Design of Permanent Magnet Synchronous Motor Power-assisted System Based on Field Oriented Control Algorithm

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Abstract. Aiming at the integrated surgical robot, a set of power-assisted control system is designed to overcome the transmission resistance between master and slave hands, so that the operator feels light and comfortable during operation. The system includes permanent magnet synchronous motor, driver, controller, torque sensor, upper computer. The field oriented control algorithm is discussed and is used to control the permanent magnet synchronous motor. STM32 is used as the main control chip, DRV8301 is used as the driving chip, and the upper computer software, which has human-computer interaction interface and real-time torque signal display interface, is written by C#. A non-contact torque sensor and corresponding signal processing module is designed. The experimental results show that with the operator's start-stop and reversing action, the q-axis current of the motor changes rapidly, and the amplitude of steady-state changes is small. This means that the designed system has the advantages of stable assist torque and fast response.

1. Introduction
With the development of minimally invasive surgery technology and robotics, surgical robots are becoming more and more popular, the number of operations performed by surgical robots is increasing at a rate of 15% each year [1]. Using surgical robots for surgery has the advantages of small wounds and short recovery cycles [2]. Unlike the master-slave separation surgical robot, the master hand and slave hand of the integrated surgical robot are connected by mechanical transmission parts. The integrated surgical robot has the advantages of simpler control and low cost. However, due to the existence of transmission resistance, the operator is prone to fatigue. Therefore, a power-assisted system is needed to help the operator overcome the transmission resistance. The electric power assist system is usually composed of sensors, controllers, power assist motors, etc. A typical example is the power-assisted steering system on a car [3]. The power-assisted system should respond quickly, output smoothly, follow the assistant movement without affecting the operating feel [4]. Permanent magnet synchronous motor (PMSM) is widely used in mechanical processing, medical machinery and other fields because of its simple structure, high reliability, high efficiency and high power density. The field oriented control (FOC) is also called vector control. Through coordinate transformation and space vector pulse width modulation (SVPWM), the three-phase current control of the motor is equivalent to the rotating two-phase current, which reduces the complexity of the control and has the advantages of stable torque, low noise, high efficiency and fast dynamic response [5]. In this paper,
the PMSM is used as the robot assist motor, and the control strategy is field oriented control. The purpose is to control the motor to output stable assist torque, and can respond quickly to operator actions.

2. Control Algorithm of Permanent Magnet Synchronous Motor

2.1. Mathematical Model of PMSM

In order to simplify the complexity of the model, some factors that have little effect should be ignored, and the following assumptions should be made when establishing the model [6]:

(1) The stator three-phase windings are exactly the same, and the stator current is a sine wave, and the electrical angle between the three is 120°;

(2) The saturation of magnetic circuit is not considered, the self-inductance and mutual inductance between windings are considered to be equal;

(3) Ignoring the magnetic flux leakage effect, ignoring the eddy current effect, the core permeability coefficient is constant;

(4) Ignoring environmental impacts such as temperature changes.

Based on the above assumptions, the voltage equation of permanent magnet synchronous motor in three-phase coordinate system is:

\[
\begin{bmatrix}
    u_A \\
    u_B \\
    u_C \\
\end{bmatrix} = \begin{bmatrix} R_S & & \\
                        & R_S & \\
                        & & R_S \\
\end{bmatrix} \begin{bmatrix} i_A \\
                             i_B \\
                             i_C \\
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_A \\
                                         \psi_B \\
                                         \psi_C \\
\end{bmatrix}
\]

(1)

where \(u_A, u_B, u_C\) are the phase voltage of the three-phase winding, \(R_S\) is the resistance of the three-phase stator winding, and \(i_A, i_B, i_C\) are the three-phase stator currents, respectively. \(\psi_A, \psi_B, \psi_C\) are the full magnetic chains of three-phase stator winding, respectively, and their expressions are as follows:

\[
\begin{bmatrix} \psi_A \\
                 \psi_B \\
                 \psi_C \\
\end{bmatrix} = \begin{bmatrix} L_{AA} & M_{AB} & M_{AC} \\
                               M_{BA} & L_{BB} & M_{BC} \\
                               M_{CA} & M_{CB} & L_{CC} \\
\end{bmatrix} \begin{bmatrix} i_A \\
                             i_B \\
                             i_C \\
\end{bmatrix} + \begin{bmatrix} \psi_{fA} \\
                                    \psi_{fB} \\
                                    \psi_{fC} \\
\end{bmatrix}
\]

(2)

According to the assumption, the stator winding self-inductance is equal, namely \(L_{AA} = L_{BB} = L_{CC}\), the mutual inductance between windings is equal, namely \(M_{AB} = M_{BA}, M_{AC} = M_{CA}, M_{CB} = M_{BC}\). \(\psi_{fA}, \psi_{fB}, \psi_{fC}\) are the cross chain between stator winding and rotor flux linkage.

The motor torque equation is:

\[
T_e = -P_m \psi_f \left[ i_A \sin \theta_e + i_B \sin \left( \theta_e - \frac{2}{3} \pi \right) + i_C \sin \left( \theta_e + \frac{2}{3} \pi \right) \right]
\]

(3)

where \(P_m\) is the pole pair number of the motor, \(\psi_f\) is the rotor linkage, \(\theta_e\) is the rotor mechanical angle.

\[
\psi_f = \frac{10 \sqrt{6}}{\pi P_m} K_e
\]

(4)

where \(K_e\) donates the back electro-motive force (EMF) coefficient of the motor.

The motor motion equation is
where $T_e$ donates the electromagnetic torque, $B$ is the coefficient of viscosity, $J$ is the rotor inertia, $\omega_e$ is mechanical angular velocity, $T_L$ donates the load torque.

2.2. Principle of FOC Algorithm

The principle is that the torque current and excitation current, namely, the cross-axis current and the straight-axis current are obtained by series coordinate transformation of the sampled three-phase current. Compared with the specified cross-axis current and the straight-axis current, six PWM waves are obtained after PI control module, inverse Parker transform and space vector pulse width modulation algorithm. PWM drives the motor through three-phase inverter module. The FOC principle of current loop and speed loop is shown in figure 1.

![Figure 1. FOC principle of current loop and speed loop.](image1)

In figure 1, the Clark transform transforms the three-phase current component into a stationary two-phase coordinate system. The constant amplitude conversion formula is as follows:

$$
\begin{bmatrix}
    i_d \\
    i_q \\
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\
    0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
\end{bmatrix}
$$

(6)

The Parker transformation rotates the $\alpha$-$\beta$ coordinate system to $\theta$ degrees, $\theta$ is the current rotor's electrical angle, as shown in the figure below:

![Figure 2. Park Transformation.](image2)

The formula is as follows:
The orthogonal d-q coordinate system, which rotates with the rotor, is obtained by Park transformation, and the decoupling control of excitation current and torque current is realized. The voltage Parker inverse transformation formula in figure 1 is:

\[
\begin{bmatrix}
U_a \\
U_b \\
U_c
\end{bmatrix} =
\begin{bmatrix}
\cos \vartheta & -\sin \vartheta \\
\sin \vartheta & \cos \vartheta
\end{bmatrix}
\begin{bmatrix}
U_d \\
U_q
\end{bmatrix}
\]

(8)

Combining formula (5) and formula (6) obtains:

\[
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} =
\frac{2}{3}
\begin{bmatrix}
\cos \vartheta & -\cos \left(\vartheta + \frac{\pi}{3}\right) & -\cos \left(\vartheta - \frac{\pi}{3}\right) \\
-\sin \vartheta & \sin \left(\vartheta + \frac{\pi}{3}\right) & \sin \left(\vartheta - \frac{\pi}{3}\right)
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_b \\
i_c
\end{bmatrix}
\]

(9)

Electromagnetic torque equation in d-q coordinate system is:

\[
T_e = \frac{3}{2} P_m \left(\psi_d i_q - \psi_q i_d\right) = \frac{3}{2} P_m \left[\psi_d i_q + (L_d - L_q) i_d i_q\right]
\]

(10)

where $\psi_d$ and $\psi_q$ are d-axis stator flux linkage and q-axis stator flux linkage respectively, $i_q$ and $i_d$ are current of d-axis current and q-axis respectively, $L_d$ and $L_q$ are inductance of d-axis and q-axis respectively. This system uses surface-mounted PMSM, the salient pole effect of the motor can be ignored, $L_d = L_q$, the electromagnetic torque equation can be further simplified as:

\[
T_e = \frac{3}{2} P_m \psi_d i_q
\]

(11)

The space vector pulse width modulation (SVPWM) algorithm is an algorithm that uses PWM pulses to control the on and off of the switching devices of the three-phase inverter bridge. It can obtain a circular magnetic field from the three-phase current of the motor stator, which can effectively improve the utilization rate of the bus voltage [7]. The specific implementation process will not be repeated here.

3. Control system construction

3.1. Principle of Control System

The overall workflow of the integrated surgical robot power-assisted system is shown in the figure below:
The torque sensor is used to detect hand movements. When the operator moves, the output voltage of the torque sensor becomes larger or smaller (depending on the direction). When the change value is greater than the threshold, the upper computer sends out an action command to the controller, and the controller performs calculations according to the pre-designed algorithm, outputs PWM waves to the driver, and the driver drives the motor to run.

3.2. Torque sensor

This system uses a non-contact torque sensor as shown in the figure below:

![Non-contact torque sensor](image)

1-Magnetic isolation sleeve  2-coil  3-coil sleeve  4-torsion bar  5-input shaft

Figure 4. Non-contact torque sensor.

One end of the torsion bar is connected with the input shaft, and the other end is connected with the output shaft. The master hand action drives the input shaft to rotate. The input shaft and the output shaft rotate relative to each other, and the torsion bar is twisted to a certain angle. The tooth-like protrusions on the outer periphery of the input shaft are exposed from the grid of the magnetic isolation sleeve, and the inductance of the coil is changed. After the circuit is processed, the output voltage and the circuit processing process are shown in the following figure:
This system uses stm32f407 to receive the torque sensor signal, and use extreme-value-removed mean filtering method to remove the disturbance data.

3.3. Controller and driver
This system chooses Odrive FOC driver board. The controller is stm32F405, this chip is based on the high-performance Arm Cortex-M4 core, the operating frequency is up to 168 MHz. Contains high-speed embedded memory (flash memory up to one million bytes, 192 kb of SRAM), can run embedded operating systems, such as FreeRtos, is a high-performance motion controller.

The driver is the DRV8301 chip, which provides a three-phase half-bridge drive circuit, dual integrated current shunt amplifiers with adjustable gain and offset, programmable dead time control and overcurrent protection functions.

3.4. Upper computer software and communication
In the VS development environment, the upper computer software was developed using C#, and the human-computer interaction interface was designed. The main functions are: receive the torque sensor signal processed by stm32f407, issue control commands to Odrive according to the size of sensor signal, and use serial communication.
4. Experiment and the result
The physical parts of the assist system are shown in the following figures.

(a) PMSM.                             (b) Torque sensor.

(c) Sensor signal processing module.  (d) Controller and upper computer.

Figure 7. Experimental physical object.

The parameters of the PMSM used are shown in the following table.

| parameters                        | value   |
|-----------------------------------|---------|
| rated moment (N.m)                | 0.4     |
| number of pole pairs              | 4       |
| phase resistance (Ω)              | 1.02    |
| phase inductance (mH)             | 0.59    |
| back EMF coefficient (Vrms/krpm)  | 4.3     |

The experimental system is based on the transmission route of the actuator shuttle degree of freedom of the surgical robot. When the master hand shuttles back and forth repeatedly, the output current value of the motor q-axis read by the upper computer are shown in the following figure:
In this degree of freedom transmission chain, the resistance torque is about 0.9N.m, the gear ratio of the reducer is 1:20, so the motor output torque is set to 0.045N.m, namely, in formula (11), \( T_e = 0.045N.m \). Combine known parameters of the motor, \( T_e \), formula (4) and formula (11), we can get \( \psi_f = 0.00838V.s \), \( i_q = 0.895A \). It can be seen from figure 8, when the master moves in the opposite direction, the motor responds quickly, and it can maintain the specified torque output stably. Due to the influence of master movement, the output current of q-axis (torque) changes in a small range, it’s normal, it does not affect the power-assisted function and hand feel of the manipulator.

5. Conclusion
In this paper, a power-assisted system based on FOC algorithm is designed. The system provides power assistance for integrated surgical robot, which is composed of torque sensor, signal processing module, controller, driver, PMSM and upper computer. The designed system is installed on the integrated surgical robot for experiment, the experiment shows that the system responds quickly, can provide a stable torque, and has an obvious boosting effect.

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