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# Servo-assisted Control of a 7-DOF Exoskeleton for Upper Limb Rehabilitation

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**Abstract.** This paper reviews the research on upper limb exoskeleton for hemiplegia rehabilitation. Under the condition of rehabilitation training for mild patients in the workspace of 7-DOF exoskeleton with uncertain trajectory, a control algorithm used for motion detection is carried. In this algorithm, the patient's operation can be detected by real-time data collected by F/T (Force/Torque) sensors and encoders, so that quantitative assistance will be supplied by exoskeleton according to the patient's motion intention. Finally, the joint simulation of ADAMS and MATLAB proves the accuracy of trajectory tracking and the feasibility of the control strategy is verified by the experiment on 3-DOF translational manipulator platform.

## 1. Introduction

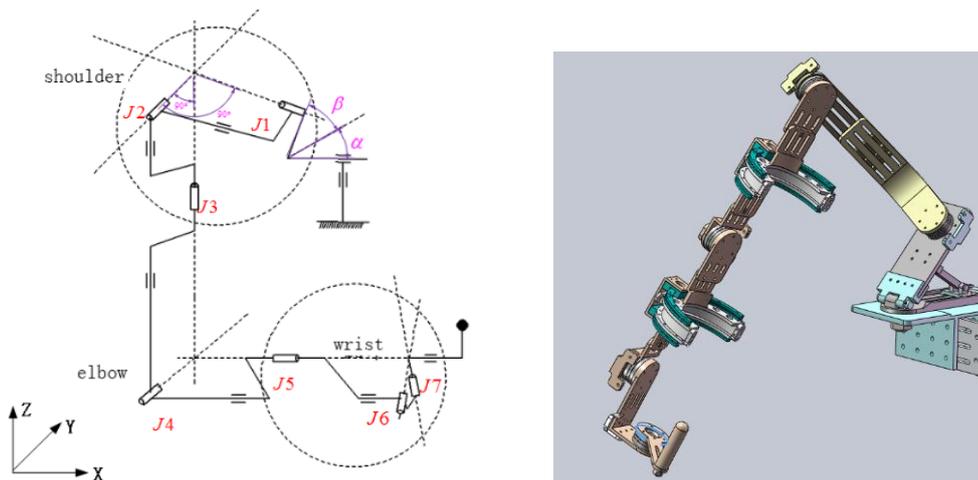
The rehabilitation effect of the traditional method is limited by the ability level and physical strength of the therapist [1, 2]. There is no continuous and intuitive data to evaluate the relationship between training intensity and rehabilitation effect. Using Rehabilitation Exoskeleton Robot for hemiplegia rehabilitation training can solve the problems existing in traditional rehabilitation training methods [3, 4]. The most appropriate rehabilitation training program can be obtained by optimizing parameters according to different degrees of patients [5]. Exoskeleton robots can make different training intensity for different patients [6]. It can also record the speed and force of affected limbs during training. Above all, it will lighten the burden of clinical medical personnel and reduce the cost of rehabilitation training for patients. Rehabilitation exoskeleton robots make remote treatment and centralized therapy have better application prospects [7]. Rehabilitation exoskeleton robots are more and more used in real life, therefore the research on control strategy of upper limb exoskeleton manipulator has broad application prospects and scientific research value [8, 9].

Aiming at the complex control phenomenon in multi-joint manipulator, this paper studies the servo-assisted control strategy of upper limb exoskeleton manipulator to help patients with mild illness who can produce the intention of autonomous motion but do not have enough power to generate the required motion independently. Through the data of F/T sensors and encoders, the motion characteristics of patients can be accurately extracted, and then the human motion intentions can be recognized. With fast response and high precision compliance control system, the patients will be able to carry out effective rehabilitation training [10,11].

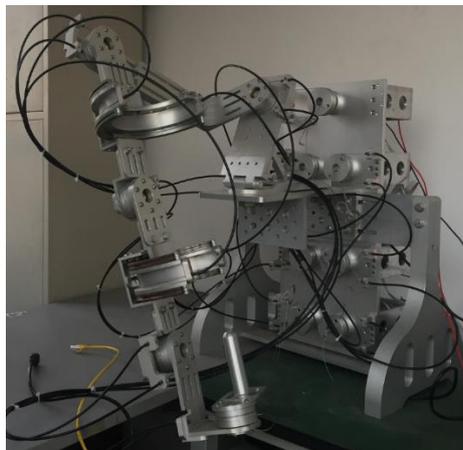
The laboratory has independently developed a 7-DOF exoskeleton manipulator. The upper limb exoskeleton manipulator consists of seven active degrees of freedom, which simulates human upper



limb movement [12]. The degrees of freedom of the mechanism are as follows: the adduction/abduction joint of shoulder (J1), the flexion/extension joint of shoulder (J2), the external rotation / internal rotation joint of shoulder (J3), the flexion/extension joint of elbow (J4), the external rotation / internal rotation joint of wrist (J5), the adduction/abduction joint of wrist (J6), and the flexion/extension joint of wrist (J7), as is shown in Fig. 1,2 and 3.



**Fig. 1** 7-DOF exoskeleton mechanism sketch **Fig. 2** 7-DOF exoskeleton mechanism model

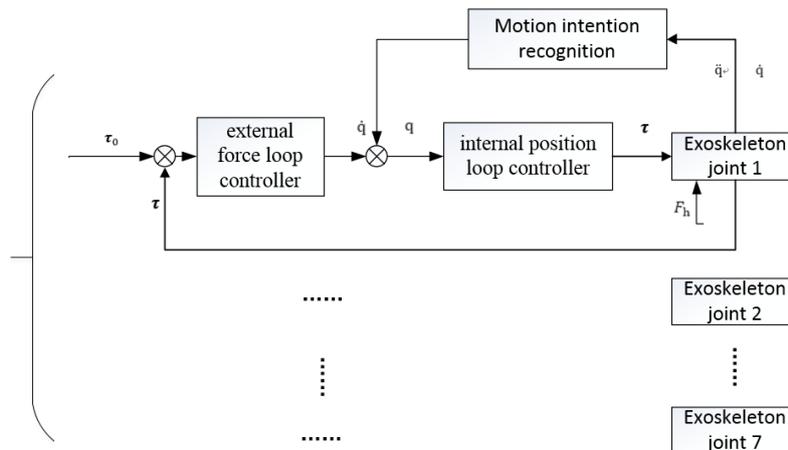


**Fig. 3** 7-DOF Exoskeleton of Upper Limb

## 2. Servo-assisted Control Strategy

### 2.1. Realization of Servo-assisted Control

The core content of the control strategy is to get patients' intention through the real-time data of each joint through the F/T sensors. When the operator wears the exoskeleton manipulator, the motion intention of the human body can be extracted by processing the feedback data of the encoder and the F/T sensors. According to the motion intention, the driving motor will be set up to provide assistance that meets the motion intention. Thus, the servo-assisted help of 7-DOF exoskeleton on human motion intention can be achieved. Control block diagram is shown in Fig. 4



**Fig. 4** Control block diagram

The external force loop controller makes the torque obtained by the F/T sensor meet the reference torque of the patient's need at all times, then obtains the reference speed of the motor. While the internal position loop controller ensures that the exoskeleton manipulator is in the working space of the designed mechanical structure through the position information of the joint obtained by the encoder. In order to meet the security requirements,  $F_h$  is an uncertain disturbance of human hand to external skeletal manipulator.

**Table 1** The range of each joint of exoskeleton

|          |                                       |                            |
|----------|---------------------------------------|----------------------------|
| Shoulder | flexion/extension                     | $-50^\circ \sim 180^\circ$ |
|          | adduction/abduction                   | $-80^\circ \sim 180^\circ$ |
|          | external rotation / internal rotation | $-90^\circ \sim 90^\circ$  |
| Elbow    | flexion/extension                     | $0^\circ \sim 140^\circ$   |
| Wrist    | external rotation / internal rotation | $-80^\circ \sim 85^\circ$  |
|          | flexion/extension                     | $-90^\circ \sim 80^\circ$  |
|          | adduction/abduction                   | $-40^\circ \sim 15^\circ$  |

Articular angle  $\theta_i (i=1\sim7)$  of each joint satisfies the working space of the designed mechanical structure, as is shown in Table 1.

$$\theta_{i_{min}} \leq \theta_i \leq \theta_{i_{max}} (i = 1\sim7). \quad (1)$$

Real-time torque of 7 Joints Obtained by F/T Sensor is as follows,

$$\boldsymbol{\tau} = (\tau_1, \tau_2, \tau_3, \tau_4, \tau_5, \tau_6, \tau_7) \quad (2)$$

Servo-assisted torque is set as follows,

$$\boldsymbol{\tau}_0 = (\tau_{01}, \tau_{02}, \tau_{03}, \tau_{04}, \tau_{05}, \tau_{06}, \tau_{07}) \quad (3)$$

The difference between  $\boldsymbol{\tau}$  and  $\boldsymbol{\tau}_0$  is as follows,

$$\Delta \boldsymbol{\tau} = \boldsymbol{\tau}_0 - \boldsymbol{\tau} \quad (4)$$

Set  $\Delta\tau$  as the input of the PID controller. Appropriate control quantity can be given by the PID controller. The motors are driven and controlled by the Pmac motion control card and driver. In the control system, the PID controller can solve the change of speed  $\Delta\dot{\theta}$ . The variation of exoskeleton angular velocity is sent to the Pmac motion control card in a specific format. After analyzing the control commands, the Pmac card will send an analog signal to the driver. When the motor driver receives the signal, it can control the speed of each joint of upper limb exoskeleton manipulator. The PID control algorithm is as follows:

$$\Delta\dot{\theta} = K_p \cdot \Delta\tau + K_I \cdot \int_0^t \Delta\tau dt + K_D \cdot \frac{d\Delta\tau}{dt} \quad (5)$$

### 2.2. Real-time Motion Intention Recognition

Appropriate sampling frequency is set and the position information of each joint motor is obtained by the encoder. The angular velocity and angular acceleration of each motor are calculated as (6) and (7):

$$\omega = \frac{d\theta}{dt} \quad (6)$$

$$\alpha = \frac{d\omega}{dt} \quad (7)$$

Through the positive and negative acceleration of each joint at present, the positive and negative motive intentions of each joint of the patient are extracted. According to the motive intentions of each joint, the magnitude of the servo-assisted torque given by each joint of the exoskeleton is set as (8):

$$\tau_0 = \tau' \operatorname{sgn} \alpha \quad (8)$$

$\tau_0$  represents the servo-assisted torque given to the patient, and  $\tau'$  represents the value of the help set.

### 3. Position simulation analysis

In view of the above control strategy, the joint simulation of MATLAB and Adams is carried out. The exoskeleton has 7 joint input variables and 14 output variables. 7 joint input variables torque1~torque7 are caused by the operator's motion, they are all realized by 7 virtual motion signals. Each motion signal is set to 3.14\*sin signal or 3.14\*step signal to simulate the operator's actual motion. In each joint of ADAMS model, 7 angle sensors angle 1~angle 7 and 7 angular velocity sensors velocity 1~velocity 7 are added to detect the angular values and angular velocities of each joint. The angular values and angular velocities are set as 14 output variables of exoskeleton to simulate the joint angles detected by encoders in real situations. The specific state variables are shown in Fig. 5.

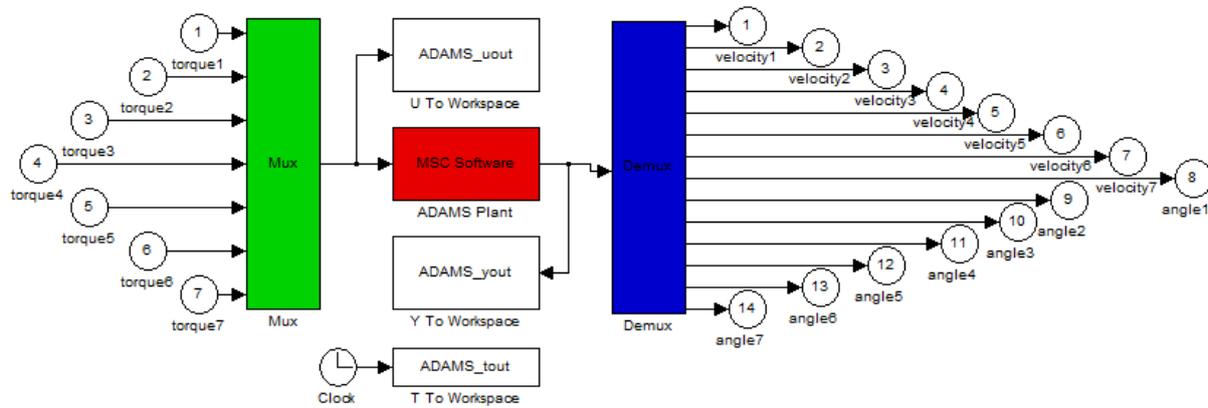


Fig. 5 State variables of exoskeleton

Open the Controls module loaded by Adams, select the joint output variables and input variables set above, use MATLAB as the joint simulation software, then use Simulink to build the simulation control system, as shown in Fig 6.

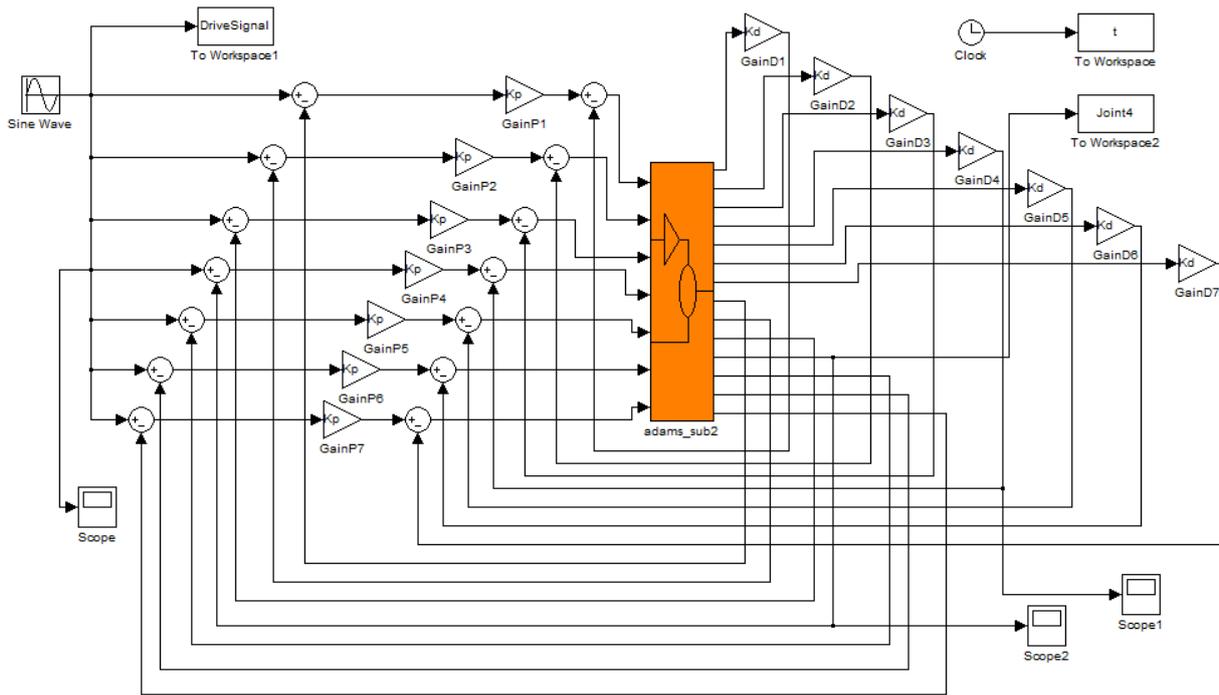
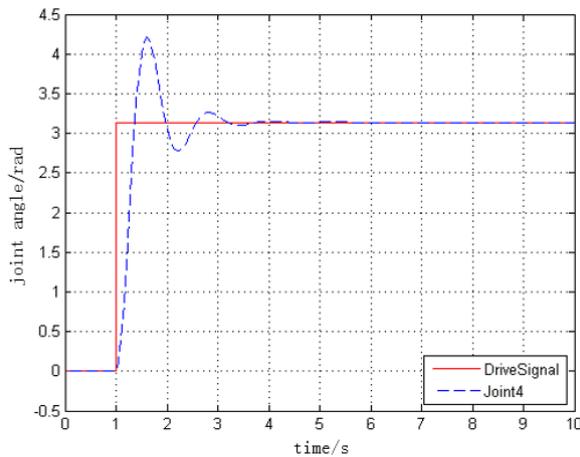
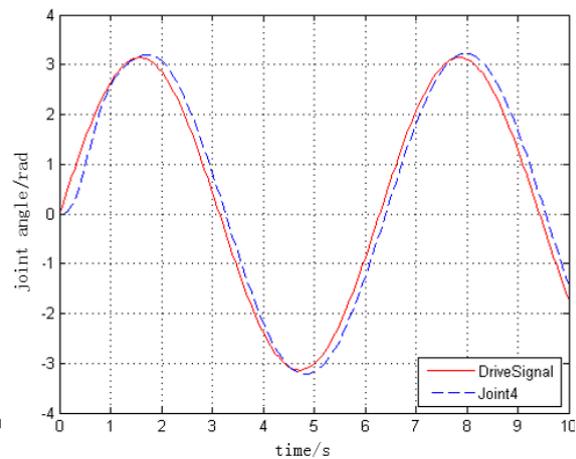


Fig. 6 Exoskeleton joint simulation control block diagram

In Matlab, the input variables are defined as step signals and sinusoidal signals. Since the seven joints of the exoskeleton are controlled separately and the control algorithm is consistent, the motion curve of the elbow joint of the exoskeleton is given only in this paper. Fig. 7 is the step response charts of the exoskeleton elbow joint, and Figure 8 is the system tracking charts of the exoskeleton elbow joint. The solid line is the driving signal introduced by the operator, and the dashed line is the actual motion of the exoskeleton elbow joint. In the simulation, the parameters of PD are adjusted to 4.15 and 3.28, respectively.



**Fig. 7** Step response characteristics of exoskeleton

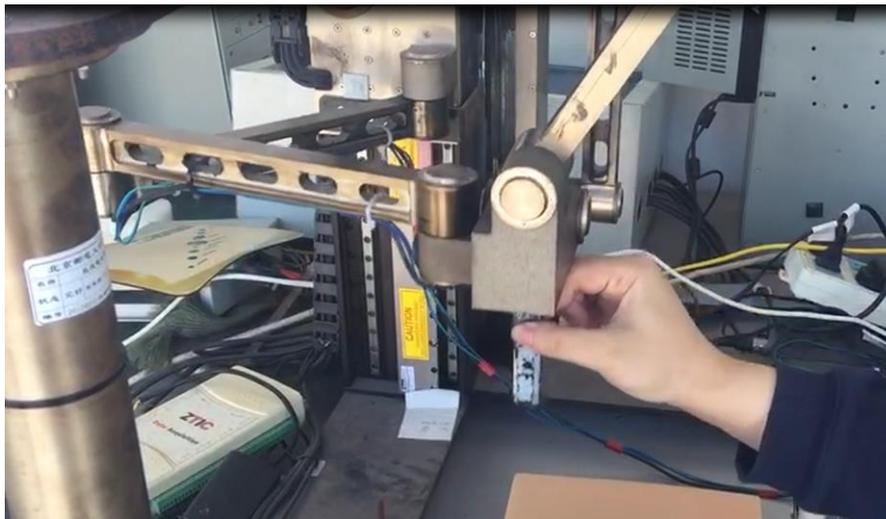


**Fig. 8** Sinusoidal response tracking of exoskeleton

According to Fig. 7, under the action of step signal, elbow joint can move from the initial position in a very short time, and immediately stabilize at the target position. This shows that the control system shown in Fig. 6 can achieve accurate and fast control of exoskeleton joint position. In Fig. 8, the operator's driving signal is set as a sinusoidal signal, which is used to simulate the actual movement of human upper limbs and detect the change of the elbow angle of exoskeleton by sensors. According to Fig. 8, the exoskeleton elbow joint can accurately track the sinusoidal signal given by the control system. The tracking condition is good and time delay is relatively small.

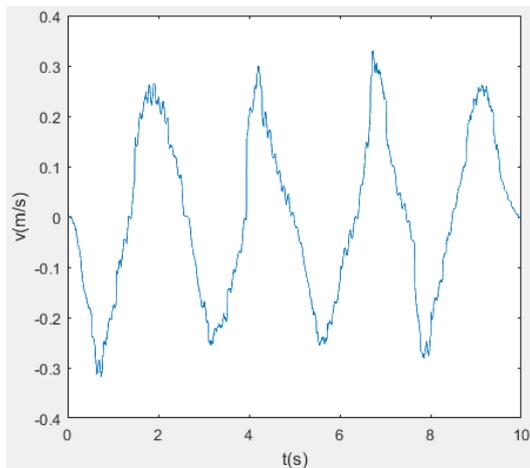
#### 4. Experimental verification of servo-assisted control strategy

The control strategy is experimented in the x-axis direction of the 3-DOF translational manipulator. Because the 7-DOF exoskeleton manipulator controls each joint independently under the servo-assisted control strategy, the positive and negative forces of the x-axis of the 3-DOF translational manipulator can represent the positive and negative torques of a single joint.

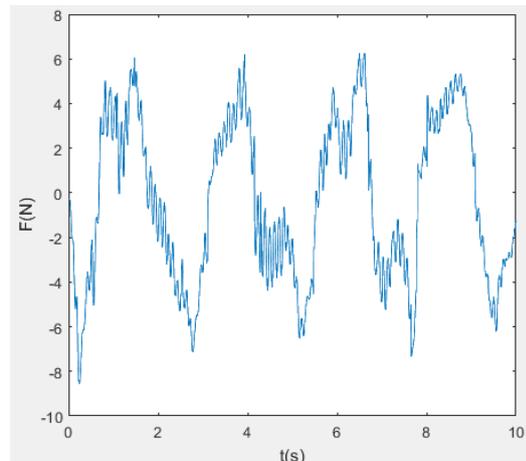


**Fig. 9** 3-DOF translational manipulator

The speed, acceleration and force values of the x-axis are obtained by the encoder and the F/T sensor respectively. The data curves are drawn by MATLAB, as shown in Fig. 10 and 11.



**Fig. 10** Velocity



**Fig. 11** Value of F/T sensor

It can be seen from Fig. 10 and 11 that the x-axis direction of the 3-DOF translational manipulator can judge the operator's motion intention in real time according to the real-time velocity and acceleration information, and exert the assistance in the direction of motion intention.

## 5. Conclusion

For patients with mild symptoms, this paper can identify the real-time intention of human arm motion only by the position information of the encoder, so that therapist can use the servo-assisted control strategy to set the servo-assisted torque, so as to realize the servo-assisted movement of exoskeleton to help patients accomplish rehabilitation trainings.

The control strategy of the 7-DOF upper limb exoskeleton manipulator is simulated and analyzed to verify the precise position tracking of each joint in the following motion. The experiment using the x-axis direction of the 3-DOF translational manipulator is carried out to verify the servo-assisted control strategy for exoskeleton single joint. The experimental results prove that the servo-assisted control strategy can only depend on the position information of the encoder to identify motion intention in real time and achieves the effect of servo assist. The control strategy in this paper will make the manipulator tremble to a certain extent, which can be solved by adjusting the sampling frequency and limiting the jump of velocity value.

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