A Resistance Compensation Control Algorithm for a Cable-Driven Hand Exoskeleton for Motor Function Rehabilitation

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Abstract. The resistance compensation, especially the friction compensation in the Bowden cable transmission is a difficult issue to be handled. Aimed to the resistance reduction requirement in the active rehabilitative motion, a resistance compensation control method is proposed. Based on the simplified transmission model, the resistance, including the cable friction as well as the mechanical moment of inertial, is formulated. To realize the compensation, force sensors are used to measure the force exerted by the human fingertip. With the proposed algorithm, the maximum finger-exerted force is reduced to less than one third of before. The experimental result demonstrates the validity of the proposed method.

Keywords: hand rehabilitation, active control mode, resistance compensation, cable/sheath transmission, hand exoskeleton

1 Introduction

As we know, the motor capability of hand is crucial and important for human-being's activity of daily life. Hands, however, as the most vulnerable limb compared with arms and legs are much easier to be injured in accident and by some diseases. The impaired motor function needs to be recovered through rehabilitation. 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 much research interests [2-7]. Some robot-assisted rehabilitation systems are developed and the corresponding control algorithms are investigated [8-11].

For some existing exoskeleton-type hand rehabilitation devices, the cable and sheath is utilized in mechanical systems to satisfy the need of remote and changeable distance transmission and reduce the weight exerted on the patient hand. Although there reaches a consensus that the friction between the cable and sheath accounts for the great part of the mechanical resistance, the problem to compensate the friction is still open and unresolved. In this paper we propose a force control algorithm which can provide resistance compensation for the active rehabilitative motion. With the proposed approach, the measured maximum force which hand output is reduced to about one third.

The remainder of the paper is organized as follows. Section 2 introduces the system architecture. Section 3 presents force control algorithm with resistance compensation. Section 4 depicts experiment and the results. Section 5 gives conclusion and future work.

2 System Description

The system architecture is shown as Fig.1, which consists of the hand exoskeleton integrated with angle and force sensors, the controller and the virtual environment.

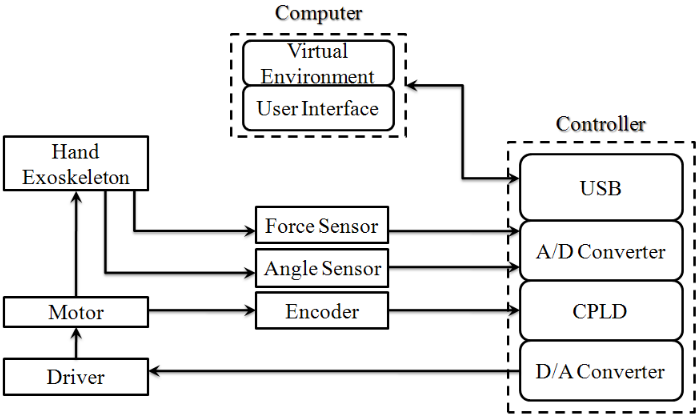


Fig.1. The System Architecture

The exoskeleton device for index finger rehabilitation has 4 degrees of freedom and consists of three parts: the actuation module, the cable transmission and the exoskeleton, as shown in Fig 2 [12].

The exoskeleton is worn on the dorsal side of the hand. It is actuated by four actuators and can implement the motion of flexion/extension for the DIP, PIP and MCP1 joints, and the motion of adduction/abduction for the MCP2 joint. To reduce the weight which is imposed on the patient hand, the actuator is placed in a distance from the hand. Corresponding to the human hand anatomical structure the exoskeleton is comprised of three parts which are attached to the phalanges – distal, middle and proximal phalanges, respectively. For each finger joint, two cables, each of which is housed in a sheath, are used to transmit force and motion from the actuator to the exoskeleton. A potentiometer is installed on the each joint shaft of the exoskeleton to measure the rotational angle of the finger joint. Honeywell_FSS force sensor is used to measure the fingertip force exerted by the human fingertips. Because the measure area (a small spherical surface) of the sensor is too small for soft fingertip to measure the reliable force, three force sensors (Honeywell_FSS shown in Fig. 3) are assembled together on the bottom of the distal module as shown in fig. 3(a) and are covered with a metal plate as shown in fig. 3(b) to ensure that the force exerted by the hand could be measured accurately. The forces on three contact points read from the force sensor are summed to obtain the resultant force which is exerted by the finger [13].

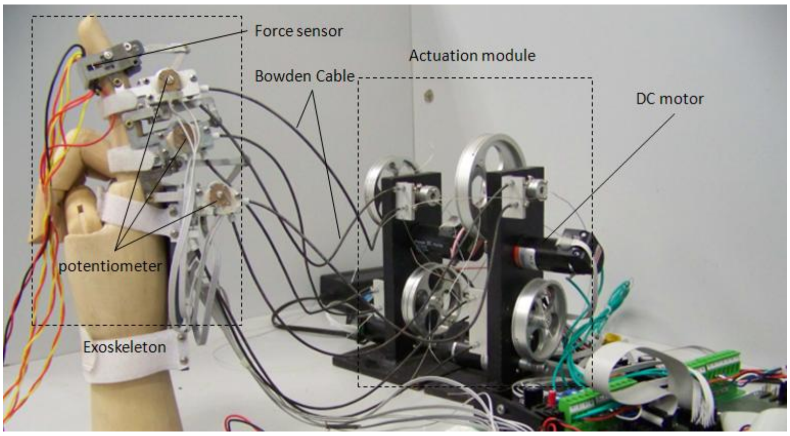
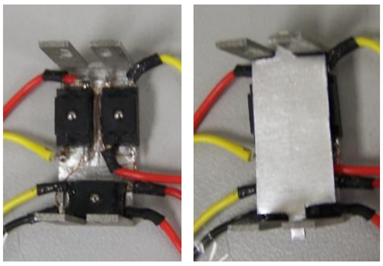


Fig. 2. Prototype of the hand exoskeleton



(a) (b)

Fig.3. (a) the Layout of Three force sensors (b) Covered by a Metal Plate

The real-time controller is developed by our research group. It could sample the angle data and the force data in real time. The controller links to the host computer by the USB, and the sampling frequency is 100HZ.

The motors are driven by the driver (EM-28 DC-MOTOR CONTROL UNIT). The driver is connected to the controller through analog output channels. And it runs under the torque control mode.

The host computer runs the virtual environment and gives the force feedback to the patient. The operation interface allows the therapist to set the training parameters for the rehabilitation therapy, for example, range of joint angle, training time, training speed and so on. In the graphic interface, the virtual hand, which is controlled by the human hand, is used to accomplish the different rehabilitation tasks.

3 Control Algorithm

During the active rehabilitation training, the virtual hand works in two different states. When it is in contact with the virtual object, we call it is in constraint space and the virtual contact force is feedback to the human finger. Otherwise it is called in free space and the human finger is supposed to move without resistance. Therefore the mechanical resistance is demanded to be compensated.

To satisfy the requirements in both spaces, the impedance control is used [14]. The block diagram of control structure is shown in Fig. 4, where, *N* is the contact forces exerted by human finger. The control method in constraint space will not be described in detail and we only focus on the resistance compensation control algorithm in the free space in the following part.

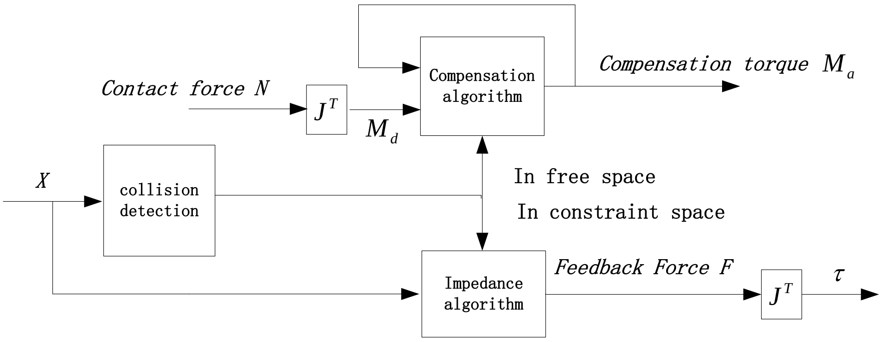


Fig.4. the block diagram of control structure

As aforementioned, in free space the exoskeleton is supposed to follow the motion of the finger and be compliant with the finger's motion. However, the friction between the cable and sheath, as well as the moment of inertial of the system, cause great resistance to the finger flexion/extension. Thus we propose a method to compensate the resistance of the finger flexion.

Taking one joint for example, the actuator module, the cable/sheath transmission and the exoskeleton module are simplified as follows (Fig 5).

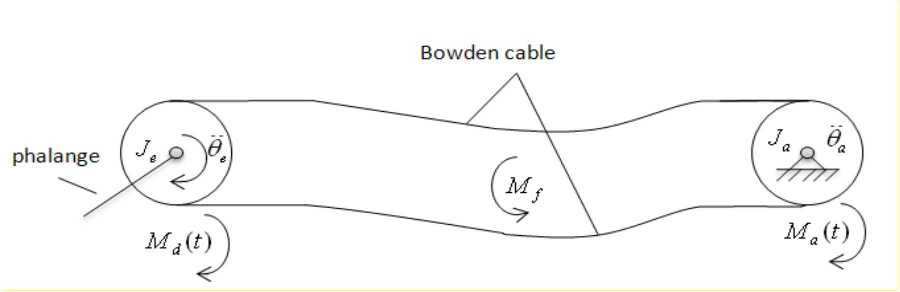


Fig.5. The simplified model for one finger joint

According to the equilibrium equation of the moment at a certain time t, we have:

$$M_d(t)+M_a(t)=J_e*\ddot{\theta}_e(t)+J_a*\ddot{\theta}_a(t)+M_f(t) \tag{1}$$

where $M_d(t)$ is the driving torque which is produced by the fingertip-exerted force;

$M_a(t)$ is the output torque of the actuator module which is used to compensate the system resistance;

$M_f(t)$ is the resistance torque due to the friction between the cables and the sheaths;

J_e and J_a are the moment of inertia of the exoskeleton module and of the actuator module, respectively;

$\ddot{\theta}_e(t)$ and $\ddot{\theta}_a(t)$ are the angular acceleration of the exoskeleton module and the actuator module, respectively.

If we want to compensate the mechanical transmission caused by the friction and the moment of inertia, the actuator module output $M_a(t)$ should be:

$$M_a(t)=J_e*\ddot{\theta}_e(t)+J_a*\ddot{\theta}_a(t)+M_f(t) \tag{2}$$

Because $M_f(t)$ at time t is unknown, so we estimate $M_a(t)$ with the value at time t-1. Considering that the time interval is small so the estimation is reasonable. So we have：

$$M_a(t)=M_d(t-1)+M_a(t-1) \tag{3}$$

The active rehabilitative motion requires that it is the human hand that drives the exoskeleton. However, if the estimated $M_a(t)$ is greater than the actual resistance, the exoskeleton is then driven by the actuator, and the active rehabilitative motion is changed to passive rehabilitative motion which is not desired. On the other hand, the human fingertip will not contact with the sensors which means the contact force can not be measured. Therefore we modify equation (3) as follows.

$$M_a(t)=\xi*[M_d(t-1)+M_a(t-1)] \tag{4}$$

where the coefficient ξ is set to be not more than 1.0 and its value could determined by experiment. The driving torque $M_d(t-1)$ could be calculated from the jacobian matrix and the contact force measured from the force sensors.

4 Experiments and Result

In the experiment, the human hand wears the exoskeleton and index finger makes the motion of flexion and extension continuously for three times in two conditions: with and without resistance compensation. In two conditions, the relative position of the exoskeleton module and the actuator module is approximately kept unchanged. The contact forces exerted by human finger in the two conditions are measured, respectively. The result is shown in Fig.6, where the coefficient ξ is set to be 0.9 and the accuracy of the force sensor is 10mN.

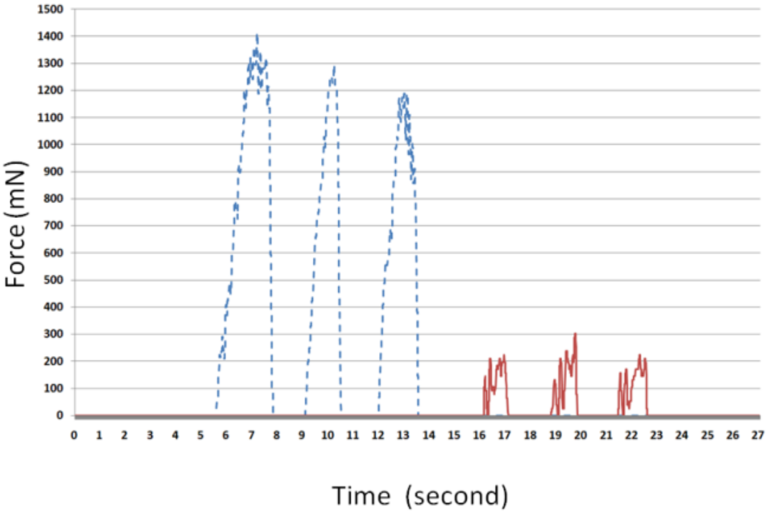


Fig.6. The measure forces exerted by the human fingertip. Blue dashed line—without the resistance compensation, red solid line—with the resistance compensation

Fig 6 shows that with the compensation control algorithm, the maximum output force of the human fingertip is less than one third of the maximum force without. And the subject felt much easier with the compensation control. The experimental result demonstrates the validity of the proposed method.

5 Conclusion

Focused on the special requirements of the active rehabilitative motion for hand motor capability, a control structure integrated with resistance compensation is proposed. With the proposed controller the undesired resistance is greatly reduced. The advantage of the algorithm is that the complicated resistance model is avoided and the method is very simple.

Next, we are going to further test the performance of the proposed control algorithm, such as the force feedback in the constraint space. We will also expand the method to compensate the resistance during finger extension and the other two rehabilitation modes, i.e. assisted and resisted mode.

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