

Design of a Master-slave Rehabilitation System using Self-tuning Fuzzy PI Controller

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Abstract - Many robotic devices have been developed for stroke patients to recover their upper limb motor function. Among them, master-slave type rehabilitation systems provide surveillance of the therapist to the patient who is performing home-rehabilitation. In this study, we proposed a wearable and light exoskeleton device for upper limb rehabilitation and designed a master-slave rehabilitation system using the exoskeleton device as slave device and a haptic device (Phantom Premium) as master device. To convey therapist's experience to patients using this system, the slave device is driven to track the motion of the master device manipulated by the therapist. In order to improve the tracking efficacy of traditional PI control, a self-tuning fuzzy PI control was proposed. Results of simulation indicated the proposed control method is more effective than the traditional PI control, particularly in tracking accuracy and response speed.

Index Terms – Master-Slave system, Self-Tuning Fuzzy PI control, Matlab/Simulink

I. INTRODUCTION

The number of persons over 65 years will increase by 73 percent till 2050 and by 207 percent worldwide in the industrialized countries according to the World Health Organization[1]. This age group inclineds to cerebrovascular accident (CVA), also called as stroke. Several rehabilitation robotic systems have been developed to assist neurological patients for motor function recovery. One of the earliest typical robot for upper limb rehabilitation is MIT-MANUS. It allows two degree of freedom for upper limb movement, including shoulder, elbow and wrist movement. It can guide or perturb the patient's upper limb movement under pre-defined task-oriented task[2]. GENTLE/s was a machine mediated therapy for neuro-rehabilitation. GENTLE/s used haptic and virtual reality (VR) technologies to deliver therapy[3]. Guo and song developed a novel rehabilitation training and assessment system for upper extremity. A haptic device and an inertia sensor constitute this system. As the system is compact, this system is adaptable for home-rehabilitation[4]. These devices belong to end-effector category. End-effector based devices are simpler to adjust to accommodate different patients. However, they can not perform human arm rehabilitation in joint respectively. Another kind of rehabilitation device is exoskeleton devices. They can solve

this problem. The ARMin robot can support the entire arm for rehabilitation. A patient-cooperative control strategy was developed to assist patient doing activities of daily living (ADL) training tasks[5]. An active upper limb rehabilitation was realized using an exoskeleton device and an inertia sensor in real-time by Guo and Song[6]. Successful rehabilitation depends on a technical rehabilitation team and the cooperation between patients and their families. Inpatient poststroke hospital stays have been shortened by two-thirds in the last decade[7]. Tele-rehabilitation system can alleviate this problem. At present, there are generally two kinds of tele-rehabilitation robotic systems. They are the unilateral training system and bilateral training system. In the setup of unilateral system, patients receive force feedback from a robot while they are viewing the graphic task on display with therapist's surveillance. In bilateral training, patient and therapist can interact with each other over the Internet with a shared virtual environment (SVE). Obviously, bilateral training has more benefit on experience deliver from the therapists to patients.

A master-slave rehabilitation system was proposed in this study which belongs to bilateral category. This system includes a haptic device in master side and an upper limb exoskeleton rehabilitation device (ULERD) in slave side. This system can alleviate the pressure of inpatient poststroke hospital stay period. Patients can receive experiences and surveillances through remote surveillance from therapists using this system. Another research introduced a master-slave robot system with haptic feedback. The therapist adjusts the rehabilitation based on the EMG signals of the patient and force feedback via Internet[8]. Different from it, the system proposed in our study (shows in Fig1) has an exoskeleton rehabilitation device in slave side.

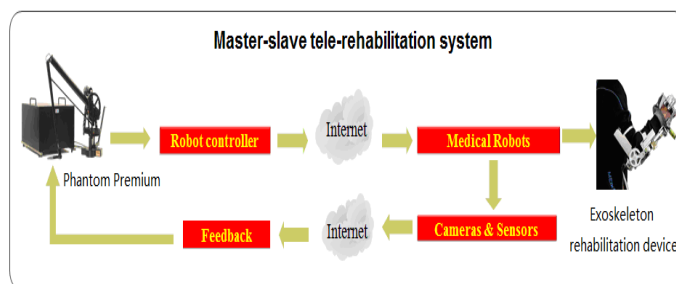


Fig1. The structure of tele-rehabilitation system

This device has three DoFs including elbow extension/flexion, forearm pronation/supination and wrist extension/flexion. It is designed with low weight and it is potential for home rehabilitation. The Phantom Premium with a wide workspace, force feedback on six DoFs is easy to operate by therapist. Considering the safe of patient, there are several mechanical designs on exoskeleton rehabilitation devices[9]. Allowing for realizing a precise control, brushless DC motor is chosen instead of other actuators. On the purpose of conveying therapists' experiences to patients using the master-slave system, the slave device should be driven to track the motion of the master device manipulated by the therapist. The experience contains two meanings. 1) when the therapist perceive the dangers occur, such as the spasm, the therapist can avoid the harm causing by slave device rapidly. 2) the therapist can adjust the rehabilitation intensity based on the state of patients. These functions must built on a precise tracking effect. In order to improve the tracking effect of traditional PI control, a self-tuning fuzzy PI control was proposed.

This paper is organized as follows. It introduces the relative research and proposed master-slave rehabilitation system. In section II, the proposed rehabilitation system is introduced respectively, including exoskeleton device and haptic device. In section III, a self-tuning fuzzy PI control strategy using for improving the tracking effect is introduced. In section IV, a self-tuning fuzzy PI control strategy using for improving the tracking effect is introduced. The last section presents the conclusion.

II. EXPERIMENTAL IMPLEMENT

A. Master part of rehabilitation system (Phantom premium)

The common surveillance approaches during rehabilitation are video and voice[10]. A more effective rehabilitation system is proposed in this study with a haptic device(shows in Fig2). It can provide force feedback. Phantom Premium provides a broad range of force feedback workspace, range of motion, stiffness, and motor force. Therapist operates the endmost handle which has 6 DOFs with the prerequisite that therapist's forearm must be fixed. Movement analysis of therapist's forearm has achieved by previous research[9]. Previous movement analysis mainly achieved three kinds of movement analysis including elbow flexion/extension, wrist flexion/extension, and forearm pronation/supination. Frame assignment for upper limb and Phantom premium shows in Fig2.

Forward kinematics of therapist arm and device handle were calculated based on the elbow central point(O1) and device central point(O2) respectively. Through relative position of above-mentioned two coordinates, device pose about device central can be obtained. With regard to a master-slave system, the two sides should move with a same mode. So, the coordinate conversion of Phantom premium is necessary for the therapist's experience delivery. Phantom premium operated by therapists may have same movement pattern with slave device.

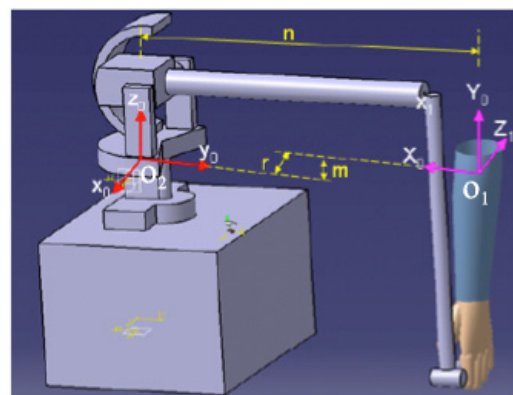


Fig2. Frame assignment for upper limb and Phantom premium

B. Slave part of rehabilitation system (Exoskeleton rehabilitation device)

A new upper limb Exoskeleton rehabilitation device(ULER-D)(shows in Fig3) has been developed in previous work[11-12]. In this study, it is used as the slave device wearing by patients. It can provide assistance to the patient's impaired upper limb. The actions include elbow extension/flexion, forearm pronation/supination, and wrist flexion/extension. It has three active DoFs in elbow and wrist joint. Another four passive DoFs were added to the elbow and wrist joints to correct any misalignment between the human and device joints. The mass of device was decreased as light as possible. The total mass is 1.3kg. A helical capstan shaft is designed apart from the motor shaft when overload. Force between the forearm and device is detected by a load cell avoiding danger. Exoskeleton device with these features is suitable for home-rehabilitation. So, it brings many convenience for the patient who is performing home-rehabilitation.

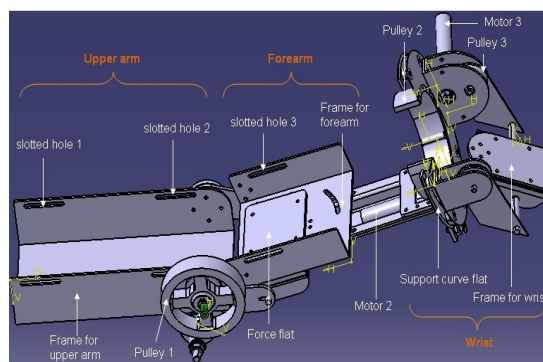


Fig3. Whole structure of exoskeleton device

III. CONTROL STRATEGY

To convey therapist's experience to patients using this system, the slave device is driven to track the motion of the master device manipulated by the therapist. In this section, the control strategy using in the master-slave system will be introduced, including the modeling, principle of fuzzy control, and the design of self-tuning fuzzy PI controller. Compared with the traditional PI control, a contrast simulation was proposed to evaluate the performance of fuzzy PI control.

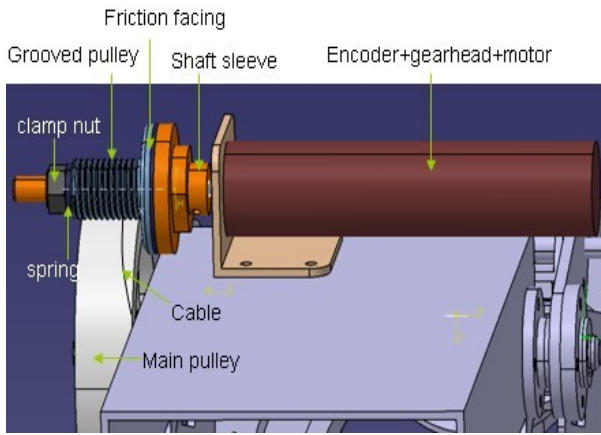


Fig4. Structure of elbow joint

A. Modeling

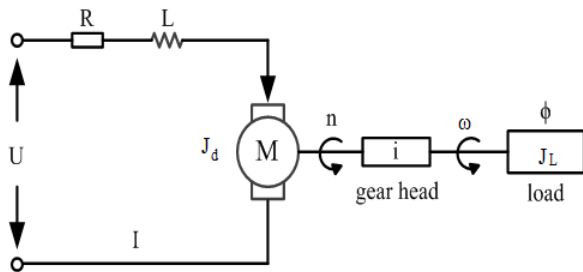


Fig5. Motor model with load

In order to improve the tracking effect of traditional PI control, a self-tuning fuzzy PI control was proposed. This paper focus on the design of master-slave rehabilitation system using fuzzy PI control. The modeling of slave device is important for the design. Elbow joint(shows in Fig4) driven by a BLDC motor is analyzed. BLDC motor has some advantages including high dynamic response, high efficiency, long operating life, noiseless operation and higher speed range. A rotational motion in consideration can be modeled as a mass system that the mass connected with flexible shaft or spring. The model can also be simplified further as a mass connected by an inertia free flexible shaft[13]. Our structure is different from the catheter system mentioned in [13], where the force between human and device is not complex. Considering about the driven strategy of elbow joint, the modeling of BLDC motor (shows in Fig5) is used.

In Fig.5, U is armature voltage; I is armature current; R is armature resistance; L is armature inductance; J_d is armature inertia; J_L is armature inertia of load; i is reduction gear ratio of motor (i=128 in our study); n is axes angular speed; ω is output angular speed of reduction gear. The Laplace transform of armature voltage equilibrium equation is calculated with electric motor armature voltage.

$$U(s) = (Ls + R)I(s) + E(s) \tag{1}$$

Counter emf of armature winding shows as equation 2.

$$E(s) = K_e n(s) \tag{2}$$

K_e is the coefficient of winding back EMF.

Relationship between angular speed of load and motor rotate speed describes as equation 3.

$$n(s) = i\omega(s) \tag{3}$$

Torque equilibrium equation of electric motor describes as equation 4.

$$M_e(s) = M_d(s) + M_L(s) \tag{4}$$

M_d(S) is resistance torque of motor itself, M_L(S) is disturbance torque of load after converting to motor axis. The transform function describes as equation 5 when disturbance torque M_L(S) is zero. The input is U(S), and the output is the angle.

$$\frac{\omega(s)}{U(s)} = \frac{1/K_e}{is(\tau_m\tau_e s^2 + t_m s + 1)} \tag{5}$$

where $\tau_m = \frac{R_a J}{K_e K_t}$, $\tau_e = \frac{L_a}{R_a}$

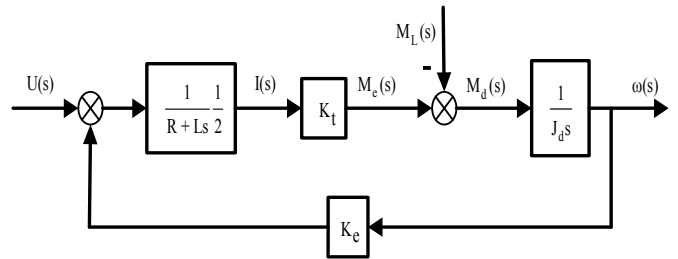


Fig6. Dynamic structure of electric motor

τ_m and τ_e represent electromechanical time constant and electromagnetic time constant respectively.

At last, the Dynamic block diagram of electric motro describes as Fig6.

B. Principle of Fuzzy control

Fuzzy control uses fuzzy sets and fuzzy inference to derive control laws. Compared with traditional control, fuzzy control needs no precise system model. To realize the trajectory tacking control, a fuzzy PID control instead of traditional control strategy is designed for the proposed therapeutic device driven by a pneumatic muscle (PM)[14]. Guo and Wei ever used a fuzzy PID control to get a stable flow rate in microfluidic system[15]. The basic idea of fuzzy control is to make use of expert knowledge and experience to build a rule base with linguistic rules[16]. A general structure of the fuzzy

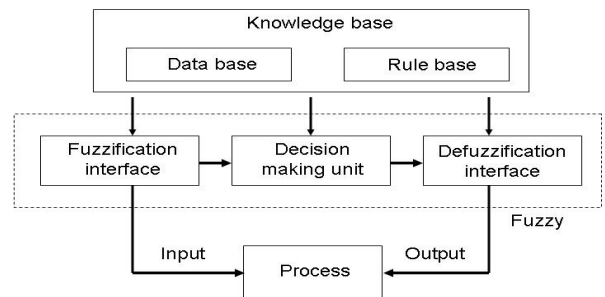


Fig7. General structure of fuzzy inference system

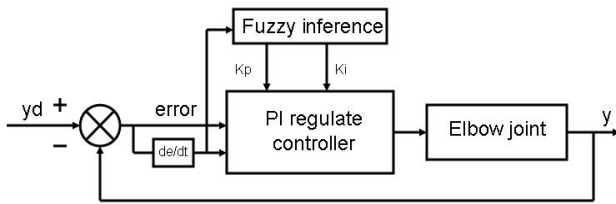


Fig8. Structure of fuzzy PI control diagram

system shows in Fig7. The structure is divided into the three categories: fuzzification, decision making unit and defuzzification. Knowledge base means rules and parameters for membership functions. Real world variables are translated in terms of fuzzy sets with the fuzzification block. Decision making unit means the inference operations on the rules. The results of the fuzzy computations are translated in term of real values for the fuzzy control action in the defuzzification block.

In our study, the fuzzification interface and defuzzification interface parts were chosen from Matlab toolbox. The Matlab fuzzy toolbox provides a dedicated editor for the design of the fuzzy controller. Through the identified input and output linguistic variables assigned table, membership functions can be selected to denote the membership of fuzzy linguistic variables.

C. Design of self-tuning fuzzy PI controller

The quality of a fuzzy control system depends on the structure of fuzzy controller, its fuzzy rules, the fuzzy strategy and the synthetic inference algorithm. The structure of fuzzy PI control diagram in our study shows in Fig8. The control deviation e and deviation change rate Δe are the inputs of fuzzy PI control system.

According to expert experience, the basic control principles of fuzzy PI controller in our study can be summarized as follows:

- 1) If the tracking speed of exoskeleton device equals to the speed of Phantom premium, the present current of motor on exoskeleton device remains the present level.
- 2) If the tracking speed of exoskeleton device is higher than the speed of Phantom premium, the present current of motor on exoskeleton device should be diminished.
- 3) If the tracking speed of exoskeleton device is lower than the speed of Phantom premium, the present current of motor on exoskeleton device should be increased. Fuzzy control rule based in our study was built with the basic control experience of fuzzy PI control mentioned above.

In fuzzy control, these process states are represented by linguistic variables. Every fuzzy set can be represented by its membership function (From Fig9 to Fig12). K_p and K_i are regulating on-line with the fuzzy inference. And then, the parameters of K_p and K_i are sent to a PI regulate controller which is a classical PI controller. A classical PI controller is described by equation 6.

$$u(t) = K(e(t)) + \frac{1}{T_i} \int_0^t e(\tau) d\tau \quad (6)$$

where K is the gain of PI controller, T_i is an integral constant, $e(t)$ is an error signal, $e(t) = w(t) - y(t)$, $w(t)$ is the desired value, $y(t)$ is the output from process and $u(t)$ is the output from controller.

To convey therapists' experience to patients using the master-slave system, the slave device should be driven to track the motion of the master device manipulated by the therapist. In practical rehabilitation, therapist operates the master device to drive the slave device with force and visual feedback. The movement pace of therapists must be not faster than the normal rehabilitation movement pace otherwise, it will results in dangers. It is still under discussion that how to choose a suitable movement pace of rehabilitation. In the research of [17], the target movement pace was equal to 1 Hz in constant frequency condition.

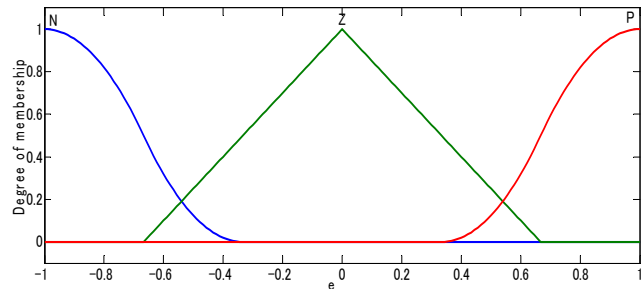


Fig9. Membership function of e

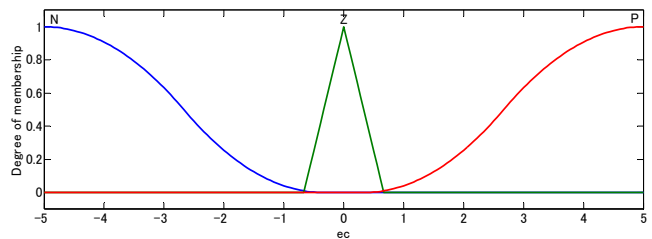


Fig10. Membership function of ec

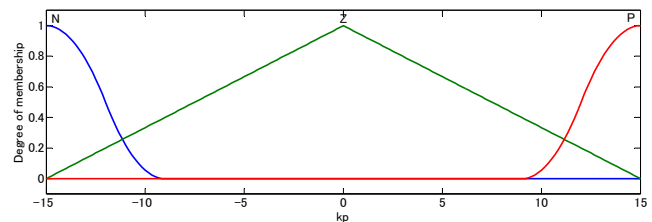


Fig11. Membership function of K_p

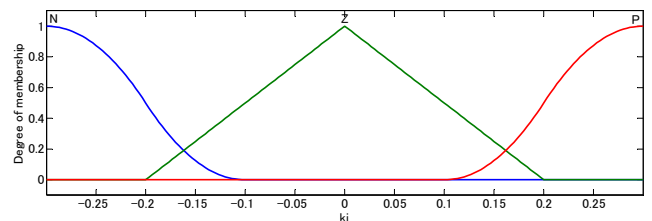


Fig12. Membership function of K_i

IV. SIMULATION AND RESULTS

In our study, compared with the traditional PI control, a contrast simulation was proposed to evaluate the performance of fuzzy PI control. In the simulation, a certain movement such as elbow flexion and extension conveyed to a patient from a therapist is supposed as some rhythm movement with 1 Hz. The simulation results shows in Fig13. The solid line means the target signal in the simulation. The red dot line shows the tracking results of proposed fuzzy PI control. Green dot line shows the tracking result of traditional PI control. It can be indicated from Fig13 that the proposed fuzzy PI controller can tracking the target signal well, especially when the target signal's speed changes fast. With this characteristic, two situation can be avoided or realized: 1) When the therapist perceives the spasm occurs, he/she should take action rapidly. In this situation, it will be dangerous when slave side can not track the master side well. The fuzzy PI control proposed in our study can solve this problem. 2) Therapists could adjust the rehabilitation intensity based on the state of patients.

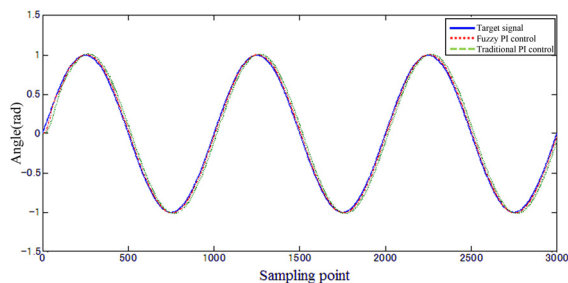


Fig13. Sine-signal tracking simulation

V. CONCLUSION

In recently, the master-slave system is researched by many researchers in remote rehabilitation of patients' motor function. This system can alleviate the problem of short inpatient poststroke hospital stays period. With therapists' surveillance through this system, the dangers especially when spasm occurs can be avoided. To convey therapist's experience to patients using the master-slave system, the slave device should be driven to track the motion of the master device manipulated by the therapist. In this study, a fuzzy PI controller was designed to improve the tracking efficacy. Compared with the traditional PI control, a contrast simulation was proposed to evaluate the performance of fuzzy PI control. In the simulation, a certain movement such as elbow flexion and extension conveyed to a patient from a therapist is supposed as some rhythm movement with 1 Hz [17]. Results show that the proposed fuzzy PI controller can increase the accuracy of tracking performance compared to traditional PI control. In the future, a force model built by OpenGL will be added to the master-slave rehabilitation system. Fuzzy PI control proposed in this study has solved the tracking problem. It gives a premise of future works.

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