# Active and Passive Control of an Exoskeleton with Cable Transmission for Hand Rehabilitation

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***Abstract*—This paper investigates the control algorithm of an exoskeleton for hand rehabilitation, which accomplishes both active and passive control mode. A double closed loop control structure is developed, which consists of position control loop and compensation control loop. The position controller is based on impedance control. The compensation controller is used for compensating the position error caused by deflection of the cable and sheath in the mechanical transmission. To realize the compensation, the spring model is used to represent the elasticity of the cable and sheath. With the proposed method, the maximum joint position error is about 1.5 degree, which satisfies the requirement in hand rehabilitation application. The experimental result demonstrates the validity of the propose method.**

***Keywords- rehabilitative training; active control mode; passive control modes；compensation controller***

## I. INTRODUCTION

As we know, the normal motor capability of hand is crucial and important for human-being's daily life. Hands, however, are apt to be injured in accident. And the rehabilitation is essential for the patients to recover after hand operation. Additionally, diseases, stoke for instance, can also result in the loss of hand function. In order to regain the motor capability, the hand rehabilitation is a fundamental therapeutic approach. The traditional rehabilitation approach is costly for patients and laborious for therapists.

Recent research showed that hand rehabilitative training using mechatronic devices and virtual reality is possible and effective [1] and is attracting more research interests [2-8]. Dependent on different design and different application, some control algorithms are investigated [6-11].

Despite of the researches, there are still some problems to be investigated. The rehabilitation usually includes four modes, i.e. passive, active, assisted and resisted rehabilitation. So far, there is no solution which has covered all of the four control modes.

Aimed at the hand rehabilitation, our research group developed a wearable exoskeleton for index finger rehabilitation [12]. In this paper, the control strategy of this exoskeleton is investigated to provide both active and passive control modes. A compensation control method is presented to reduce the position error due to deflection of the cable and sheath in the mechanical transmission. To do this, a double closed loop structure is developed, which is used for realizing the position control and error compensation, respectively. With the proposed method, the maximum joint position error is less than 1.5 degree, which satisfies the requirement in hand rehabilitation application.

The remainder of the paper is organized as follows. Section 2 introduces the mechanical structure of the exoskeleton. Section 3 describes the control algorithm of active and passive control modes. Section 4 depicts experiment and the results. Section 5 gives conclusion and future work.

## II. MECHANICAL STRUCTURE

The device for index finger rehabilitation has 4 degrees of freedom and consists of two parts: actuator module and the exoskeleton module. The exoskeleton is actuated by the DC-motors with encoder and worn on the dorsal side of the hand. For simplicity we take the PIP joint for example, as shown in Fig. 1. To reduce the weight that is imposed on the patient hand, the actuator is placed far away from the hand. Two cables in two sheaths, two ends of each of which are fixed on the actuator module and exoskeleton module, are used to transmit force and motion to the exoskeleton. A potentiometer is installed on the joint shaft of the exoskeleton to measure the rotational angle of the PIP joint.

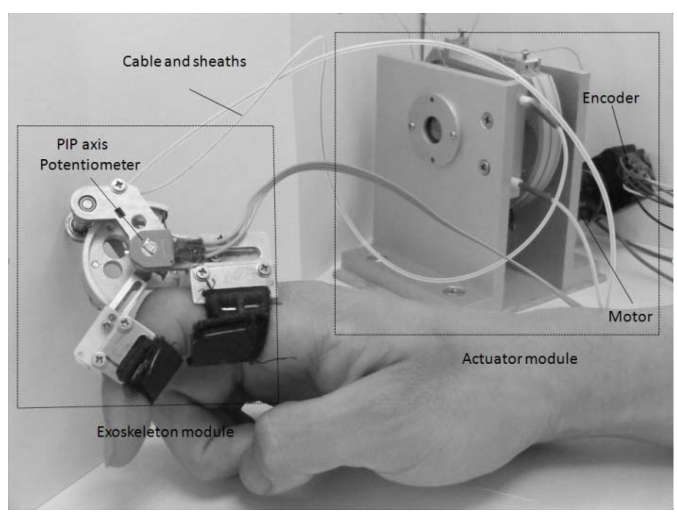


Figure 1. Prototype of the hand exoskeleton

## III. Control Algorithm

For the passive and the active rehabilitation mode, the controller is different. In general, a position controller is suitable for the passive mode to enable imposition of specific trajectories. A force controller is needed in the active control mode to provide feedback force to the patient. It is also used to reduce the impedance of the device when needed. To accomplish both active and passive control modes in a controller, a control algorithm is presented.

As aforementioned, the cable and sheaths are used in transmission. Due to their elastic deformation, the actual motor position may deviate from the desired position. We call the deviation the position error. The position error should be compensated in order to control the motion precisely.

To satisfy all of the requirements, the double closed loop control scheme is developed. The closed position control loop is used to achieve a desired motion. And the compensation control loop is in charge of compensation for position error. The block diagram of control structure is shown in Fig. 2. The detailed control algorithm is described in the following subsections.

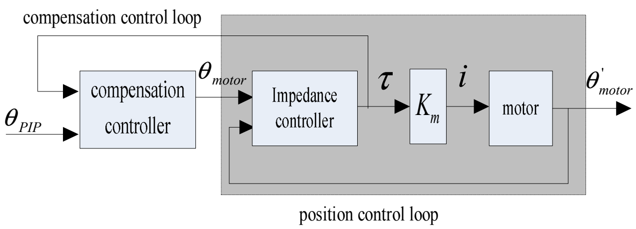


Figure 2. The block diagram of control

### A. Compensation for position error

Similar with the SEA control [10, 11], we model the cable and sheath as a spring. This principle is schematically illustrated in Fig. 3.

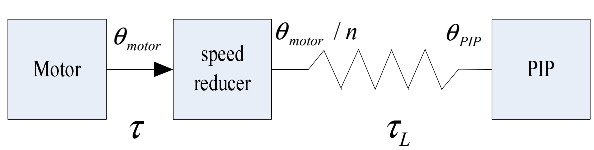


Figure 3. The compensation control mode

Therefore we can obtain the position error of the PIP joint.

$$\theta_{err} = \frac{\theta_{motor}}{n} - \theta_{PIP} \tag{1}$$

where $\theta_{err}$ is the position error caused by the spring elastic deformation, $\theta_{motor}$ is the position of motor, $n$ is the transmission ratio, and $\theta_{PIP}$ is the position of the PIP joint.

Assuming the motor output torque is $\tau$, and the spring produces the torque $\tau_L$, then we have

$$J_A \cdot \frac{d^2\theta_{motor}}{dt^2} / n = \tau - \tau_L \tag{2}$$

$$\tau_L = K_s \cdot \theta_{err} \tag{3}$$

where $J_A$ is the moment of inertia of the speed reducer about the output axis, and $K_s$ is the equivalent spring constant, which could be determined by experiment.

By substitution of (1) and (3) into (2), the relationship between $\theta_{PIP}$ and $\theta_{motor}$ could be calculated as follows.

$$\theta_{PIP} = \frac{J_A}{K_s \cdot n} \cdot \frac{d^2\theta_{motor}}{dt^2} - \frac{\tau}{K_s} + \frac{\theta_{motor}}{n} \tag{4}$$

### B. Active mode control

In the active motion mode, the human finger moves actively. The exoskeleton follows the motion of the finger and should be compliant with the finger's motion during the free motion of the finger.

Due to the friction between the cable and sheaths, as well as the transmission ratio, it is somewhat laborious when the patient moves the finger actively wearing the device. Therefore a force controller is appropriate. The impedance control is used here because it can directly control the interaction between the end-effector and environment.

In addition, because of the elastic deformation of cable, the movement of finger and exoskeleton is not synchronizing. We use the potentiometer to solve the problem.

Define

$$\Delta\theta_A = \theta'_{motor} - \theta_{motor} \tag{5}$$

where, $\theta'_{motor}$ is the instant actual motor angle read from the encoder, $\theta_{motor}$ is the equivalent target position of the motor after the compensating control, which could be calculated from (4). Here, $\theta_{PIP}$ is the instant PIP angle measured by the potentiometer. And $\Delta\theta_A$ is the position difference between $\theta'_{motor}$ and $\theta_{motor}$.

The motor output torque is defined as follows.

$$\tau = M \cdot \frac{d^2\Delta\theta_A}{dt^2} + B \cdot \frac{d\Delta\theta_A}{dt} + K \cdot \Delta\theta_A \tag{6}$$

where $M$, $B$ and $K$ represent the inertial properties, damping and stiffness coefficients, respectively. In the process of rehabilitative training, the exoskeleton moves at low speed constrained by the motor capability of the patient. So the item of inertial properties force could be neglected. In active control mode, the human finger moves actively. The control structure is used for overcoming mechanical resistance. To maintain the curve of $\tau$ continuous, it consists of two parts, operation and transition phase. Therefore, the equation be used for calculating output torque is as follows.

$$\tau=\begin{cases}+A+F(t) & (\Delta\theta_A>r)\\ A\cdot(K_A\cdot\Delta\theta_A+B_A\dfrac{d\Delta\theta_A}{dt})+F(t) & (-r\le\Delta\theta_A\le r)\\ -A+F(t) & (\Delta\theta_A<-r)\end{cases} \quad (7)$$

where, $A$ represents the minimum torque driving the hand exoskeletons. F(t) represents the interaction force. Constant r is the positional accuracy parameter to maintain the curve of $\tau$ continuous. $K_A$ and $B_A$ could be calculated from comparing (6) and (7), whose value are the ratio of $K$ over $A$ and $B$ over $A$, respectively.

The block diagram of active control mode is shown in Fig. 4.

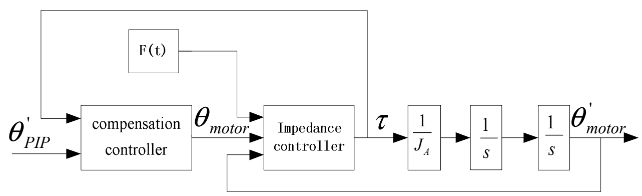


Figure 4. The block diagram of active control mode

## C. Passive mode control

In the passive motion mode, the human finger is driven by the hand exoskeleton. Thus, the position control is carried out.

To be integrated with the active control mode in a same controller, the position control used here is also based on impedance control [13]. The difference is that the PIP joint angle is predefined. The motor output torque is determined by comparing the predefined value with actual value of PIP joint angle. The motor keeps to output torque until the actual angle reaches the target.

Based on the theory of impedance control, comparing the objective position with practical position, the relationship is shown:

$$\Delta\theta_P=\theta'_{motor}-\theta_{motor} \quad (8)$$

Similar to (5), $\theta'_{motor}$ is the actual angle of motor read from the motor encoder, $\theta_{motor}$ is the equivalent target position of the motor after the compensating control, which could be calculated by (4). $\Delta\theta_P$ is the position difference between $\theta'_{motor}$ and $\theta_{motor}$.

The impedance control function can be rewritten as follows.

$$\tau=\begin{cases}+A & (\Delta\theta_P>r)\\ A\cdot(K_P\cdot\Delta\theta_P+B_P\cdot\dfrac{d\Delta\theta_P}{dt}) & (-r\le\Delta\theta_P\le r)\\ -A & (\Delta\theta_P<-r)\end{cases} \quad (9)$$

The block diagram of active control mode is shown in Fig. 5.

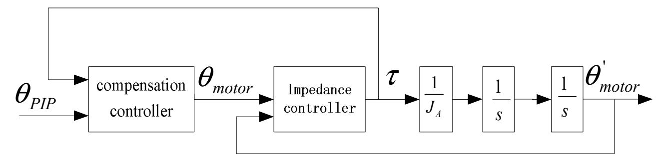


Figure 5. The block diagram of passive control mode

# IV. EXPERIMENTAL RESULT

The experiment is done using QUANSER system (Q8 Control Board, WinCon, Quanser Consulting Inc, Canada). The QUANSER could carry out the force control of real time.

## A. Experiment on passive control mode

In this mode, the patient is in the early phase of rehabilitation, whose motor capability is limited. Therefore fast undesired movements must be averted. The target is to let the exoskeleton follow a predefined trajectory, here sine wave is chosen. Its amplitude is $\pi/2$ radian, and the angular velocity is 1rad/s. The spring constant $K_s$ is measured in our lab, and the other system parameters are determined by adjustment. $K_s$ =161.82Nmm/rad, $K$=2.5, $B$=0.0007, $A$=6.06Nmm. The experimental results are shown in figure 6 and figure 7.

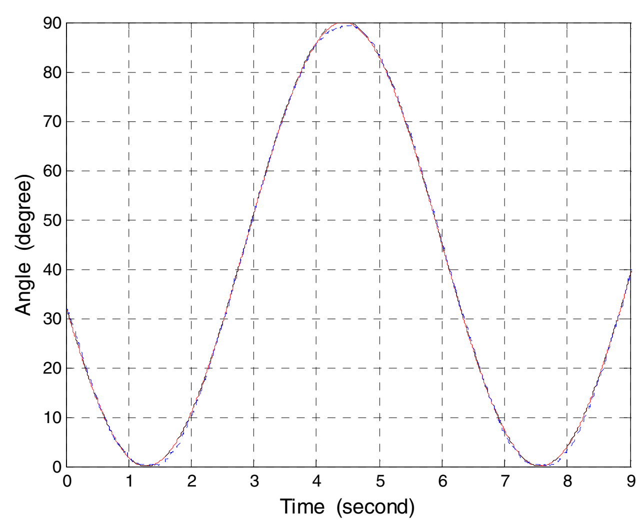


Figure 6. PIP joint trajectories, solid line—expected trajectory of PIP joint,dash dot line —calculated trajectory from motor encoder, dashed line—actual trajectory from potentiometer

The Fig. 6 shows that the actual trajectory follows the expected one well.

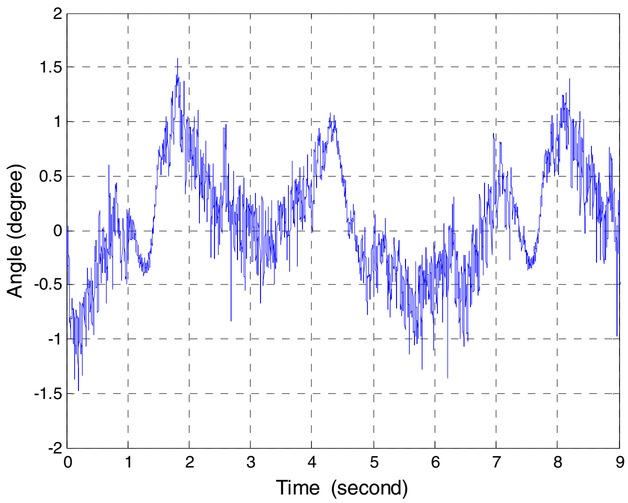


Figure 7. The position error between the expected and the actual trajectory

The position error between the expected and the actual trajectory is shown in Fig. 7. The maximum position error is less than 1.5 degree. The precision requirement of hand rehabilitative training is not high. Thus, the result could meet the need of the hand rehabilitative training.

### *B. Experiment on active control mode*

In this experiment, the target is to let the subject move the finger freely wearing the hand exoskeleton and to feel unhindered. Therefore the interaction force $F$(t) is set to be zero.

To evaluate the proposed control algorithm the experiments are carried out without and with active mode control. The parameters are $K_s$ =161.82Nmm/rad, $K$=2.5, $B$=0.00072, $A$=6.06Nmm. The results are shown in Fig. 8 and Fig. 9.

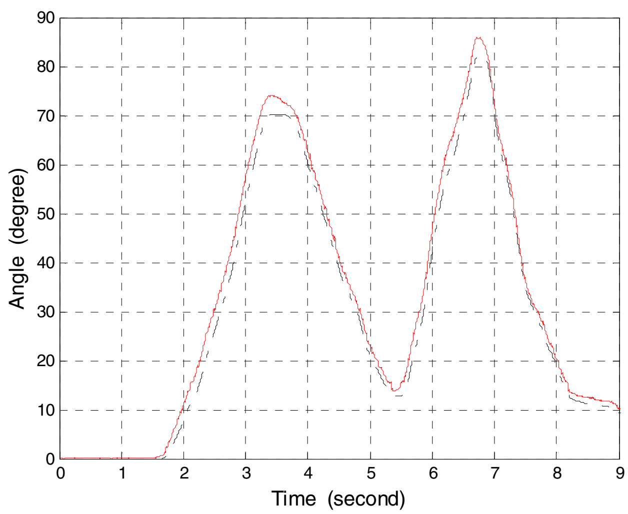


Figure 8. Without the active control, solid line— expected value, dash line—actual value

Fig. 8 shows that the error between the expected position (solid line) and the actual position (dash line) is obvious. The motor doesn't move synchronally with the exoskeleton. The subject felt somewhat hard to move the finger.

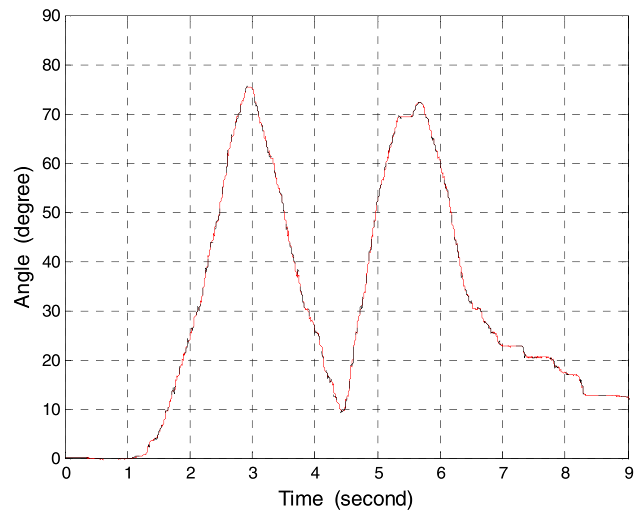


Figure 9. With the active control

Fig. 9 shows that the motor moves synchronally well with the exoskeleton. And the subject felt easily to move the finger in the experiment.

## V. CONCLUSION AND FUTURE WORK

Focus on the special requirements of the hand rehabilitation, a multi-layer control structure is proposed. Different algorithms for active control mode and passive control mode are realized in a controller. Besides, the deflection of cable and sheath is modeled as a spring, and the position error caused by the deformation is compensated. The experimental results demonstrate the feasibility of the proposed control algorithm.

Next, we are going to further test the performance of the proposed control algorithm, such as the response characteristics. We will also expand the method to the other two rehabilitation modes, i.e. assisted and resisted mode.

## ACKNOWLEDGMENTS

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