was disconnected from the input of the six bar mechanism and a simple link was connected to the torque sensor shaft as it can be seen in Figure 2b.

IV. CONTROL SYSTEM

A. Admittance control

Admittance control is one of the types of the indirect force control (Figure 3). Admittance control uses the relation between the velocity and the applied force. Similarly, in rotational direction, the velocity and the applied force is altered to a rotational velocity and the applied torque respectively. This control type focuses on the force tracking by specifying a force set point. It is suitable for non-back-drivable actuators. Mechanical admittance on the linear direction can be given by Equation (1), whereas Equation (2) is the mechanical admittance on the rotational direction.

$$Z_m = \frac{v}{F} \quad (1)$$

$$Z_m = \frac{w}{\tau} \quad (2)$$

where Z_m is the mechanical admittance, v is the linear velocity, F is the applied force, w is the angular velocity and τ is the applied torque. Since utilized rehabilitation system in this study works on the rotational direction Equation (2) was used.

In Cartesian space, the virtual admittance gain is considered as in the Equation (3).

$$m_v \dot{v}_{ref} + c_v v_{ref} = F \quad (3)$$

where m_v is the virtual mass, c_v is the virtual damping and v_{ref} is the reference velocity to be set by admittance gain. Since the system does not rely on a fixed point and it is free in space, there is no stiffness term in the Equation (3). By taking the equation into the Laplace domain, the admittance gain becomes;

$$A(s) = \frac{1}{m_v s + c_v} \quad (4)$$

Admittance gain creates the reference velocity to be fed into the inner loop, which is basically a PID velocity controller.

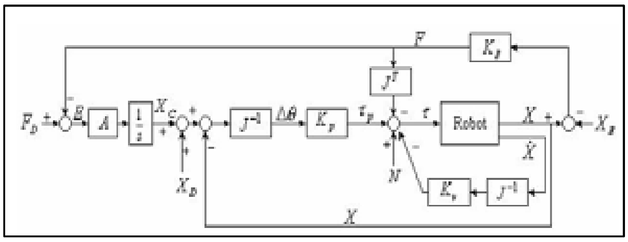

Figure 3. Admittance control block diagram [6]

B. Motion activation by user intention

Most of the robots in the literature being driven by admittance control are equipped with force/torque sensors at the end effector and they get the force or torque intention directly from the user. Motion is activated by the help of the signal coming from the attached end effector sensor. In such cases, when the user stops giving the force input, motion activation also stops. In the case utilized rehabilitation system, the torque sensor is affected by the user as well as the actuator itself. For this reason, the main aim for the proposed controller is to keep the torque sensor reading zero values. However, when the user intention is cut, the actuator keep transferring torque due to the system inertia. This makes the system act with overshoots and the settling time of the system becomes large. For this reason, this study proposes to use current feedback of the actuator to be used in calculating the pure torque generated by the actuator. Also, by using the sensor data

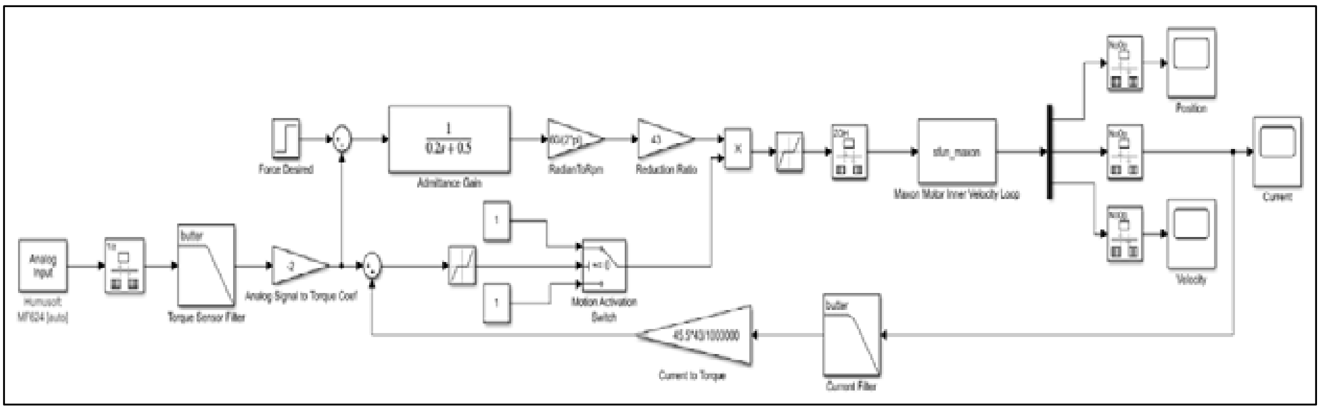

Figure 4. Simulink block diagram

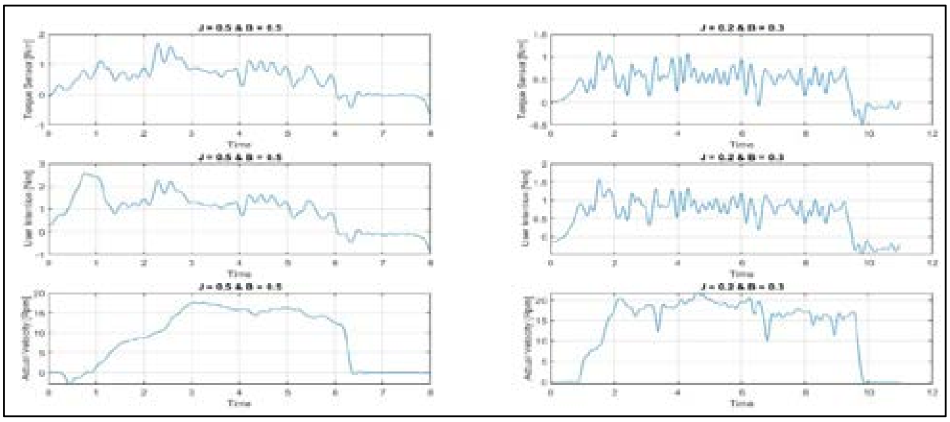

Figure 5. Admittance control performance with two different admittance gains

from the torque sensor, intention torque of the user can be calculated as,

$$\begin{aligned} \tau_{actuator} &= i_{actuator} k_t \\ \tau_{measured} &= \tau_{user} - \tau_{actuator} \\ \tau_{user} &= \tau_{measured} + \tau_{actuator} \end{aligned} \qquad (5)$$

where in Equation 5, τ represents the torque value of the subscript and k_t is the torque constant of the actuator taken from the datasheet. Utilizing all of this information, admittance control strategy for the rehabilitation system was constructed as seen in the block diagram (Figure 4).

V. Tests and Results

The inner loop of the system is controlled by the EPOS2 driver system. In velocity mode, the reference velocity is fed to the system by the admittance gain, which is the part of the outer loop of the control system.

The performance of the overall control system is tested with two different admittance gains. In the first experiment virtual inertial effect and virtual damping coefficients are chosen as 0.5 kgm^2/rad and 0.5 Nms/rad respectively. In the second experiment, the values are altered to 0.2 kgm^2/rad and 0.3 Nms/rad. As seen in Figure 5, while the intention torque of the user is almost the same in two cases, the resultant velocity is reached to a stable value faster in the 2^{nd} case as it has less inertial and damping effects. In both cases, when the intention of the user is cut, the system stops to move rapidly thanks to the new control algorithm applied to the system.

VI. Conclusion and Future Works

In this work, admittance control principles are discussed and applied to the existing hand rehabilitation robot. During the study, connection type of the torque sensor was the main challenge on the control system, since the sensor is affected by both the actuator and the user. During the utilization of classical admittance control approaches, when the user intention was cut, due to the inertial effects on the system, effect of the actuator was keeping on, which results in overshoots and greater settling times. In order to get rid of this problem, user intention torque was also calculated by using real time current value measured from the actuator. This information was used in the control algorithm to render the system stop immediately after the removal of motion intention. Throughout the study two different virtual admittance gain values are applied to the system and they were compared. The results were promising to perform the rehabilitation process as the next step by connecting six-bar mechanism to the system. It is also planned to implement virtual graphical environment for visual and auditory feedbacks to increase cognitive effects during the treatment.

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