

Design and implementation of a PMSM servo drive system applied to intelligent patrol robots

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Abstract. With the intelligent patrol robots become popular used in industrial places, the demands of their motor drive systems become much higher, especially in performance, efficiency and cost. In this paper, a permanent magnet synchronous motor (PMSM) servo drive system applied to intelligent patrol robots is designed. The motor drive system hardware circuit design is realized, and the software programming is based on the field orientated control (FOC) algorithm. The theory analysis and simulation are both carried out in this paper to evaluate the feasibility and performance of FOC algorithm used in the special hardware topology, and the experiment is also carried out to test the PMSM servo drive system performance. Both the simulation and experimental results shows the PMSM servo drive system has great dynamic and smooth performance.

1. Introduction

In recent years, as the rapid development of artificial intelligence technology, the intelligent patrol robots become widely used in substations, chemical plants and coal mines. Motor drive system as the core of the intelligent patrol robots is the key to complete patrol tasks in different conditions. Today, the mainstream motor drive systems used in patrol robots include brushed DC motor drive systems as Olson et al. designed in their patrol robot [1] and brushless DC motor drive systems [2-3]. However, although the brushed DC motor drive system has great advantages in reducing cost and control difficulty, the life of carbon brush and commutator constrict the whole service life of patrol robots. On the other hand, the traditional trapezoidal Back-Emf BLDC has the disadvantages in high torque ripple and noise [4], especially when the motor works in low-speed region. In this respect, this paper focus on designing a Permanent Magnet Synchronous Motor (PMSM) servo drive system applied to intelligent patrol robots. Compared with traditional patrol robots motor drive systems, it has great performance in reducing torque ripple, improving motor startup features and speed dynamic response.

2. The Motor Drive System Design

The design schematic diagram of the PMSM servo drive system is shown in figure 1, which consists of a permanent magnet synchronous motor, inverter circuit, drive circuit, sampling circuit, etc.



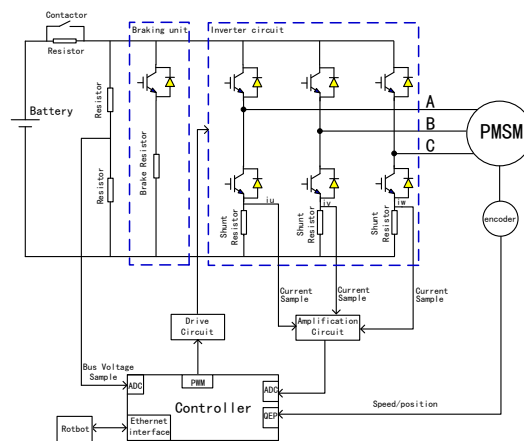


Figure 1. The schematic diagram of the PMSM servo drive system

2.1. Motor

Intelligent patrol robots are usually designed as two-wheel drive or four-wheel drive, and because of the limit of battery capacity, the single motor power of the robots usually ranges between 50W and 400W. The PMSM servo drive system designed in this paper adopts a DC48V 200W surface mounted PMSM, and the parameters of motor are shown in Table 1.

Table 1. Motor parameters

$R_{\text{phase}}(\Omega)$	$L_{\text{phase}}(\text{mH})$	Pairs	$K_e(\text{V/krpm})$	$T_n(\text{Nm})$	$r_n(\text{rpm})$
0.45	0.5	3	9	0.64	3000

2.2. Inverter and Drive Circuit

As shown in figure 1, the inverter circuit adopts the typical three-phase full bridge topology [4], which makes up of six MOSFETs. By overall evaluating the motor parameters, the MOSFET performance and the cost, the models of the inverter MOSFETs are all chosen as IRF540N, which is a popular model used in motor drive systems. Meanwhile, because IRF540N is a kind of N-channel MOSFET, in order to drive the three phases' MOSFETs, the bootstrap circuits are designed in this drive system. The typical one phase's bootstrap circuit used in the drive system is shown in figure 2, which is designed on the basis of the IR2110, and the other two phases' bootstrap circuits are the same with it. On the other hand, in order to complete voltage level conversion and electrical isolation between input PWM signals and output PWM signals, the high speed optical coupler circuits on the basis of TLP715 are also designed, as shown in Fig2.

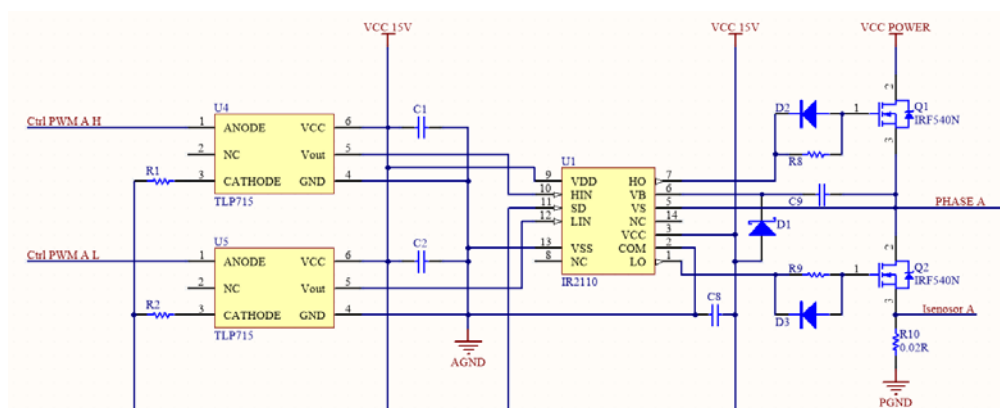


Figure 2. Inverter and drive circuit

2.3. Brake Unit Circuit

Because of the BEMF's existence, the bus voltage will be raised during the motor working in brake or slow down conditions, which will damage the battery. To solve this problem, the brake unit circuit is designed which is shown in figure 3. When the bus voltage is greater than the protection value, the MOSFET and transistors in figure 3 will be enabled for seconds, then the energy will be consumed in the braking resistor, and the bus voltage will be back to the normal value.

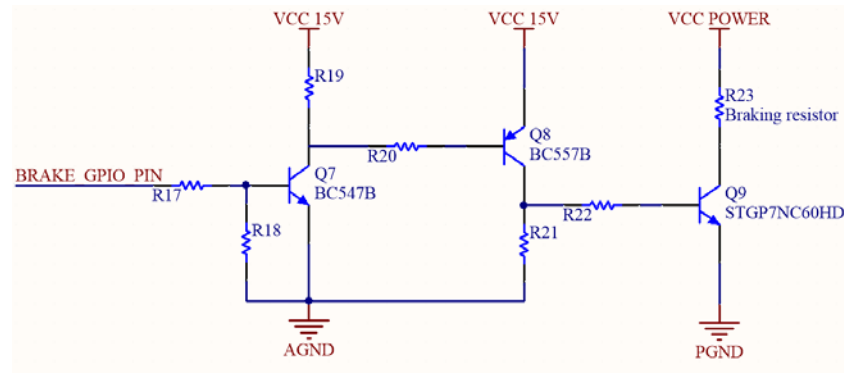


Figure 3. Brake unit circuit

2.4. Sampling Circuits

As shown in figure 1, the current sample circuit adopts the three shunt resistors topology, which has great advantage in saving cost compared with using current transformer. When the motor working, the phase current flows through the shunt resistor, the voltage will be generated and then amplified by the amplification circuit. The amplified signal will be inputted into the controller to complete A/D convert. The typical one phase current sample amplification circuit used in this drive system is shown in figure 4, and the other two phases' are the same with it.

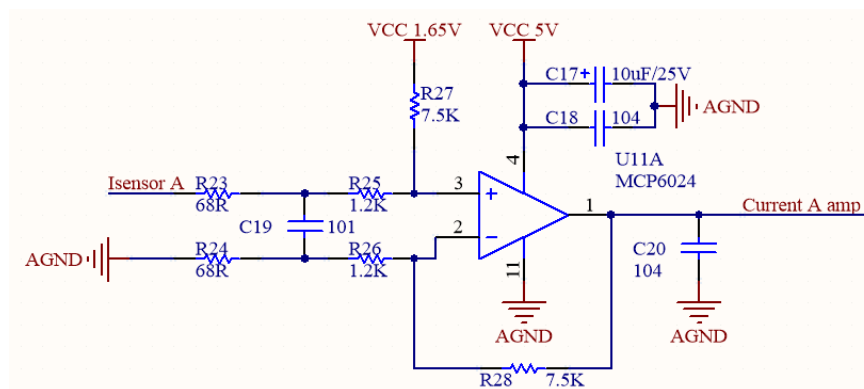


Figure 4. Amplification circuit

The bus voltage sample circuit is relative simple, which consists of two voltage division resistors, as shown in figure 1.

The 2500ppr encoder is used to complete motor speed and position detection in this motor drive system. Compared with other speed/position detection methods, it has much higher accuracy and stability.

2.5. The Controller

The controller as the core of the motor drive system is the key to implement control algorithm. By overall evaluating various controller models, the final choice used in this intelligent robot motor drive system is STM32F407 series processor. Compared with the common DSP+FPGA scheme, although

the process speed and sample frequency of the STM32F407 series processor is relative lower, it has great advantage in saving cost and rich peripheral interfaces. Meanwhile, the STM32F407 series processor is integrated with DSP instructions and floating point unit, which are enough for the robot motor control algorithm programming. Apart from the drive and detection function, the communication function of the controller is also important, in this PMSM drive system, the Ethernet communication is adopted, and the Ethernet interface circuit is designed as figure 5.

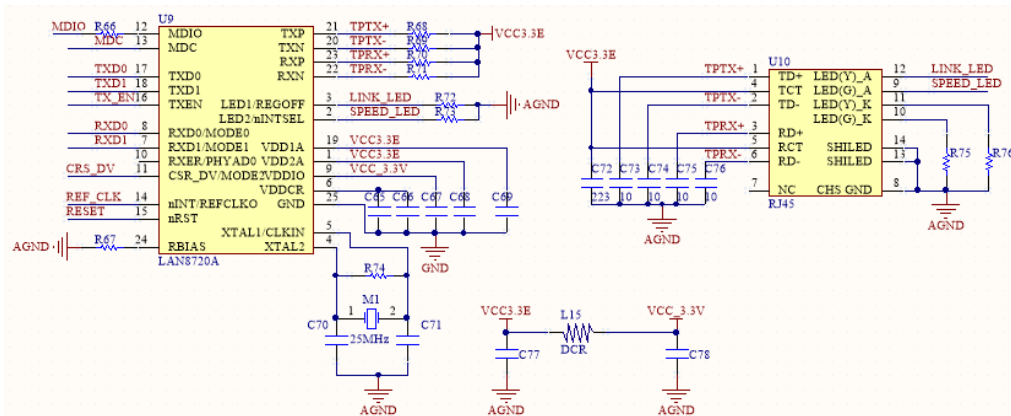


Figure 5. Ethernet communication circuit

3. FOC algorithm Analysis and Simulation

3.1. Theory Analysis

The software design of the PMSM servo drive system is based on field orientated control (FOC) algorithm [5]. FOC is an advanced control method that by controlling the two rotator currents perpendicular to each other i_d and i_q , which are mathematical transformed from the stator currents, makes control permanent magnet synchronous motor just like brushed DC motor. The FOC control schematic diagram used in this motor drive system is shown in figure 6.

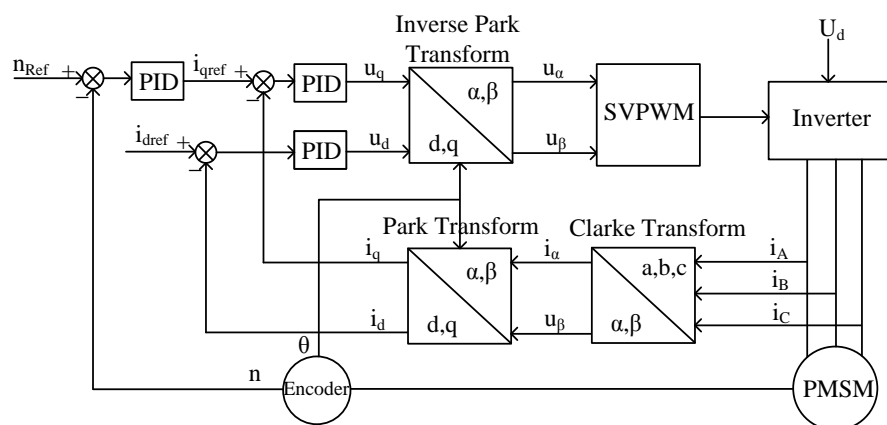


Figure 6. The schematic diagram of FOC algorithm

The first step in using FOC algorithm is to get the three phase currents i_A , i_B and i_C , and the relationship of them is shown in Eq. 1. For this motor drive system, the phase currents could be obtained by using the current sample circuits introduced in the last section.

$$i_A + i_B + i_C = 0 \quad (1)$$

As shown in figure 6, the stator currents i_α , i_β and rotator currents i_d , i_q could be derived from the

Clarke Transformation and Park Transformation after the phase currents are obtained[5]. The transformation equations are expressed as:

Clarke Transformation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (2)$$

Park Transformation:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

Here, the ϕ is the angel between the α axis and d axis, which could be calculated according to the encoder in this motor drive system.

Just like the brushed DC motor, the rotator currents i_d and i_q are vertical to each other, which could be controlled independently. The i_d is used to adjust the motor magnetic field, and the i_q is used to adjust the motor torque. As shown in figure 6, after the rotator currents i_d and i_q are derived, the errors between the rotator currents i_d , i_q and the reference currents i_{dref} , i_{qref} as the input signals of the PID controller would be converted into the rotator voltages u_d , u_q . Then the Inverse Park Transformation is used to convert u_d , u_q into the stator voltage u_α , u_β , which would be used as the input signals of the SVPWM module. After processed by the SVPWM method [6], the new PWM control signal would be generated to control the inverter circuit. The Inverse Park Transformation equation is expressed as the following:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4)$$

3.2. Simulation

Based on the FOC algorithm and combined with the hardware topology of the PMSM servo drive system introduced in the last section, the simulation is carried out in this paper. The motor drive system simulation diagram and the mathematic transformation simulation diagram are shown in figure7 and figure8.

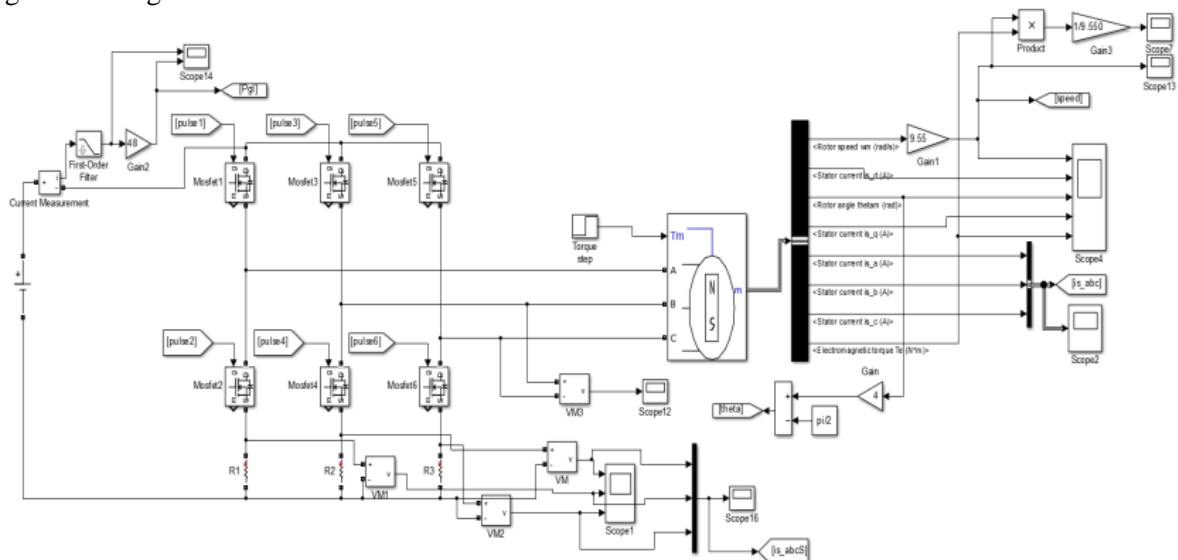


Figure 7. The simulation of the PMSM servo drive system

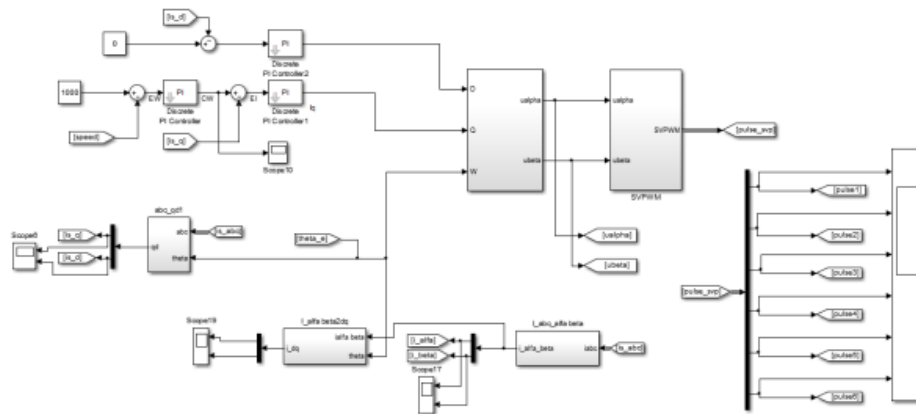


Figure 8. Transformation modules

The simulation results are shown in figure 9 and figure 10. In figure 9, the researched parameters from top to bottom are respectively rotor speed n , rotator current i_d , rotor angle φ , rotator current i_q and the electromagnetic torque T_m . In figure 10, the three phase currents i_A , i_B and i_C are watched. The simulation results show the measured stator current i_q traces the reference value fast, and the torque ripple is low. Meanwhile, the motor speed dynamic response is great, and the trace of speed in the steady state is also stable.

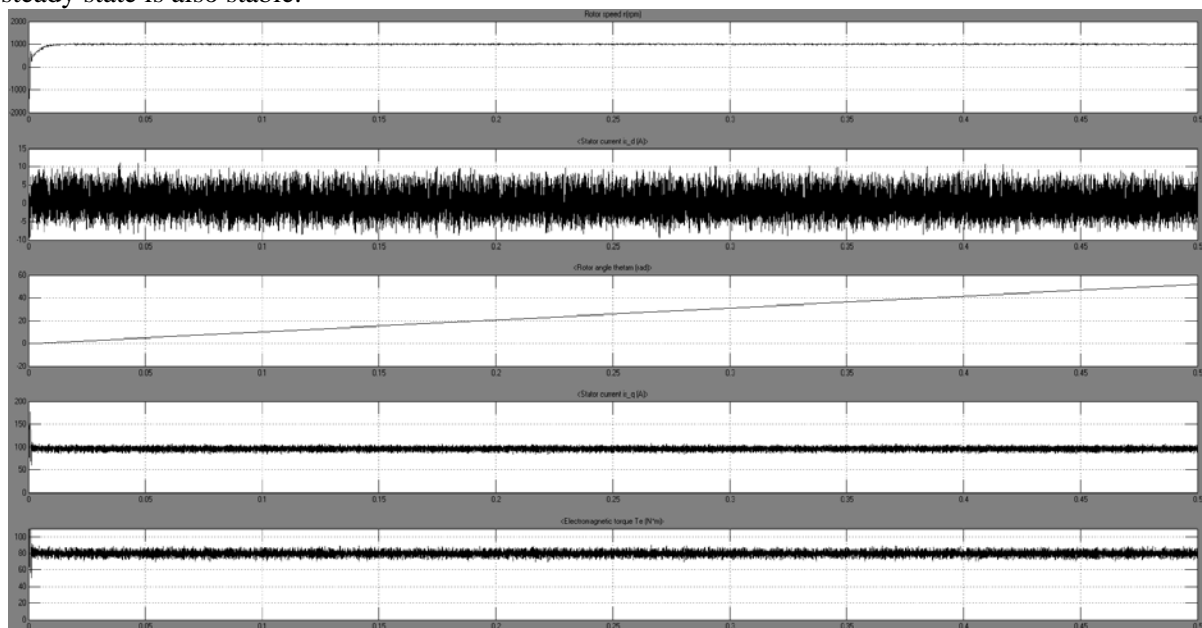


Figure 9. Simulation result 1

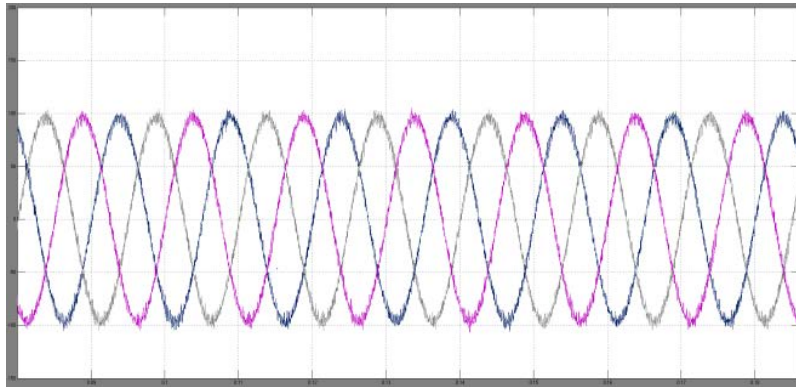


Figure 10. Simulation result 2

4. Experiment and Result

The experiment is carried out by using the typical hardware topology and FOC algorithm introduced in the last sections which is shown in figure 11. The speed step response result is shown in figure 12, it shows that the dynamic response of the motor speed is very fast, and the measured speed trace the reference speed accurately in the steady state.

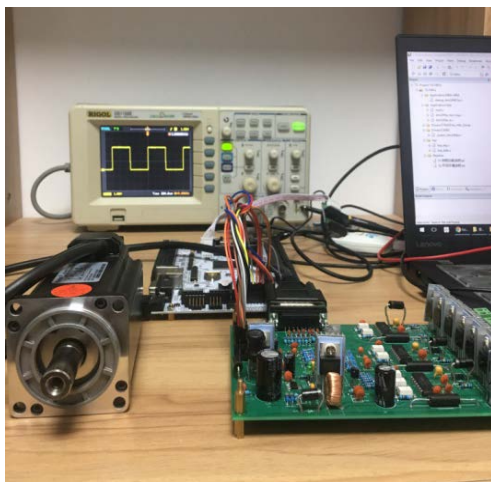


Figure 11. The experiment of the PMSM servo drive system

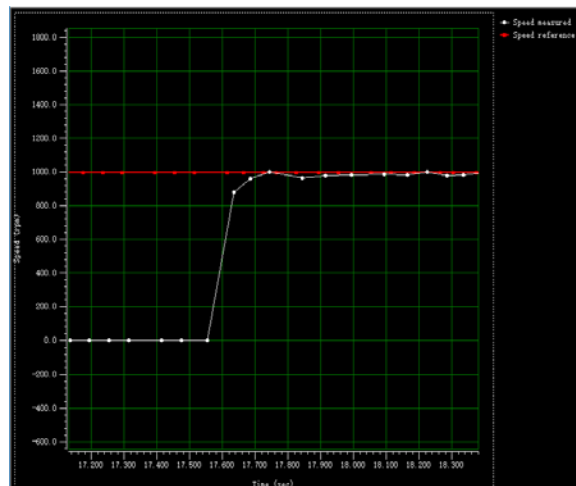


Figure 12. Experiment result

5. Conclusion

Both the simulation and experiment results show the PMSM servo drive system designed for intelligent patrol robots has great dynamic and smooth performance. Taking into account the relative low system hardware cost and great motor performance, this paper provides a great PMSM drive scheme for robotic field.

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