Research on fuzzy control of permanent magnet synchronous motor for a mobile robot

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Abstract: In this paper, a biped robot powered by permanent magnet synchronous motor (PMSM) is proposed, and each leg of the robot is a 6-degrees of freedom (DOF) parallel mechanism. Due to highly nonlinear characteristics of the leg structure, the conventional PID control strategy based on trial-error process cannot maintain the high performance of the PMSM. In order to improve the robustness of PMSM servo system and the dynamic stability of the robot, the PID controller based on fuzzy theory is developed. Fuzzy PID controller can improve the tracking accuracy and load rejection capability of PMSM, which makes the real-time system response faster without overshoot. The simulation results show that compared with conventional PID, fuzzy PID can reduce position tracking error of PMSM and deal with the external disturbance effectively.

1. Introduction

Recently, more and more researchers have focused on the research and problems related to mobile robots. Many robots, such as Atlas of Boston Dynamics and Cassie of Agility Robotics, already have excellent dynamic performance [1, 2]. However, for most biped robots, it is still very difficult and complex to walk stably on the flat surface, and the balance of biped robots has always been a challenging topic [3-5]. Robot structure has been studied by many scholars, where Atlas’s hydraulic power unit (HPU) and leg structure are made by 3D printing technology [6], Cassie’s leg is a four-bar mechanism [7]. Researchers also have done a lot on the control strategy of robot and the power system. Fuzzy control is an important branch of intelligent control, its important feature is that it can deal with the mathematical model of nonlinear system. Professor L.A. Zadeh was responsible for the theory and method of fuzzy control, who provided the basis for fuzzy control from 1965 to 1973 [8,9]. In 1974, E.H. Mamdani made the first fuzzy controller for steam engine [10,11], and then the fuzzy theory and application developed rapidly.

In the fields of robot and PMSM control, there are many application examples of fuzzy theory. Songkran kantawong developed a RFID dressing robot, the robot's body size could be adaptively reset with fuzzy controller [12]. T.A. Mai designed an adaptive fuzzy controller for a two-wheel-self-balancing robot, which would allow a more effective and robust control [13]. Chao, Fei et al. proposed a new robot control scheme based on fuzzy system and ant colony optimization algorithm, and the
stability of the adaptive fuzzy controller was proved by Laypunov theory [14]. Ouledali O presented a strategy of direct torque control of the PMSM with fuzzy comparator in controlled by space vector modulation [15]. Du L used a fuzzy PID control method for a dual axis turnable servo system to reflect the sun light [16]. M.Z.F.B.M. Zawawi compared PID and fuzzy logic controller for DC servo motor which used in lower extremity exoskeleton for rehabilitation [17]. In addition, S. Lu, S.N.M. Isa and others had studied fuzzy control of servo motor’s position loop, speed loop and current loop [18,19]; Deepa Bajpai had studied the effect of the size of rule-based of fuzzy control on PMSM control[20].

In this paper, a new biped robot is designed, and the PID parameters of PMSM servo system are calculated according to the robot modal analysis. The MATLAB simulation result shows that PMSM controlled by conventional PID cannot track the position command quickly and accurately, and the robot keeps continuous shaking in actual operation. To analyze and solve this problem, the text is expanded from the following parts: 1. According to the robot structure, the modal analysis under the specified state (the worst stiffness) of the robot is carried out, and the first order natural frequency of the robot is obtained; 2. Without considering the load effect, the position loop, speed loop and current loop PID controller parameters of PMSM are designed; 3. Design fuzzy PID controller for position loop and speed loop respectively; 4. Compare the command tracking accuracy and the ability of resisting external disturbance between fuzzy PID and conventional PID by MATLAB.

2. Robot structure and modal analysis

2.1. General structure of the robot

The biped robot is composed of two parallel mechanisms, including two legs and an upper platform. Since each leg has three support points which are far away from each other, the stability of the robot is excellent, as shown in Fig. 1. Every leg consists of the upper platform, a lower platform and 6 branches which are driven by PMSM and lead screw. By controlling the relative position relationship between the upper platform and the two lower platforms, various motions of the robot can be realized.

![Fig.1 Structure diagram of the robot](image)

Because the natural frequency of each link in the servo system has an important influence on the stability, accuracy and rapidity of the robot, in general, the structural natural frequency of the mechanical system should be 2-8 times higher than the frequency of the drive system [21], as shown in formula (1).

\[ f_{\text{min}} \geq (2 ~ 8) f \]  

where \( f_{\text{min}} \) is the minimum natural frequency of the robot, \( f \) is the frequency of the servo system.

2.2. Modal analysis of the robot

In the process of robot motion, it can be concluded that the farther the relative distance between the upper platform and lower platform of the leg is, the lower the first order natural frequency of the robot is. Therefore, taking the structure of the robot with two legs at the maximum length as the analysis object, the modal analysis is carried out. The three support points of leg 1 are fixed on the ground, and the first three natural frequencies of the robot are obtained, as shown in Fig. 2.

From Fig. 2, the first three modes of the robot can be obtained: the first mode and the second mode
are translational vibration in the horizontal plane; the third mode is torsional vibration of the leg around the center. It can be seen that \( f_3 \) is significantly higher than \( f_1 \) and \( f_2 \), which indicates that the translational stiffness of the robot leg is poor, so the servo bandwidth is mainly affected by \( f_1 \) and \( f_2 \), and \( f_1 \) is the criterion in the controller design.

Fig. 2 Modal analysis of the robot

3. Design of servo system controller

3.1. Design of PMSM conventional controller

The servo bandwidth of the robot drive system depends on the lowest natural frequency \( f_1 \). Firstly, the PMSM control system is established according to \( f_1 \) and the PMSM parameters, in which the position loop uses P control, the speed loop and the current loop use PI control. The structure of vector control PMSM is shown in Fig. 3, where APR, ASR and ACR are position regulator, speed regulator and current regulator respectively.

![Fig. 3 Block diagram of PMSM servo vector control system](image)

The main motor parameters are shown in Tab. 1.

| Tab. 1 PMSM parameters |   |
|------------------------|--|
| Rotor inertia(×10^4kg.m²) | \( J = 1.13 \) |
| Armature inductance(mH) | \( L = 3.53 \) |
| Torque constant(Nm/A) | \( K_t = 0.47 \) |
| Armature resistance(Ω) | \( R = 0.42 \) |
| Back EMF constant(Nm/A) | \( K_e = 0.32 \) |
| Friction coefficient(×10^6Nm/(rad/s)) | \( B = 3 \) |

According to equation (2), the PMSM control parameters are designed from current loop, speed loop and position loop without considering the load and disturbance.
\[\begin{align*}
\omega_p < \omega_s < \omega_c \\
\frac{1}{3} f_1 < f < \frac{2}{3} f_1 \\
\omega_p = 2 \pi f
\end{align*}\]  \hspace{0.5cm} (2)

where \(\omega_p\), \(\omega_s\), and \(\omega_c\) are the position loop bandwidth, speed loop bandwidth and current loop bandwidth of PMSM respectively. In the case of neglecting the friction effect (B), the control parameters of APR, ASR and ACR are designed and calculated, as shown in Tab. 2, where PC is proportional coefficient and IC is integral coefficient.

|               | PC of APR | \(K_p=10\) | PC of ASR | \(K_s=0.124\) | IC of ASR | \(K_{si}=21.27\) | PC of ACR | \(K_c=21\) | IC of ACR | \(K_{ci}=2500\) |
|---------------|-----------|-------------|-----------|---------------|-----------|----------------|-----------|-------------|-----------|----------------|

3.2. Mechanical transmission model

The coupling effect of each leg’s 6 branches is quite obvious in the robot movement, which means that the load \(T_L\) that ultimately acts on the PMSM rotor changes in a large range, and this is the reason why parameters designed in Tab. 2 do not consider the influence of \(T_L\). To analyze the performance of PMSM with \(T_L\) and adjust PID parameters, it is necessary to establish the mathematical model of PMSM and lead screw. PMSM rotor and the lead screw form a coaxial connection, and the deceleration ratio is 1. Ignoring the friction, clearance and other nonlinear factors, the transmission part is equivalent to a mathematical model mainly considering its stiffness, damping and moment of inertia, as shown in Fig. 4.

![Fig. 4 Mechanical transmission equivalent model](image)

When the PMSM rotates, there is a torque \(T_L\), which is the load torque for the motor and the drive torque for the load. Electromagnetic torque \(T_e\) and torque \(T_L\) act on the rotor with moment of inertia \(J\); \(T_r\) and load torque \(T_m\) act on the lead screw with moment of inertia \(J_L\) (\(J_L=1.59*10^{-5}\) Kg·m²). \(K_L\) (\(K_L=1005\) Nm/rad) is the rotational stiffness, \(C_L\) (\(C_L=0.088\) Nm/(rad/s)²) is the viscous damping coefficient. According to the equivalent model shown as Fig. 4, equation (3) can be obtained from the mechanical analysis.

\[\begin{align*}
J_L \ddot{\theta}_L + C_L \dot{\theta}_L &= T_L - T_m \\
T_L &= K_L (\theta_r - \theta_L)
\end{align*}\]  \hspace{0.5cm} (3)

The closed-loop transfer function of the PMSM and lead screw is obtained by using the Laplace transform of equation (3). Taking \(\theta_L\) as the system output, \(\theta_r\) as the system input and \(T_m\) as the disturbance input, the closed-loop transfer function is shown as equation (4).

\[G(s) = \frac{\theta_L}{\theta_r} = \frac{K_L}{J_L s^2 + C_L s + K_L}\]  \hspace{0.5cm} (4)

According to equation (3) and equation (4), the motion control model of PMSM and lead screw can be obtained as shown in Fig. 5.
3.3. Design of fuzzy PID controller

P control of APR can improve the dynamic response performance of PMSM position; the use of PI control in ASR is mainly to suppress the impact of load disturbance on the motor speed and improve the anti-interference ability of the system. However, the effect of CPID controller in the application of nonlinear time-varying system is not ideal, and the performance is very unstable due to the influence of load disturbance $T_L$. Therefore, in order to improve the tracking accuracy and stability of the servo system, fuzzy PID (FPID) controller is proposed. In the FPID controller, the fuzzy P control is designed for the position loop, the fuzzy PI control is designed for the speed loop, and the parameters of the current loop are not changed. According to the error $E$ of the controlled quantity and the error change rate $EC$, using the fuzzy rules to carry on the fuzzy inference, the fuzzy controller can output $\Delta K_p$, $\Delta K_i$, $\Delta K_d$. $\Delta K_p$, $\Delta K_i$, $\Delta K_d$ are respectively added to proportional coefficient, integral coefficient, and differential coefficient of CPID, the controller parameters are modified to meet the requirements of different $E$ and $EC$. Taking the speed loop as an example, after adding the fuzzy control algorithm to the PI control, the improved PI parameters are shown in equation (5).

$$\begin{aligned}
K'_s &= K_s + \Delta K_s \\
K'_{si} &= K_{si} + \Delta K_{si}
\end{aligned}$$ (5)

where $\Delta K_s$, $\Delta K_{si}$ are the increment of the ASR. When fuzzy controller is added to the ASR, the variables $\Delta K_s$, $\Delta K_{si}$ are improved in real time according to the control requirements, so that the PI parameters of the speed loop can be modified online. Through the same process, the P of APR can be adjusted.

When designing the fuzzy controllers, the fuzzy variables of the deviation of position loop and speed loop are marked as $EP$, $ES$ respectively, the deviation variation corresponding to $EP$ and $ES$ is marked as $EPC$ and $ESC$. The membership functions of $EP$, $ES$, $EPC$ and $ESC$ are the same, as shown in Fig. 6.

The output control quantity of the position fuzzy controller is only one $\Delta K_p$, while the output of the speed fuzzy controller is two respectively proportional control quantity $\Delta K_s$ and integral control quantity $\Delta K_{si}$. The domain and membership function are shown in Fig. 7.

The input-output mapping of fuzzy control adopts the following form of fuzzy implicit relation: IF $\mathcal{A}$ and $\mathcal{B}$ THEN reasoning $\mathcal{C}$ and $\mathcal{D}$. The center of gravity method is used for defuzzification, the 3D surface viewer of fuzzy controller shown in Fig. 8(a), (b) can be viewed to get a perspective of rules.
4. Simulation and analysis

The model of CPID controller is built in MATLAB, as shown in Fig. 9(a), when the model of FPID controller is shown in Fig. 9(b). The quantization factors of position loop fuzzy controller are marked as \( K_{ep}, K_{cp}, \) and the scale factor is marked as \( K_{up} \); the quantization factors of speed loop fuzzy controller is marked as \( K_{es}, K_{csi}, \) and the quantization factors are marked as \( K_{us}, K_{usi}. \)

In the case of no load, the response of each controller to the position step signal \( \theta_{ref} (\theta_{ref}=1 \text{rad}) \) is compared, as shown in Fig. 10(a). And \( \theta_{ref} = \theta_{o} \sin(2\pi ft) \) is given as a continuous signal, where the amplitude \( \theta_{o} = 5 \text{rad}, f = 0.5 \text{Hz}, \) the response are observed as shown in Fig. 10(b).
that for the sinusoidal signal with a frequency of 0.5Hz, at the first peak, the CPID has a phase lag of 0.098s and an amplitude deviation of 0.19rad (attenuation of 3.8%), and the FPID are 0.045s and 0.04rad (attenuation of 0.8%) relatively. **Fig. 10(a)** and **Fig. 10(b)** illustrate that FPID is able to not only improve the transient response performance of the system, but also track the continuous position instructions with higher accuracy.

**Fig. 11(a)** shows the position step response of CPID and FPID control system with load disturbance $T_m = 1\text{Nm}$ at $t = 0.5s$, while in **Fig. 11(b)** $T_m = T_0 \sin(2\pi f_1 t)$, $T_0 = 0.2\text{Nm}$, $f_1 = 5.93\text{Hz}$.

From **Fig. 11(a)** and **Fig. 11(b)** it can be concluded that FPID control system is much more robust to the load interference compared with the CPID. This means that FPID is able to make the system more stable when the robot legs are subjected to instantaneous external force or there is continuous and serious coupling force in the motion. In the other aspect, the coupling effect brings heavy load disturbance to PMSM, and the CPID is not able to adjust PMSM to reach the designated position and maintain stability. PMSM's continuous regulation, in turn, will strengthen the coupling effect, resulting in the deterioration of mechanical system and control system performance.

5. **Summary**

In this paper, a new type robot is designed firstly, and then the conventional controller is designed according to the robot modal analysis and PMSM parameters. Next, in order to analyze the influence of load on PMSM, the model of PMSM and lead screw is established. It is found that robustness of the CPID controller is poor and CPID controller may cause robot vibration. To solve this problem, a FPID controller is designed and applied to realize the real-time adjustment of PID parameters. The simulation shows that the FPID control strategy can adjust parameters online according to the error and error change rate, improve the response speed of PMSM and effectively restrain the effect of load change. FPID controller is suitable to adjust the servo system to be a control system with fast response, no overshoot and strong robustness.

**Acknowledgments:**

Defense Industrial Technology Development Program (JCKY2019411B001).

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