

Servo control algorithm of handling manipulator based on disturbing observer

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Abstract. The purpose is to study the servo control algorithm of the handling robot based on the disturbance observer. In order to meet the high precision positioning requirements of the manipulator, the control algorithm of the motor is discussed and studied. The mathematical model of permanent magnet synchronous motor is analyzed. Aiming at the problem of controller tracking performance degradation, a permanent magnet synchronous motor disturbance observer and a speed controller based on fuzzy control are designed. The speed and current double closed loop control system is constructed. By using a disturbance observer, the system disturbance is estimated. According to this, the torque and current compensation are generated, and feed forward control of the speed loop is corrected. The final amount of current is optimized. The results show that the control algorithm has good dynamic performance and steady-state performance. It provides a theoretical basis for high-precision positioning of manipulator. Therefore, it can be concluded that the system achieves the purpose of suppressing the disturbance.

Key words. Manipulator, observer, servo control algorithm, permanent magnet synchronous motor.

1. Introduction

With the rapid development of modern industry and the continuous advancement of machine replacement, the application of manipulators is becoming more and more extensive [1]. It is widely used in marine development, space exploration, aerospace, machining, and civil production. In addition, all kinds of new mechanical hand are still emerging. The robot can complete many repetitive and tedious works. It can also replace mankind in dangerous environments to complete dangerous work [2]. Therefore, the emergence and application of manipulators not only greatly improve the level of human production, but also improve the working environment of workers. Nowadays, many countries begin to pay more attention to the research and

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exploration of machine hand and robot [3]. It has achieved breakthrough results, while it also has created many practical and innovative robots or robotic devices. In recent years, the equipment manufacturing industry in our country has developed rapidly [4]. However, the cost of employing people is increasing year by year, and a considerable extent has affected the sustained development of China's manufacturing industry. With the gradual promotion of industrial transformation and upgrading, the "China made 2025" project was launched. In order to reduce costs and improve efficiency, the demand for intelligent equipment represented by industrial robots in the domestic manufacturing industry has also ushered in an unprecedented period of explosion [5]. However, compared with the expensive and complex robot, high cost performance, simple structure and convenient manufacturing will be the primary choice for the majority of minor enterprises [6]. To sum up, based on modern mechanical design technology, computer technology and automatic control technology, it is of practical significance to develop a simple, low-cost and high-precision manipulator for small and medium enterprises.

2. State of the art

Servo control technology is a technique that can effectively track and control the position, speed and acceleration of moving object [7]. The servo system is able to track incoming instructions and perform actions. Therefore, it has higher control accuracy. In the process of industrial production, people pay more and more attention to the requirement of accuracy. Today, many electromechanical devices have servo control functions, such as high-precision manipulator, robot, and finishing lathe and so on [8]. The type of servo control system is numerous and the structure is different. From the point of view of automatic control principle, the servo control system usually includes five parts: controller, controlled object, execution link, comparison link and detection link. The component diagram of the servo system is shown in Fig. 1.

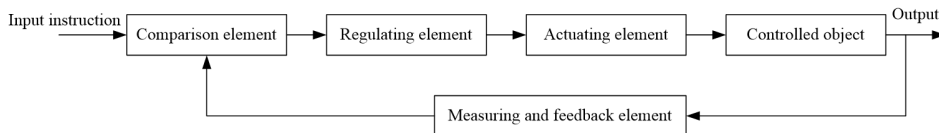


Fig. 1. Schematic diagram of the composition of the servo system

The servo system generally has good dynamic and static performance. Most of the movement of the actuator is driven directly by the motor or indirectly through the transmission mechanism. In order to ensure the accuracy of the positioning of the moving parts, the servo system needs a very high positioning accuracy. In the process of moving the mechanical parts, it is often necessary to control or adjust the speed of the moving unit. Therefore, a high-precision servo system also needs to have better speed and anti-disturbance ability. For the control performance of the servo control system, the speed range and the torque output at low speed need to be considered. The speed range R_N refers to the servo motor which can provide the

ratio of the maximum speed R_{\max} and the minimum speed R_{\min} .

In order to simplify the analysis, the permanent magnet synchronous motor is modeled on the following assumptions:

- (1) Ignored is the core saturation effect.
- (2) Air gap magnetic field has the sinusoidal distribution.
- (3) Eddy currents and hysteresis losses are not considered.

The voltage equations of the permanent magnet synchronous motor in the three-phase stationary coordinate $u - v - w$ can be written in the form

$$\begin{pmatrix} u_u \\ u_v \\ u_w \end{pmatrix} = \begin{pmatrix} R_a + PL_u & PM_{uv} & PM_{wu} \\ PM_{uv} & R_a + PL_v & PM_{vw} \\ PM_{wu} & PM_{vw} & R_a + PL_w \end{pmatrix} \begin{pmatrix} i_u \\ i_v \\ i_w \end{pmatrix} + \begin{pmatrix} e_u \\ e_v \\ e_w \end{pmatrix}. \quad (1)$$

In formula (1), u_u, u_v, u_w are the stator voltages. Quantities i_u, i_v, i_w are the phase stator currents. Symbols e_u, e_v, e_w denote the permanent magnet magnetic field in the u, v, w phase armature winding induced electromotive force. Quantity P is the differential operator, and R_a is the stator winding resistance. Symbols L_u, L_v, L_w are the stator winding self-inductances and M_{uv}, M_{vw}, M_{wu} are the mutual inductances between the windings.

The d -axis of the two-phase synchronous coordinate system is the same as the u -axis of the three-phase stationary coordinate system, that is, the direction of the d -axis and the direction of the fundamental magnetic field of the permanent magnet are the same. According to the transformation matrix, it can be changed from the three-phase stationary coordinate system $u - v - w$ to the rotation coordinate system $d - q$, and the transformation matrix is

$$[C] = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos \theta & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta + \frac{2}{3}\pi) \\ -\sin \theta & -\sin(\theta - \frac{2}{3}\pi) & -\sin(\theta + \frac{2}{3}\pi) \end{pmatrix}. \quad (2)$$

By using the above transformation matrix, the voltage equation in the d - q rotating coordinate system can be obtained, as shown in the following equation:

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = \begin{pmatrix} R_a + PL_d & -\omega L_q \\ \omega L_d & R_a + PL_q \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} + \begin{pmatrix} 0 \\ \omega \psi_f \end{pmatrix}. \quad (3)$$

In formula (3), u_d, u_q are the stator currents in axes d and q , i_d, i_q are the phase stator currents and L_d, L_q are the stator winding self-inductances.

The electromagnetic torque can be expressed by the sum of the product of the permanent magnet flux linkage and the armature winding current. According to the coordinate transformation process, the expression of the electromagnetic torque can be obtained in the form

$$T_e = P_n [\psi_f i_q + (L_d - L_q) i_d i_q]. \quad (4)$$

Finally, the equation of motion of the system is

$$\frac{J}{P_n} \frac{d\omega}{dt} = T_e - T_L - B\omega. \quad (5)$$

Here, T_L is the load torque, J is the moment of inertia of the system, and B is the viscous friction coefficient.

3. Methodology

3.1. PID control and fuzzy control

In the continuous system control theory, PID controller is the most mature and most widely used control mode [9]. The feedback control used by the general PID plays a controlling role in the ratio, integral and differential of the deviation. The PID controller usually contains three parameters, which are K_p , T_i , and T_d . They represent the scale factor, integral time constant and differential time constant, respectively. By adjusting the K_p , T_i , and T_d , three parameters can change the output of the controller, it allows the output of the system to follow the input changes, in order to achieve the system performance requirements.

In continuous systems, the relationship between the output $u(t)$ of the PID controller and the input $e(t)$ is

$$\begin{aligned} u(t) &= K_p \left[e(t) + \frac{1}{T_i} \int e(t) dt + T_d \frac{de(t)}{dt} \right] = \\ &= K_p \left[e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \right]. \end{aligned} \quad (6)$$

In the upper form, $e(t) = r(t) - y(t)$, supposing that the value $r(t)$ is the measured deviation, K_p is the proportional gain, T_i is the integral time constant, T_d is the differential time constant, K_i is the integral gain, and K_d is the differential gain.

Fuzzy control is a new type of controller, which has the advantage of allowing the mathematical model of the controlled object to be biased against the actual model. As the core of the control system, fuzzy controller can be divided into four parts: fuzzification, knowledge base, fuzzy reasoning and defuzzification.

Fuzzification refers to the precise value of the input quantity of the control system [10]. By fuzzy quantification, the fuzzy variable value is transformed into corresponding fuzzy value. This transformation is done by the corresponding membership function. That is, the input space is divided into several fuzzy domain sets. By defining the membership function on the set of fuzzy sets, the input variables are mapped to the corresponding values in the fuzzy domain, and the exact quantities are transformed into fuzzy quantities.

The knowledge base has specific knowledge about the control domain. It consists of two parts: database and rule base. The database mainly has the membership function and quantization factor of the corresponding fuzzy language and the division

of the fuzzy domain. The rule base mainly includes a series of fuzzy control rules, that is, "if... then..." form; they represent the embodiment of expert control experience.

The fuzzy reasoning is the core part of fuzzy controller. The reasoning process is based on fuzzy logic and control rules. In general, it is described in the form of "If A and B, then C". According to the fuzzy rules, the input variables are analyzed synthetically. An output in vague language is obtained.

At present, the common method of fuzzy reasoning is Mamdani's max-min synthesis method. The details are as follows: $A_i \times B_i \times C_i$ in the fuzzy rule base is treated as a collection on the X , Y , and Z domains, respectively. The relationship between the control rules is

$$\mu_{R_i}(X, Y, Z) = \mu_{A_i}(x_i) \wedge \mu_{B_i}(y_i) \wedge \mu_{C_i}(z_i) \quad \forall x \in X, \forall y \in Y, \forall z \in Z. \quad (7)$$

Then, the fuzzy relation of all fuzzy rules is: $R = \bigcup_{i=1}^n R_i$.

The membership function of R is $\mu_{R_i}(X, Y, Z) = \bigvee_{i=1}^n (\mu_{R_i}(X, Y, Z))$.

When the input variables E and EC become fuzzy sets A and B , respectively, the control quantity U can be obtained according to the lower form $U = (A \times B) \circ R$.

The membership function of U is

$$\mu_U(Z) = \bigvee_{\substack{x \in X \\ y \in Y}} \mu_R(X, Y, Z) \wedge [\mu_A(x) \wedge \mu_B(y)] \quad (8)$$

The defuzzification is the output link of fuzzy system. Its function is to convert the fuzzy output from fuzzy inference into accurate value. It contains two parts: scale mapping and defuzzification. The former converts the fuzzy output value into the exact value of the domain by defuzzification. The latter converts the exact values within the domain into actual control values.

3.2. Design of PI controller and fuzzy controller

Speed current double closed loop control is usually used in permanent magnet synchronous motor servo control system. As an inner loop, the action of the current loop is to cause the current to follow a given change. The current loop adopts PI controller. The given input of the current loop is the output of the speed ring. As a result, the transfer functions from the current setpoint i_q^* to i_q can be calculated:

$$G_1(s) = \frac{i_q(s)}{i_q^*(s)} = \frac{\frac{K_{cp}}{L_a} s + \frac{K_{ci}}{L_a}}{s^2 + \frac{K_{cp} + R_a}{L_a} s + \frac{K_{ci}}{L_a}}. \quad (9)$$

The current loop is mainly based on following performance. Therefore, the current loop transfer function is designed as the first order inertial link, that is, $G_1(s) = 1/(T_0 s + 1)$. Symbol T_0 is a time constant. By calculation, the gains of PI

controller K_{cp}, K_{ci} can be obtained:

$$K_{cp} = \frac{L_a}{T_0}, \quad K_{ci} = \frac{R_a}{T_0}. \quad (10)$$

A fuzzy controller with two inputs and one output is designed for the speed loop by fuzzy control. The error E and the error change rate EC are used as inputs to the fuzzy controller, and the U is the output of the fuzzy controller. The error E , the error rate EC and the output U are divided into 7 grades. The scope of the domain is -5.5 . The language fuzzy subset definition is NB NM NS ZE PS PM PB. The membership function of input E and EC is triangular, and the membership function of output U is Gaussian. According to the controlled object characteristics, the fuzzy control rules are shown in Table 1.

Table 1. Fuzzy variable rules

	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	PS
NM	NB	NB	NM	NS	NS	NS	PS
NS	NB	NM	NS	NS	ZE	ZE	PM
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	ZE	ZE	PS	PS	PM	PB
PM	NS	PS	PS	PS	PM	PB	PB
PB	NS	PS	PS	PM	PB	PB	PB

3.3. The design of disturbance observer

Fuzzy control belongs to nonlinear control. It can achieve better control without the accurate mathematical model of the controlled object. However, the influence of load perturbation TL on the system is not considered before design, and viscous friction is neglected. When the control system is disturbed by disturbances, the steady-state performance of the system will decrease, resulting in greater steady-state error and fluctuation of speed. In this experiment, the disturbance observer is used to compensate the disturbance rejection capability of the fuzzy controller. The disturbance observer can estimate the non measurable disturbance from the measurable information of the system, and then generate a torque current compensation. The i_q^* is modified in advance, so as to improve the anti-interference ability of the system. The block diagram of the disturbance observer is shown in Fig. 2.

In the figure, the upper part of the dashed box is the motor body model. Quantity $G_n(s) = 1/(Js + B)$ is the nominal model. $G_n^{-1}(s)$ is the inverse of the nominal model. The input of the disturbance observer is the measured value of the speed and current signals. When the load of permanent magnet synchronous motor is changed and the disturbance of the system friction torque is affected, the transfer function of the nominal model is

$$G_n(s) = 1/(J_1s + B_1). \quad (11)$$

Among them, J_1 is the system equivalent moment of inertia, and B_1 is the

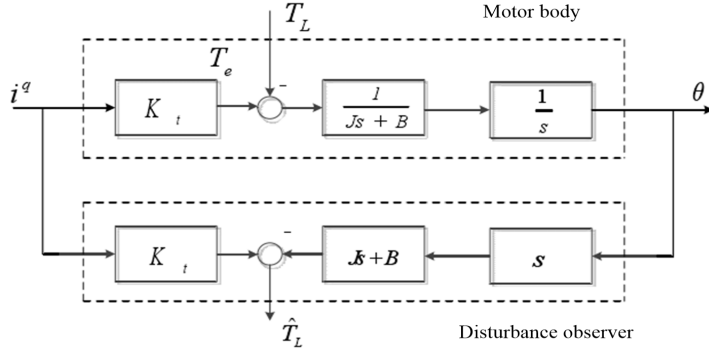


Fig. 2. The principle of disturbance observer

equivalent friction coefficient.

In the process of design, in order to reduce the speed measurement error of the motor, and the influence of the factors such as the current sensor measurement accuracy limit and the CPU calculation error, the filter link needs to be introduced. According to the function and design method of filter, the general form of filter $Q(s)$ can be obtained

$$G(s) = \frac{1 + \sum_{m=1}^{n_q-p_q} f_m s^m}{1 + \sum_{m=1}^{n_q} f_m s^m}. \quad (12)$$

Here, n_q is the order of $Q(s)$, and p_q is the relative degree of $Q(s)$. The relative order of the actual model and the nominal model can be obtained by formula (13). The filter $Q(s)$ must meet the condition of $p_q \geq 1$. For general permanent magnet synchronous motor control systems, the load disturbances can be discretized, which are equivalent to step error disturbances. Therefore, the step disturbance error can be eliminated by only one integral operation. The $Q(s)$ is designed as a first-order low-pass filter form:

$$Q(s) = \frac{\omega}{s + \omega}. \quad (13)$$

In the formula, ω is the cutoff frequency of the low-pass filter. The cutoff frequency of the low-pass filter will directly affect the disturbance suppression capability of the system. In order to minimize the impact of perturbation on the system, and taking into account the stability of the system, the value of ω needs to take into account the appropriate value.

Combining the disturbance compensator, the current loop PI controller and the speed loop fuzzy controller, the permanent magnet synchronous motor servo system block diagram can be obtained, as shown in Fig. 3.

4. Result analysis and discussion

The motor parameters used in the simulation program are presented: the stator winding resistance $R_a = 2.875 \Omega$. Stator d phase and q phase winding inductances

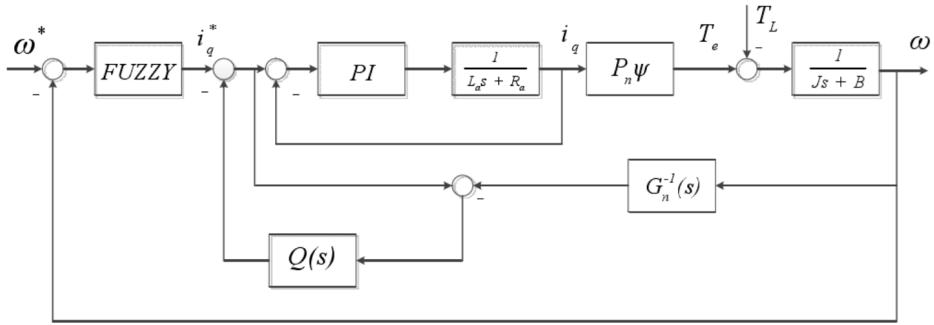


Fig. 3. Block diagram of permanent magnet synchronous motor based on fuzzy control and disturbance observer

$L_d = L_q = L_a = 0.0085$ H, $J = 0.0008$ kg m², the flux linkage amplitude $\Psi = 0.175$ Wb, the pole-pair number of the motor $P_n = 4$.

To illustrate the effect of FUZZY-DOB control, it is compared with the conventional fuzzy algorithm and the PI algorithm. In the four algorithms, the current loop of PMSM is controlled by conventional PI, and the parameters are the same. According to the principle of the first inner ring, the back outer ring, the current loop is selected, and the desired regulation time is 5 ms. Then, $t_s = 3T_0$, the parameters of the PI current controller $K_{cp} = 5.1$, and $K_{ci} = 1275$. The PI speed controller parameter is $K_{cp} = 0.15$, $K_{ci} = 0.6$. The speed controller based on the fuzzy algorithm is described as above. The disturbance observer parameter is: $J_1 = 0.001$ kg m², $B_1 = 0.003$ N m s/rad, and the filter cutoff frequency $\omega = 200$ rad/s. The simulation results are as follows. Figures 4, 5 and 6 show the comparison of the simulation curves of the four control algorithms. Tables 2 and 3 contain comparisons of specific data.

As shown in Fig. 4, when the given speed is 1000 rpm, the control system based on fuzzy control and disturbance observer is stable within 0.1 second. The steady-state error is 3 rpm. There is no overshoot. The overshoot of the PI controller is 8%, and the stability time is more than 0.3 seconds.

The system load response is added to the system at 1 second, and the speed response characteristic of the system is shown in Fig. 5. The local zoom diagram is shown in Fig. 6. The speed fluctuation of the control system is 20 rpm based on fuzzy control and disturbance observer. Within 0.05 seconds, it can recover to its initial speed. The disturbance of the control system is 50 rpm based on the PI controller and disturbance observer. The speed fluctuation of the control system without disturbance observer is 140 rpm, and the regulation time is longer.

5. Conclusion

Firstly, the electric servo drive technology is briefly introduced, and the PID control and fuzzy control principle are summarized. On the basis of analyzing the mathematical model of permanent magnet synchronous motor (PMSM), the current

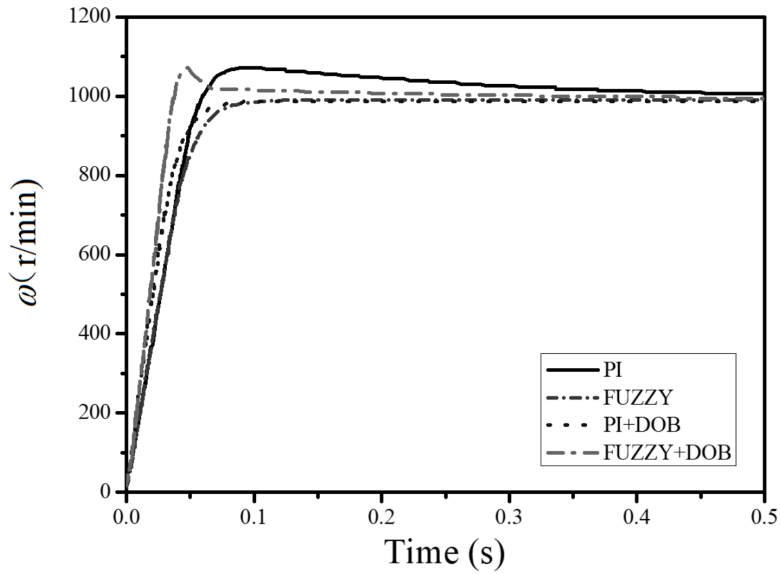


Fig. 4. Comparison of speed characteristic curves of four controllers

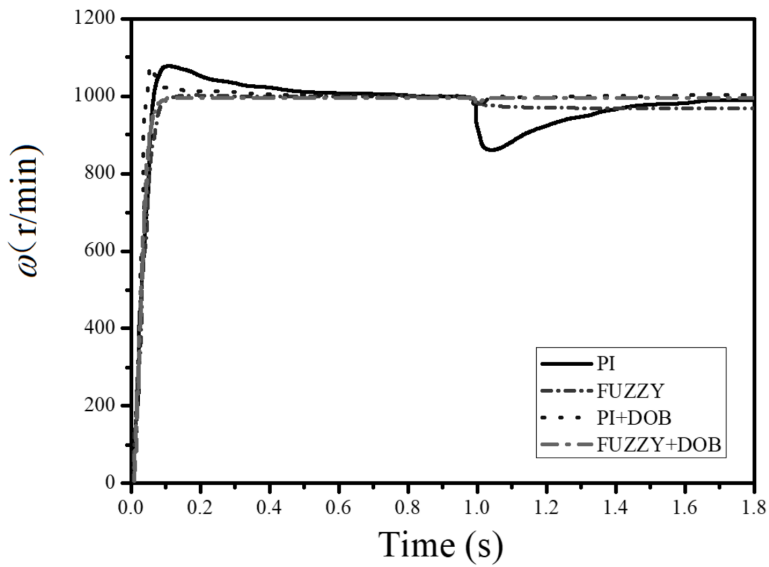


Fig. 5. Comparison of speed characteristic curves under sudden load

loop based on PI control and the speed loop based on fuzzy control are designed. Aiming at the problem of perturbation of servo control system, a double closed loop servo motor controller based on fuzzy control and disturbance observer is proposed. It effectively suppresses the impact of sudden disturbance on the system.

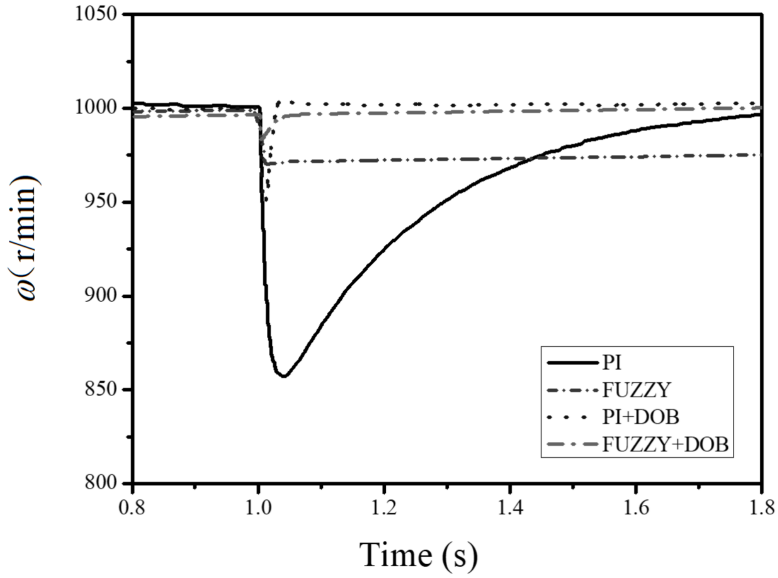


Fig. 6. Partial enlargement of speed characteristic curve during sudden loading

The simulation results show that the proposed control algorithm has good dynamic performance and steady-state performance. It not only provides a theoretical basis for the research of high performance control strategy of PMSM control system, but also provides a theoretical basis for high-precision positioning of robot manipulators.

Table 2. Comparison of four control algorithms

Control method	Rise time (s)	Regulation time (s)	Overshoot	Steady-state error
PI	0.036	0.221	8%	0
FUZZY	0.041	0.056	0	0
PI+DOB	0.018	0.047	8.5%	0
FUZZY+DOS	0.031	0.046	0	3

Table 3. Comparison of four control algorithms in disturbance change

Control method	Maximum velocity fluctuation (r/min)	Regulation time (s)
PI	142	0.94
FUZZY	27	Infinity
PI+DOB	52	0.30
FUZZY+DOS	13	.04

References

- [1] T. WINTHER, H. WILHITE: *An analysis of the household energy rebound effect from a practice perspective: Spatial and temporal dimensions*. Energy Efficiency 8 (2015), No. 3, 595–607.
- [2] K. G. CHAN, K. GURU, P. WIKLUND, J. CATTO, B. YUH, G. NOVARA, D. G. MURPHY, T. AL-TARTIR, J. W. COLLINS, A. ZHUMKHAWALA, T. G. WILSON, PASADENA CONSENSUS PANEL: *Robot-assisted radical cystectomy and urinary diversion: Technical recommendations from the Pasadena Consensus Panel*. European Urology 67 (2015), No. 3, 423–431.
- [3] P. BACKÉ, M. FELDKIRCHER, T. SLAČÍK: *Economic spillovers from the euro area to the CESEE region via the financial channel: A GVAR approach*. Focus on European Economic Integration (2013), No. 4, 50–64.
- [4] K. SALONITIS, L. D’ALVISE, B. SCHOINORITIS, D. CHANTZIS: *Additive manufacturing and post-processing simulation: Laser cladding followed by high speed machining*. International Journal of Advanced Manufacturing Technology 85 (2016), Nos. 9–12, 2401–2411.
- [5] K. SÖDERHOLM, P. SÖDERHOLM, H. HELENIUS, M. PETERSSON, R. VIKLUND, V. MASLOBOEV, T. MINGALEVA, V. PETROV: *Environmental regulation and competitiveness in the mining industry: Permitting processes with special focus on Finland, Sweden and Russia*. Resources Policy 43 (2015), 130–142.
- [6] R. MOREAU, M. T. PHAM, M. TAVAKOLI, M. Q. LE, T. REDARCE: *Sliding-mode bilateral teleoperation control design for master–slave pneumatic servo systems*. Control Engineering Practice 20 (2012), No. 6, 584–597.
- [7] X. WU, H. WANG, S. HUANG, K. HUANG, L. WANG: *Sensorless speed control with initial rotor position estimation for surface mounted permanent magnet synchronous motor drive in electric vehicles*. Energies 8 (2015), No. 10, 11030–11046.
- [8] S. HODGSON, M. TAVAKOLI, M. T. PHAM, A. LELEVE: *Nonlinear discontinuous dynamics averaging and PWM-based sliding control of solenoid-valve pneumatic actuators*. IEEE/ASME Transactions on Mechatronics 20 (2015), No. 2, 876–888.
- [9] D. TANG, L. CHEN, E. HU, Z. F. TIAN: *A novel actuator controller: Delivering a practical solution to realization of active-truss-based morphing wings*. IEEE Transactions on Industrial Electronics 63 (2016), No. 10, 6226–6237.
- [10] R. ERROUSSI, A. AL-DURRA, S. M. MUYEEN, S. LENG: *Continuous-time model predictive control of a permanent magnet synchronous motor drive with disturbance decoupling*. IET Electric Power Applications 11, (2017), No. 5, 697–706.

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