Improved SVM algorithm for upper limb rehabilitation mechanical arm Study on the Prediction of Track Tracking Control

Chu Zenan¹, Wang Wei¹, Wang Di²

¹Department of Computer Science and Information Engineering, Anyang Institute of Technology, Anyang, Henan, 4655000, China
²Department of Electronic Information and Electrical Engineering, Anyang Institute of Technology, Anyang, Henan, 4655000, China
*Corresponding author’s e-mail: chuzenan@163.com

Abstract. Aiming at the strong coupling, nonlinear and time-varying characteristics of upper limb rehabilitation training manipulator, a trajectory tracking predictive controller based on SVM (support Vector Machine) is designed. The input and output data of the manipulator system are collected, and the generalized inverse system is obtained by SVM identification, which is decoupling from the original system in series. For the decoupling system, the improved SVM algorithm is used to predict the trajectory tracking control, and the SVM algorithm is improved by combining the predictive function control method of PSO optimized rolling control sequence. The improved SVM algorithm can predict the trajectory of upper limb rehabilitation manipulator with high precision, and the experimental results show that the improved algorithm has good adaptability to the stability and robustness of the system.

1. Introduction

Scientific and reasonable rehabilitation training is of great importance for patients suffered from stroke, brain trauma and spinal cord injury, which is beneficial to the rehabilitation and improvement of limb movement. Currently, the traditional one-on-one manual training by physicians can no longer meet the market requirements. Therefore, intelligent robot begins to be applied in this area, and brings out great convenience for patients and physicians. The upper limb rehabilitation training robot arm can help to reduce recovery cost, improve training efficiency, meanwhile, it also can record recovery data, which make it broad application prospect and arouse a common attention.

The upper limb rehabilitation training robot arm has a series of advantages such as multiple degrees of freedom, large movement range, strong coupling and non-linearity. Considering the specificity of objects, the robot must adjust its positions in a fast, stable and precise manner, so that it can meet the requirements of different patients. The traditional control method for robot arm cannot realize high-efficiency trajectory tracking and real-time control. Therefore, in this paper, the stable and fast tracking control is achieved, by using decoupling system of generalized inverse system based on support vector machine and origanal system, and PSO optimized predictive function control structure. The predictive function control applies control strategies include predictive model, rolling optimization and feedback compensation[1-2], which lowers the dependence on the precision of system model[3-4]. The most important feature of predictive function control is the emphasis on structure form of control variables[5-
The control process output is predicted by historical information and future input within prediction horizon\[7\]set. Moreover, the prediction control adopts rolling optimization within finite horizon to address uncertainties resulted from model mismatch, time variance and inevitable disturbance, the control effect can be improved through repeated on-line optimization\[8\]. By applying generalized inverse system method, problems of multi-variable decoupling and feedback linearization faced by complicated multilinear systems can be solved well\[9\]-[10]. Because of the excellent nonlinear approximation and generalization ability, the subsystem applies SVM identification generalized inverse decoupling can help to improve model precision\[11\]-[12]. In order to improve dynamic control performance, PSO is used to optimize control sequence coefficient. In addition, since particle swarm optimization algorithm has advantages of good robustness and distributed computation, it is suitable to the rolling optimized solution of predictive control\[13\]-[15].

2. Dynamic Model

Coordinate system is built by D-H method, the spatial relationship between each joint and fixed coordinate system is represented by homogeneous transformation, the spatial relationship between neighbour joints is represented by homogeneous transform matrix. Therefore, the homogeneous transform matrix of terminal executor coordinate system corresponds to basis coordinate system can be deduced, and the space coordinate system of terminal executor can be established. After the establishment of transformation relation between terminal executor coordinate system and basis coordinate system, the dynamic model can be built according to Lagrange modeling principle:

$$
\tau_i = \sum_{j=1}^{6} D_{ij} \ddot{q}_j + I_{i(\text{act})} \dddot{q}_i + \sum_{k=1}^{6} \sum_{l=1}^{6} D_{ikl} \dot{q}_k \dot{q}_l + D_i
$$

Of which, \(\tau_i\) is inertia main force acted on No. \(i\) joint, \(i=1,2,\ldots,6\). The first section of right side of this equation represents for angular acceleration inertia, the third section represents for Coriolis force and centripetal force, the forth section represents for gravity. \(q\), \(\dot{q}\), \(\ddot{q}\) represents for the position, velocity and acceleration of each joint, respectively. Because of the three-dimension mass distribution of mechanical arm, driving force inertia \(I_{i(\text{act})}\) is difficult to be determined. In addition, factors such as moment caused by joint-friction, external disturbance and parameters precision can generate trajectory tracking error and affect the determination of precise dynamic model. Therefore, by applying prediction control algorithm which is dependant on model precision, the control and tracking precision will be improved.

Wherever Times is specified, Times Roman or Times New Roman may be used. If neither is available on your word processor, please use the font closest in appearance to Times. Avoid using bit-mapped fonts if possible. True-Type 1 or Open Type fonts are preferred. Please embed symbol fonts, as well, for math, etc.

3. Prediction function control

One the one hand , the prediction function model has three basic features of prediction control: prediction model, rolling optimization and feedback compensation. On the other hand, it also emphasizes the structure of control variable, which is set as the linear superposition of basis functions related to tracking fixed value and nature of controlled object, including step signal, ramp signal, etc.

When tracking fixed value is \(c(k)\), the corresponding expression for PFC control variable is:

$$
u(k) = k_c(k)c(k) - y(k) + k_m(k)X_n(k)
$$

Of which, \(k = 1,2,\ldots,N\), \(k_c(k) = [\mu_1(k)\cdots\mu_{n1}(k)]\), \(k_m(k) = [\mu_2(k)\cdots\mu_{n2}(k)]\).

For upper limb rehabilitation training robot arm, step function and ramp function are selected as basis functions to satisfy the system requirements of control precision. According to the generalized inverse system by SVM identification and pseudo linear system obtained by cascade, the prediction function control system is designed and shown in Figure 1. In which, \(c(k)\) is tracking fixed value, i.e., the given position of upper limb rehabilitation training robot, \(u(k)\) is control variable output, \(y_g(k)\) is
the output value of controlled object, \( y_m(k) \) is the output value of prediction model, \( y(k) \) is position output of upper limb rehabilitation training robot, \( e(k+i) \) is the error between system actual output and prediction model output.

In general, the system output is compensated by calibrating the error between system actual output and prediction model output \( e(k+i) \), therefore, the performance of prediction function control is rely on the precision of prediction model. The dynamic characteristics of upper limb rehabilitation training robot can be presented by mathematical model, which is non-linear and reversible, described by kinematical and kinetic equations, and applies generalized inverse to realize control of non-linear systems. However, accurate mathematical model is often difficult to get and has a complicated inversion process which is hardly realized in industrial processes, therefore, SVM identification generalized inverse system is often used as an alternative. In order to simplify algorithm, after decoupling, the prediction model of six controllers can be obtained by SVM identification. After that, plugging the results of PSO off-line optimization into rolling optimization control sequence, then design closed-loop controller, perform trajectory tracking and real-time control.

![Overall control block diagram](image)

Figure 1. Overall control block diagram

First, confirm that you have the correct template for your paper size. This template has been tailored for output on the US-letter paper size. If you are using A4-sized paper, please close this template and download the file for A4 paper format called CPS_A4_format.

### 3.1 SVM identification generalized inverse system

Amid all linearization methods of non-linear feedback, inverse system method is easy to understand, and can be displayed directly. After linearization and decoupling of inverse system, the obtained pseudo linear system is pure integral system, and stable closed-loop system is hard to get. Generalized inverse decoupling can realize arbitrary assignment of poles in pseudo linear system, which will further enhance the dynamic property of system. In order to improve the precision of system model and simplify inversion process, SVM is used to identify the inverse model. The expression for dynamic model of upper limb rehabilitation robot is shown as equation (1). In original system, \( \tau_1, \tau_2, \ldots, \tau_6 \) is system input, \( q_1, q_2, \ldots, q_6 \) is system output. When identifying inverse systems, the output of original system is considered as the input of identification system, the input of original system is considered as the output of identification system, six SVMs are used. Firstly, take square signal as drive signal, and select 100 groups of data from the original system as identification data, of which, each group of data contains \( \tau \) and \( q \) from six joints. Since the system is a kind of second-order system, so the collected data need to go through further processing. The first-order derivative \( \dot{q} \) and second-order derivative \( \ddot{q} \) of \( q \) are obtained to show the velocity and acceleration of each joint, besides, identification data are also obtained as \( (q_i, \dot{q}_i, \ddot{q}_i, \ldots, q_{i6}, \dot{q}_{i6}, \ddot{q}_{i6}, \tau_i) \), of which \( i = 1, 2, \ldots, 6 \), \( j = 1, 2, \ldots, 100 \). The first 80 groups of data are training data, and the last 20 groups of data are testing...
data, radial kernel function is selected as SVM kernel function. The penalty parameter $c$ of SVM, RBF kernel parameter $g$ and $p$ are optimized by PSO optimal seeking method. After identification, generalized inverse system can be obtained. At last, cascade the obtained generalized inverse system and mechanical robot system to create pseudo linear system and realize dynamic decoupling. Therefore, after decoupling, the transfer function of pseudo linear system is

$$G_{1,2,\ldots,6}(s) = \frac{1}{(s+1)^2}$$

(3)

Figure 2. Generalized inverse system based on SVM identification

3.2 PSO-based rolling optimization for prediction function

In order to ensure good tracking performance, the optimization object of prediction function is often selected as the squares sum of error between system prediction output and reference track:

$$\min J(k) = \sum_{i=1}^{n_p} [y_p(k + h_i) - y_r(k + h_i)]^2$$

(4)

Of which, $n_p$ is the number of fit point in prediction horizon, $h_i$ is the numerical value of No. $i$ fit point. The target of optimization is to obtain a group of control coefficient $\mu_1(k), \mu_2(k), \ldots, \mu_n(k)$ to make the system prediction output in whole optimization horizon close to reference trajectory; on the other hand, to make equation (4) obtain the minimum value. Traditional prediction functions, such as gradient descent, get control sequence through numerical solution of objective functions, which generally require large amount of calculation, complicated calculation process, and cannot guarantee globally optimal solution. For six decoupled pseudo linear control system $G_{1,2,\ldots,6}(s) = \frac{1}{(s+1)^2}$, the optimization target is to get six groups of optimum control parameters $c_1$ and $k_n$.

Here is the resolution of joint 1 control coefficient. When the tracking signal is set as step signal, $c(k+i) = c(k)$, then in equation (3), $k_1(k+i) = k_1(k), k_2(k+i) = k_2(k)$, control coefficient $\mu_1$ and $\mu_2$ should be resolved. Therefore, $\mu_1$ and $\mu_2$ are set as the x and y axis position of globally optimal solution to continuously update the position of particles so that the minimum equation (4) value could
be obtained. Resolution of prediction function control sequence by PSO can be realized according to following steps:

- Determine the fitness function, select prediction function control shown in equation (4) to optimize object function, collect input signal and the difference value between input signal and output signal.
- Initialize the population and velocity of particle swarm. By enlarging the population size, local minimum problem caused by random initialization could be solved to some extent. Experiment results show that the optimal value could be obtained when population size is 50.
- Plug collection input signal and the difference value between input signal and output signal, calculate fitness function, update velocity and individual, conduct continuous optimization to get the optimal solution and control coefficient $\mu_1, \mu_2$.
- Output the position of globally optimal particle, assign value to $\mu_1, \mu_2$ and plug them into prediction function controller to verify control effect.

The results of simulation and experiment show that through PSO off-line optimization, satisfied control coefficient and good control effect can be achieved.

3.3 SVM identification and prediction model

Since it is difficult to get accurate dynamic model for upper limb rehabilitation training robot, therefore, in order to avoid complicated mathematical calculation and derivation, SVM is applied to identify the prediction model in prediction function control. In addition, when the internal structure and control mechanism of actual control system are hard to describe accurately, prediction model identified by SVM can also simplify control algorithm. For the single input single output system after decoupling

$$q_i(k + 1) = f[q_i(k), \dot{q}_i(k), \ddot{q}_i(k); \tau_i(k)]$$

Of which, $i = 1, 2, \ldots, 6$, then introduce a regression vector

$$X_j = [q(j), \dot{q}(j), \ddot{q}(j); \tau(j)]$$

then,

$$q(j + 1) = f(X_j)$$

Regression vector and actual position of joints are combined as training sample for support vector $\{X_j, q(j + 1)\}$, $j = 1, 2, \ldots, m$, $m$ is the number of identification data. When perform training modeling, radial kernel function is selected as SVM kernel function. The penalty parameter $c$ of SVM, RBF kernel parameter $g$ and $p$ are optimized by PSO optimal seeking method. Firstly, amid 100 groups of collected data mentioned in section 3.1 SVM identification generalized inverse system, select 80 groups of data as the training sample, of which, the first 50 groups of data for training set, the last 30 groups of data for testing set, optimized $c$, $g$ and $p$ are applied to facilitate training, so that the prediction model of each joint is obtained. Figure 3 represents for optimization parameters and prediction effect of joint 1 training prediction model.

![Figure 3. Prediction model based on SVM identification](image-url)
4. Experiment and analysis
Plug PSO-optimized rolling control parameters into the above-mentioned system, then design the closed-loop controller of prediction function to conduct trajectory tracking on the mechanical body. Of which, set value \( c = 1 \), sampling period \( T_s = 1 \) s, time constant of reference trajectory \( T_r = 30 \) s, prediction step \( H_1 = 10 \), \( H_2 = 20 \). From the picture, \( \text{link1}, \text{link2}, \ldots, \text{link6} \) is the position output of No. \( i \) joint, \( i = 1, 2, \ldots, 6 \), standard represents for standard \( 1/(s+1)^2 \) system response. The given signal for 6 joints is a same step signal, Figure 5 shows the tracking performance. Figure 4 shows that the response of each joint goes in line with the set standard system, preset decoupling result is realized. In addition, the output static error is 0, which shows trajectory tracking with no static errors could be achieved.

![Figure 4. System responses with no disturbance](image)

In order to verify the robustness and stability of prediction function control, system responses under disturbance should be observed and compared to traditional PID control effect. For the above-mentioned system, PFC and PID control are performed upon the single input single output system after decoupling, when \( t = 12 \) s, disturbance of \( d = 0.1 \) is added. Figure 5 shows the control effect of PFC and PID on position response of joint 1, the position response curve of joint 1,3-6 is the same with that of joint 2.

Analysis on Figure 5 shows that compare to PID control, prediction function control has a smooth output and non-overshoot curve, yet requires a long adjusting time. Therefore, for the upper limb rehabilitation training robot, the prediction function control can realize smooth control and high control precision.

![Figure 5. Comparison of control effects of two control strategies.](image)

5. Conclusion
In conclusion, decoupling system and prediction model based on SVM generalized inverse system and original system, as well as prediction function method based on PSO optimized control sequence are used in upper limb rehabilitation training robot with posture adjustment function, therefore, movement
tracking with high precision can be realized. The application of generalized inverse system in decoupling can help to simplify controller and avoid complicated resolving process. The closed-loop controller of prediction function, which is based on SVM identification prediction model and PSO optimized control sequence, further improve the robustness of the system. The experimental results show that the structure of the improved algorithm is simple, there is no need to adjust the parameters online, and it is easy to be realized by rehabilitation training.

References
[1] ZHANG Ri-dong, WANG Shu-qing, (2007) Adaptive predictive functional control for a class of nonlinear systems, CONTROL AND DECISION, 22:711-715.
[2] Resquín F, Gonzalez-Vargas J, et al. (2007) Adaptive hybrid robotic system for rehabilitation of reaching movement after a brain injury: a usability study. Journal of NeuroEngineering and Rehabilitation, 14:102-104.
[3] Resquin F, Ibanez J, Gonzalezvargas J, et al. (2016) Combining a hybrid robotic system with a brain-machine interface for the rehabilitation of reaching movements: A case study with a stroke patient. Conf Proc IEEE Eng Med Biol Soc, 2016:6381-6384.
[4] WANG Di, HU Li-kun, (2013) The SVM identification and control of the six-axis manipulator generalized inverse system, Journal of Guangxi University (Natural Science Edition), 38:1202-1207.
[5] Reinkensmeyer D J, Boninger M L, (2012) Technologies and combination therapies for enhancing movement training for people with a disability. Journal of NeuroEngineering and Rehabilitation, 9:17-19.
[6] PAN Lizheng, SONG Aiguo and XU Guozheng etc, (2012) Real-time Safety Control of Upper-limb Rehabilitation Robot, Robot, 34:197-203.
[7] ZHU Rui, WU Minjun and JIN Hongsheng etc, (2015) A Mechanic Arm and Hand Control System Design Based on Infrared and Color Image Sensors, Chinese Journal of Electron Devices, 38:805-811.
[8] Maria P, Stefano L, Cristina S, etc. (2018) A Robotic System for Adaptive Training and Function Assessment of Forelimb Retraction in Mice, IEEE Transactions on Neural Systems and Rehabilitation Engineering, 18:1-1.
[9] Kutlu M, Freeman C T, Hallewell E, etc. (2016) Upper-limb stroke rehabilitation using electrode-array based functional electrical stimulation with sensing and control innovations[J]. Medical Engineering & Physics, 38(4):366-379.
[10] TANG Yao-Hua, GUO Wei-Min and GAO Jing-Huai, (2010) SVM Parameter Selection Algorithm Based on Maximum Kernel Similarity Diversity, PATTERN RECOGNITION AND ARTIFICIAL INTELLIGENCE, 23:210-215.
[11] LIU Guohai, ZHANG Jin and ZHAO Wenxiang etc, (2011) Internal Model Control Based on Support Vector Machines Generalized Inverse for Two-motor Variable Frequency System Applications, Proceedings of the CSEE, 31:85-91.
[12] SAI Jierhu, DAI Shengfang and DONG Aihua etc, (2014) Sensor Fault Diagnosis of the Automobile Active Noise Control System Based on SVM and RBFN, Chinese Journal of Sensors and Actuators, 27:512-517.
[13] QU Jian, CHEN Hongyan and LIU Wenzhen etc, (2015) Application of Support Vector Machine Based on Adaptive Mutation Particle Swarm Optimization in Analysis of Gas Mixture, Chinese Journal of Sensors and Actuators, 12:1262-1268.
[14] HU Li-kun, WANG Di and HUANG Wen-qin etc, (2014) Internal Model Control Based on GASVM and Inverse System of Manipulator, Control Engineering of China, 38:415-418.
[15] Kutlu M, Freeman C T, Hallewell E, etc. (2015) Goal-Orientated Upper-Limb Stroke Rehabilitation Utilising Functional Electrical Stimulation with Advanced Sensing and Control. 20:45-49.