Discussion on Fuzzy Logic Operation of Impedance Control for Upper Limb Rehabilitation Robot

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Abstract. For the influence caused by illness condition of suffered limb on system stability when robot makes rehabilitation training on assisted suffered limb, on the basis of the traditional impedance control method, this paper puts forward one kind of impedance control method based on fuzzy neural network. This method adopts mechanical impedance parameter of suffered limb which can correctly reflect illness characteristics of suffered limb as controller input, the impedance control parameter based on position is applied in robot for upper limb rehabilitation. It makes simulation by simulink and makes analysis on influence of target impedance parameter on control ability of system. The analysis and simulation result indicate that method after improvement can effectively adapt to illness change of patient than the traditional impedance control method, and it has better smoothness and stability.

Introduction

With the development of robot technology, applying auxiliary treatment technology by robot into rehabilitation training of patients has already been emphasized by researchers both in China and abroad, and it has gradually become to be the important topic and hot point[1,2,3] in the research field of rehabilitation project. Rehabilitation robot technology is one kind of new motor nerve treatment technology. In the process of making rehabilitation movement by robot, one of the important aspects is that rehabilitation robot can timely perceive illness condition of patients and adopt corresponding control measures, so that system can keep stable when illness condition of suffered limb changes. In recent years, there are many researchers have made research on this problem, of which those have universal application are as follows: force control strategy [4], control method based on force field and biological signal etc [5]. As one kind of effective force control method by robot force, impedance control has been universally applied in movement control of rehabilitation robot [6,7]. With the development of intelligent control technology, traditional impedance control method combines with intelligent control method, which has made up the shortages in traditional methods and enhanced effect [8,9] of rehabilitation training. However, in the above mentioned impedance control strategy by robot, most of them are make design on controller according to force signal perceived by sensor, and in the design process of intelligent controller, study algorithms directly adopts the traditional and optimal BP algorithm to make optimization easily to fall into local.

For the above problems, this paper is based on robot on upper limb rehabilitation and adopts myoelectric signal to realize rehabilitation training based on body movement intention control. In addition, on the basis of modeling of pneumatic muscle it respectively puts forward control algorithm of slide model and dynamic surface control algorithm based on non-linear disturbance observer to realize control of high precision by pneumatic muscle. Considering complication on modeling of pneumatic muscle and difference in people on robot dynamics model for upper limb rehabilitation, for the unknown conditions of model, it puts forward impedance control method based on fuzzy neural network. This method adopts mechanical impedance parameter of suffered limb which can correctly reflect illness characteristics of suffered limb as controller input. Through theoretical analysis and test demonstration, this algorithm can enhance response speed, target trace tracking and simultaneous precision of rehabilitation training robot on upper external bone to drive joint.

EMG intention identification on suffered mechanical impedance parameter

Impedance control adds error input signal of force control to the input end of position control, it realizes control by adjustment of position loop, impedance control theory is different from mixed control strategy, it is one kind of control method on indirect force, impedance control by contact environment to receive and input is the dynamic relations by adjusting terminal stiffness force and position of robot, and it integrates force control and position control into one frame, and it uses the same control strategy to realize it, it has stronger robustness for undefined interference factors, so it gets universal application in realizing force and position control of robot.

The target impedance model adopted by this paper is indicated by the following formula:

$$M_d(X_r(t)-X(t))+C_d(\overline{X}_r(t)-\overline{X}(t))+K_d(\overline{\overline{X}}_r(t)-\overline{\overline{X}}(t))=F_d-F_t \quad (1)$$

Of which, $X(t)$, $\overline{X}(t)$, $\overline{\overline{X}}(t)$ respectively indicates position, speed and vector of accelerated speed of robot end limb, $X_r(t)$, $\overline{X}_r(t)$, $\overline{\overline{X}}_r(t)$ respectively indicates target position, speed and vector of accelerated speed of robot limb end, Md indicates expected inertia matrix of robot limb, it will have great impact when there is movement of high speed or movement producing impact force, Ck indicates target inertia matrix of robot limb, it has great impact on movement at middle speed or stronger interference force Kd indicates the ideal stiffness matrix of robot, it will have great impact by nearby movement of low speed, Ft indicates the expected contact force of robot, Fd indicates force vector of robot limb by restraint environment..

Because the collected signals are typical disperse order, it uses disperse wavelet package to analyze and deal with EMG signal. Analysis algorithm of multi-resolution ratio, which can get parameter of small wavelet package: of which, j is scale factor, k is time-lapse factor and n is frequency factor.

$$\omega_{j,n,k} = < f, W_{j,k}^{n} > = < f, 2^{j/2} W^{n}(2^{j} t - k) > \quad (2)$$

If each (j, n) indicates one small wavelet package, then its node energy can be defined as follows: according to each couple of different j and n, it can indicate detailed signal energy of certain frequency range.

$$e_{j,n} = \sum_{k} \omega_{j,n,k}^{2} \quad (3)$$

Define this characteristic choice method as PWMFS and non-parameter weight characteristic to extract characteristic reflection to realize characteristic choice and dimensionality reduction. Suppose these are L kinds of identifying objects, dimension of original characteristic space is n, it uses PWMFS characteristic to choose algorithm.

Impedance control strategy based on fuzzy neutral network

Control structure of impedance: With changes in illness condition of suffered limb, stiffness and damp of mechanical impedance parameter are gradually changing. According to the above analysis, this paper consider adopting mechanical impedance parameter of upper limb of patients as controller input, control parameter of target impedance is controller input. According to the online mechanical impedance parameter of patients, this paper uses fuzzy neutral network to directly adjust target impedance control parameter.

Impedance controller based on fuzzy neutral network is to increase 2 controllers of online study target impedance control parameter on the basis of traditional controller, respectively defines it as stiffness controller of fuzzy neutral network and damp controller of revolution fuzzy network. Diagram 1 gives self-adaptation impedance control structure of upper limb rehabilitation by robot based on revolution fuzzy neutral network. It uses stiffness controller of revolution fuzzy neutral network to make analysis, its structure is indicated by diagram2, and it is similar to analysis method of damp controller. This controller adopts network structure of 5 layers, mechanical impedance parameter of suffered limb bˆ e ,kˆ e respectively regarded as controller input, Kd is controller output. The input and output fuzzy set discourse domains are defined as [-6, 6]. In this discourse domain, respectively defines 7 fuzzy language variables, negative large, negative medium, negative small, zero, positive small, positive medium, positive large.

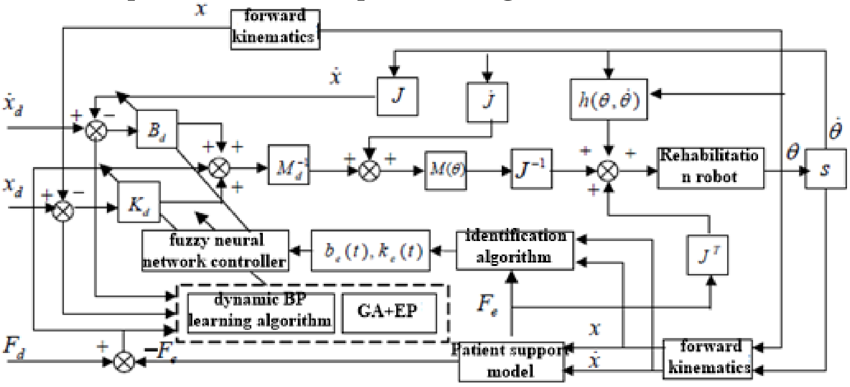


Diagram. 1: Impedance control structure of revolution fuzzy neutral network of upper limb rehabilitation robot

The subordinated function of each language viable uses Koski function

$$u(x = \exp(-\frac{(x-b)^2}{c^2}) \quad (3)$$

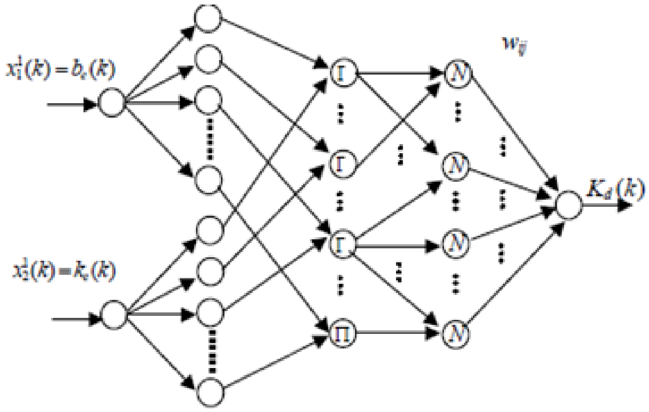


Diagram .2 :Stiffness controller structure of revolution fuzzy neutral network

Study and control algorithm of impedance controller:ESN is one kind of dynamic recursion neutral network; it is much more suitable for description of dynamic characteristic of complicated non-linear system. This paper combines ESN and PLS to realize online self-adaptation identification of ESN. ESN of combining RLS algorithm online study can be regarded as RLSESN. ESN just only needs to adjust output weight value, if output unit of ESN is linear unit, this kind of ESN structure makes study process of ESN adopt RLS algorithm similar to process of self-adaptation filtration to use RLS algorithm.

If expected output of EXN in k step is yd(k)，Wout(k) is the output weight value in k step, v is unit state vector connected with output weight value in ESN. Then all the errors before k step can be indicated as follows:

$$e(i\,|\,k) = y_d(i) - W^{out}(k)v(i\,||\,k) \quad (4)$$

ESN adopts RLS algorithm, which can make network iterative to minimum target function of the k step.

$$J = \sum_{i=1}^{k} \gamma^{k-i} e^2(i\,|\,k) \quad (5)$$

Of which, Γ is reduction factor; its usual value is approximately 1 or less than 1.

: According to principle of minimum mean square error, RLS algorithm can be indicated as follows:

$$\lambda(k)=\frac{P(k-1)v(k)}{v^T(k)P(k-1)v(k)+\gamma} \tag{6}$$

$$P(k)=\gamma^{-1}P(k-1)-\lambda(k)v^T(k)P(k-1) \tag{7}$$

$$\overline{y}(k)=W^{out}(k-1)v(k) \tag{8}$$

$$e(k)=y_d(k)-\overline{y}(k) \tag{9}$$

$$W^{out}(k)=W^{out}(k-1)+\lambda(k)e(k) \tag{10}$$

Of which, λ is the gain matrix of Kalman filter; v is vector of internal neutral cell state. Yd is vector of target value, $\overline{y}(k)$ is output vector of ESN, e is the prior error of each iteration. P is inverse matrix of relevant matrix in internal activated vector. P is diagonal matrix in initialization, and its value is relatively larger, it is indicated as follows:

$$p(0)=\delta^{-1}I(\delta>0) \tag{11}$$

Of which, δ is one smaller positive number, I is one unit matrix. Considering matrix P will easily cause instability of RLS algorithm under long-time and non-dynamic signal. In order to solve this problem, this paper adopts self-relevant matrix reset to avoid this problem. If trace of matrix P is located in one relatively smaller positive number, then rest as primary state.

The detailed algorithm process is indicated by diagram3.

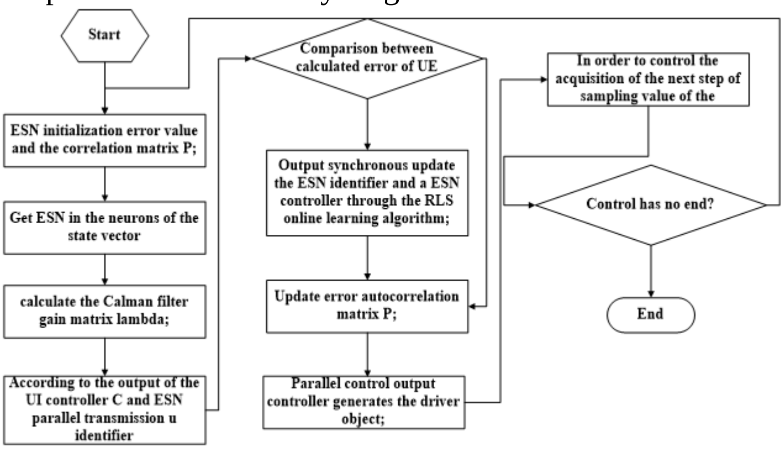


Diagram. 3: Algorithm process

Online adjustment:In the online study stage, put offline target impedance control network after optimization into system for operation, network can make small adjustment online according to dynamic algorithm, so that it can further optimize target impedance control parameter, of which, target function of FNN stiffness controller and damp controller are respectively defined as follows:

$$\frac{1}{2}M_d(X_r(t)-X(t))+C_d(\overline{X}_r(t)-\overline{X}(t))+K_d(\overline{\overline{X}}_r(t)-\overline{\overline{X}}(t))=\frac{1}{2}(F_d-F_t) \tag{12}$$

Through RLSESN, it can construct ESN reverse controller to realize feed forward control. As for object of model position, it can use controller to realize feed back control. The control frame based on feed forward and feed back, it is constructed by ESN reverse controller based on RLSESN parallel control. Of which, ESN reverse controller realizes most control output by feed forward, meanwhile, it realizes one kind of control compensation according to tracking error. It can realize system stability by choosing suitable control parameter and feed back control. For the unknown object of model, controller based on RLSESN combines with merits of feed forward and feed back control to realize tracking and control with high precision on control objects.

Simulation of example demonstration

In order to demonstrate effectiveness of algorithm put forward by this paper, now it gives simulation test of rehabilitation robot. In the robot control on upper limb rehabilitation, the contact force between robot and patients becomes increasingly important; control capacity on control ability can directly reflect system stability and safety performance. In the joint space impedance control based on position, the mechanical limb of upper limb rehabilitation and contact force of patient are measured by force sensor, it is replaced by spring flexibility in the simulation, its formula is as follows:

$$F = K_e(X - X_e) \tag{13}$$

Of which, Ke is environment stiffness; X e is the primary environment position. The impedance control algorithm Simulink model for upper limb rehabilitation robot is indicated by diagram 4. From zero to ten, there is one restraint plane in space position of ϴ=5°, suppose there is no fraction between mechanical limb and environment, environment stiffness K e=2，the stress condition completely adopts spring to replace it. When it requires robot to contact with environment, there contact stress should be kept at 10N 。

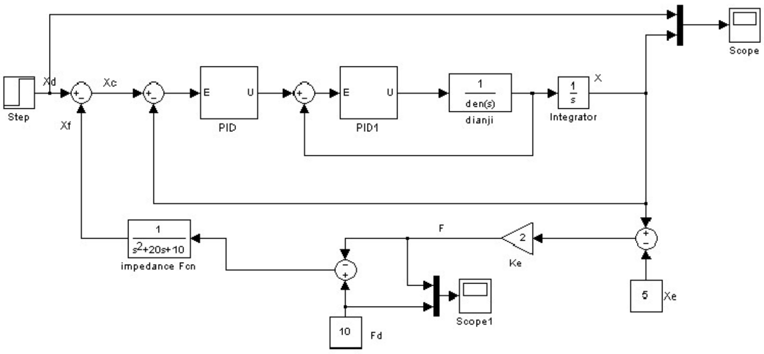
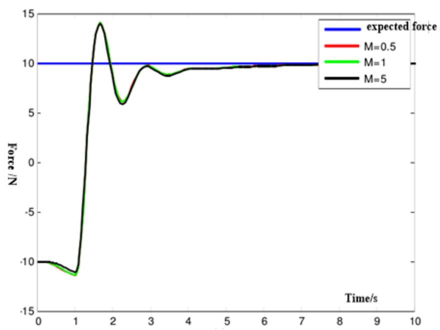


Diagram .4: Simulink simulation model based on impedance control algorithm

Keep damp B =20，stiffness K =10，environment stiffness K e=2 has no change，inertia of adjustment target is 0.5, 1 and 5,simulation time is 10S，the performance curve of resistance control is indicated by diagram 5.



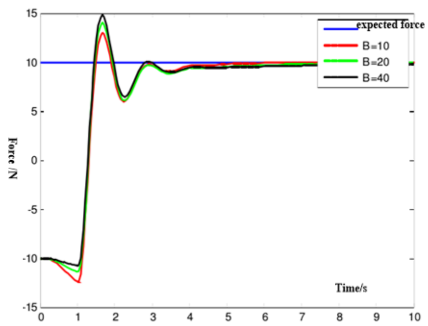


Diagram. 5: Performance curve 1 of resistance control

Diagram .6 :Performance curve 2 of resistance control

When target inertia changes, performance index of each one is indicated by the following table.

Table 1: Control performance index table of different target inertia M

M	peak（ N m)	Stable value（ N　m)	Stable time（ S ）
0.5	14.14	10.00	6.70
1	14.16	10.00	6.80
5	14.18	10.00	6.85

From table we can see when inertia parameter increases, peak of contact stress gradually increases, but the change fluctuation is very small, and it can stabilized above 10N in the end, this is because rehabilitation robot of upper limb moves at low speed, the speed change is very little and target inertia has effect on change of accelerated speed, so on inertia joint M has little effect on resistance control of upper limb robot.

Keep inertia M =1，stiffness K =10，environment stiffness K e=2 has no change，inertia of adjustment target is 10, 20 and 40, simulation time is 10S，when target stiffness changes, the performance curve of resistance control is indicated by table 2.

Table 2: Control performance index table of different target inertia K resistance

K	peak（ N □ m）	Stable value（ N □ m）	□ stable time（ S ）
10	14.00	10.00	6.50
20	14.52	10.00	5.65
40	15.20	10.00	5.50

Target stiffness K reflects stiffness of mechanical limb, it directly reflects whether mechanical limb presents stiffness or flexibility when contacts with environment, when target stiffness K gradually increases, peak value of contact stress gradually becomes large, but its stable time gradually becomes short. From the simulation result based on position impedance control strategy we know: through adjustment on target impedance parameter, force control of robot is different, the setting of target impedance parameter will directly affects system control performance and safety performance.

Conclusion

When rehabilitation robot contacts with patients, in order to guarantee safety and comfort in the training process, at the same time of making trace tracking, we must consider the mutual force between control robot and patient, because suffered limb of patients is very weak, if the mutual stress is too large, it will possibly pull suffered limb of patient, this is not absolutely allowed. By using impedance control, and position control to get effect of indirect control force, although the position error is large, force control is much more important as for force control. From certain meaning, impedance control is to increase force control performance at the cost of position precision.

When rehabilitation robot makes training with patients, it will choose reasonable impedance parameter according to different environment, and it controls acting force between rehabilitation robot and patients within the range that one patient can bear, so that it guarantees the safety and stability in the whole rehabilitation training process.

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