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Design of the autonomous underwater vehicle control moment gyro system based on DSP

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Abstract: To improve the low velocity control performance of Autonomous Underwater Vehicles (AUVs), a single gimbal Control Moment Gyro (CMG) is introduced as the attitude control system, the drive system of which consists of four brushless DC motors and four reducer motors. Considering the need of AUV for CMG motors, a steady-speed control system is presented in which the brushless DC motors and worm gear reducer motors are based on TMS320F2812. The DSP controller module, PWM optoelectronic buffer module, drive module, JTAG interface module, RS-232 SCI module and software program of the system are included. In building the peripheral circuit, only a single DSP chip is employed to control the starting or stopping and realize the measurement of the working statement of the four brushless DC motors, and the forward or reverse response speed of the worm gear reducer motors can also be accepted. The experiment shows that the designed DSP control system of CMG can satisfy the attitude control requirements of AUVs.

Key words: autonomous underwater vehicle; moment control gyro; attitude control; Digital Signal Processor (DSP); brushless DC motor

CLC number: U674.941

0 Introduction

The motion attitude control of AUV is the prerequisite and guarantee of completing the designated task. As the AUV is more specialized and diversified in the application of ocean field, a new built-in AUV attitude control actuator and gimbal CMG are put forward in succession in order to enhance the AUV's working efficiency, life span, maneuverability and capacity of resisting the bad environment[1]. The additional moment generated by rotating device gyro effect is expected to control the attitude of AUV. The AUV has broad development prospect and great application value in survey and exploitation of marine resources and strategic disposition of naval weapons. Compared with traditional actuator of "propeller and rudder", the internal CMG actuator not only can avoid seawater corrosion, but also doesn't rely on the relative motion of the fluid; besides, it can even be used in the occasion of low velocity and zero velocity. It is conducive to the protection of integrality of shell and is easier to optimize design.

CMG is a kind of momentum exchange device and consists of outer gimbal of uniformly rotating gyro rotor and support rotor. The moment output is realized by changing the angular momentum direction of gyro rotor via gimbal rotation. The large output moment of CMG, fast dynamic response and stable and credible work satisfy the requirements of large spacecraft attitude control and fast maneuvering. Currently, it is

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widely used in spaceflight field in China and abroad[2]. Tang et al.[3] created a kinematics and dynamics model of AUV based on CMG and took the large attitude angle maneuvering into consideration. They adopted the method of Euler quaternion for modeling, studied and analyzed the issue via in-depth theory, fully affirmed the application value of CMG in AUV attitude control system and designed and developed the corresponding attitude CMGs[4]. The driving system consists of four high-speed brushless DC motors and four worm gear reducer motors.

The brushless DC motor replaces electric brush and mechanical commutator of traditional DC motor with electronic commutator, greatly enhancing the working efficiency and speed control performance of electrical machine and having the merits of stable speed and reliable operation in driving gyro rotor[5]. With large output moment and stable rotation, the worm gear reducer motor is used to drive gyro gimbal, satisfying the requirements of system control. There are many control schemes of electrical machine, such as motor speed-regulation control system based on single chip microcomputer[6], motor drive control system based on FPGA[7] and control system which takes Digital Signal Processor (DSP) as the main controller[8]. As DSP has high control precision, strong data handling capacity and rich interfaces, the present study will take TMS320F2812DSP chip as control core and designs speed-regulation drive control system of brushless DC motor and worm gear reducer motor.

1 Principle of control system

In the AUV attitude control system, four single gimbal CMGs are arranged inside the AUV in pyramid configuration and form CMGs which are fixed by two parallel guide slots inside the AUV as shown in Fig. 1 (the propeller at the tail of AUV is removed). The rotation of gyro's outer gimbal will change the angular momentum direction of gyro rotor, further generate gyro moment effect on gimbal base (shell of AUV) and actuate the AUV to complete the task of attitude maneuver. The rotor has fast revolving speed and speed stabilization with high precision and adopts the control of brushless DC motor with permanent magnet. With rapid change of speed, the gyro gimbal has low revolving speed and adopts the drive control of worm gear reducer motor. Therefore, the core of AUV attitude control system based on CMGs is to control the revolving speed of four brushless DC motors and four worm gear reducer motors, adjust the operative mode of motor in real time and ensure the realization of stable triaxial moment output. The overall diagram of attitude control system is shown in Fig. 2.

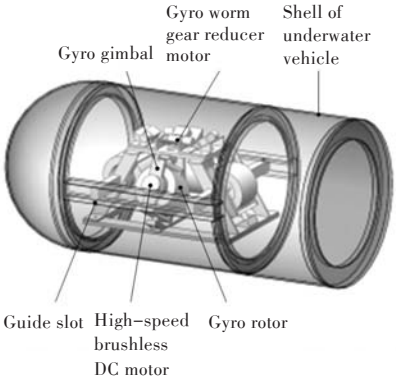

Fig.1 The configuration and installation diagram of CMGs

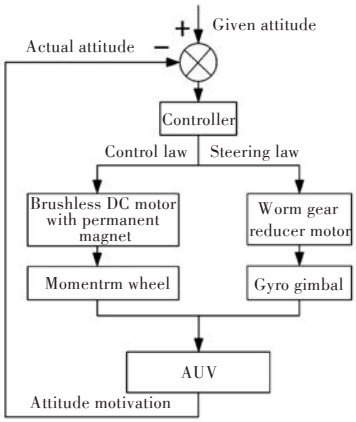

Fig.2 Control system block diagram

2 Main hardware circuit design of system

The system adopts a DSP chip whose type is TMS320F2812, peripheral circuit and drive circuit to realize the control of four high-speed brushless DC motors and four worm gear reducer motors. The diagram of motor control system principle is shown in Fig. 3 (the figure only lists the control principle of a brushless DC motor and two worm gear reducer motors. Other motor control methods are similar to them).

The motor control system mainly consists of PC upper computer, main control chip 2812, optoelectronic isolation circuit and drive circuit. PC upper computer mainly sends data, receives and displays tasks. The control part which takes TMS320F2812 chip as the core is in charge of controlling operation, outputting PWM speed pulse and measuring speed. The drive circuit amplifies the power of weak current control signal output by DSP chip and outputs strong

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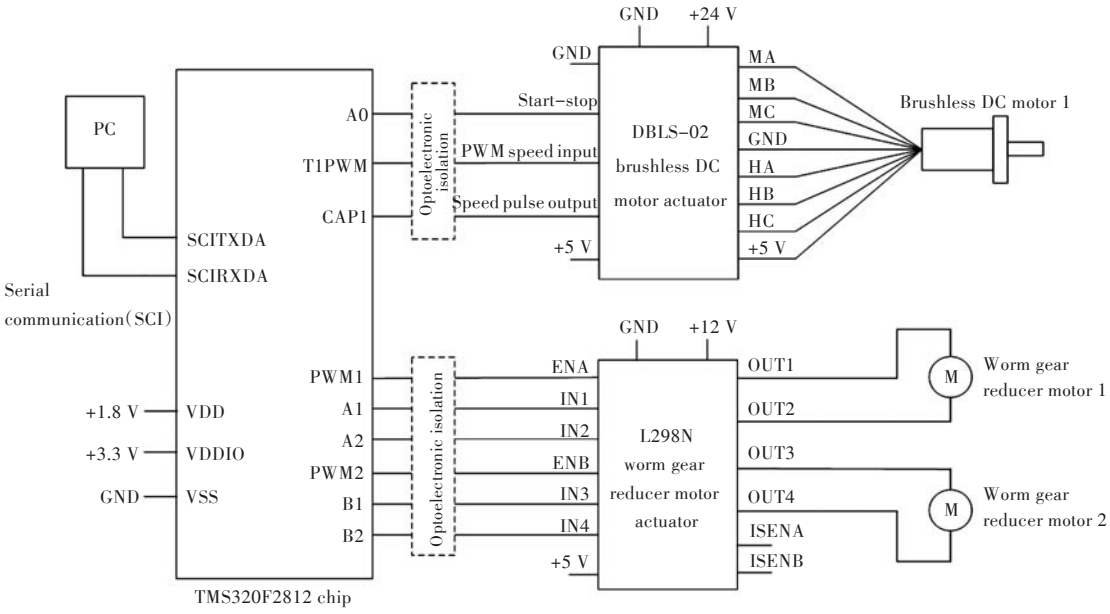

Fig.3 The control system block diagram of motors

current signal with a certain drive capability to control the operation of motor. The operating voltage of DSP controller chip's I/O interface is 3.3 V while the pin operating voltage of selected integrated driver DBLS-02 of brushless DC motor and drive chip L298N of worm gear reducer motors are 5 V. It means that the control signal output by TMS320F2812 DSP chip is insufficient to trigger the on-off of power tube inside the motor actuator. Therefore, the system needs to adopt an optical coupler to isolate control part and power drive part by way of photoelectricity, which can both realize the signal conversion among different voltages and avoid the electromagnetic interference between control circuit and drive circuit.

2.1 Drive circuit of brushless DC motor

The drive circuit of brushless DC motor uses intelligent integrated driver DBLS-02. The control actuator is closed-loop speed controller and adopts the newest IGBT and MOS power devices. The control link is equipped with PID speed-regulation adjuster which realizes closed-loop speed control through doubling frequency of brushless DC motor's Hall signal. The motor actuator has the protection functions of undervoltage detection, overcurrent protection and Hall signal failure warning. Its chopping frequency reaches 1 kHz and the duty ratio changes among 0%-100%. It can deal with standard logical signal with the electrical level of 0-5 V. The connection mode of brushless DC motor and actuator is shown in Fig. 4.

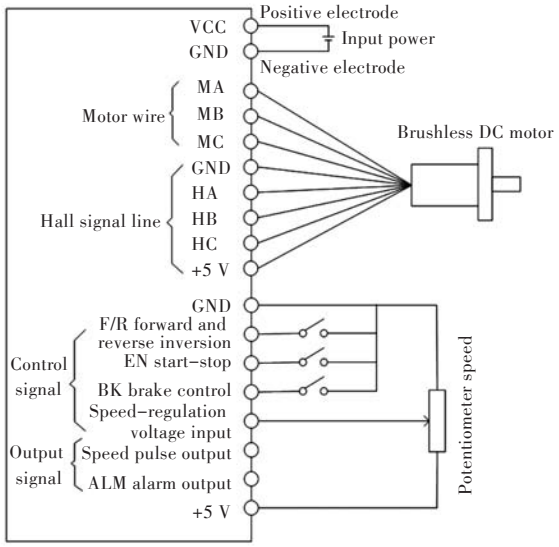

Fig.4 Drive's wiring diagram

The brushless DC motor's start-stop, forward and reverse inversion and brake signals are controlled by high and low electrical level output by DSP chip pin. After receiving motor speed signal fed back by Hall sensor, DSP can output PWM whose amplitude value is 5 V and frequency is 1 kHz through control algorithm disposition and optoelectronic isolation circuit. The signal is imposed on speed-regulation voltage input end of actuator. The revolving speed of motor is subject to linear regulation of duty ratio.

2.2 Drive circuit of worm gear reducer motor

The drive system of worm gear reducer motor was set up by L298N drive chip and peripheral circuit.

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The drive circuit principle is shown in Fig. 5. L298N is a high efficient small PWM power amplification device with strong drive capability which was produced by SGS Company. Its interior includes 2 full H-bridge drive units with high voltage and current. The standard TTL logic level control is used to drive 2 DC dynamos[9]. The pin ENA (ENB) is Enable end and PWM speed-regulation signal output by circumscribed DSP chip realize the speed control of worm gear reducer motor 1 (motor 2). IN1 and IN2 (IN3, IN4) are the motor steering control input ends and control the motor's start-stop and forward and reverse inversion through introducing two pins into high and low electrical levels with different combinations. D1-D8 are free-wheeling diodes which are used to release the self-induced electromotive force generated by coil winding at the moment of the motor's start-stop and protect the power switching devices. D9-D12 are motor rotation direction indicators which are used to display the motor's forward and reverse states.

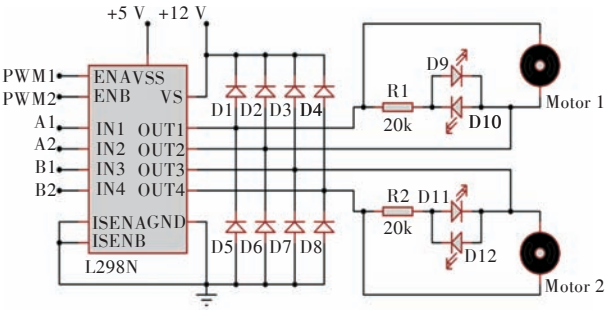

Fig.5 The drive circuit diagram of L298N

2.3 Optoelectronic isolation circuit

The system adopted optical coupler 6N137 to isolate control part and power drive part in the way of optoelectronic isolation. The interior of 6N137 chip consists of a LED with the wave length of 850 mm and an integrated detector. The integrated detector is used to recognize the optical signal sent out by LED, convert it into electrical signal, control the on-off of peripheral circuit and realize optoelectric isolation. The 6N137's peripheral connection circuit is shown in Fig. 6. The amplitude value output by main control chip TMS320F2812 is 3.3 V. After being disposed by optical coupler 6N137, PWN waveform whose frequency is 1 kHz can get PWM control signal whose amplitude value is 5 V and frequency is 1 kHz. It can both realize the signal conversion among different voltages and avoid the electromagnetic interference between control circuit and drive circuit.

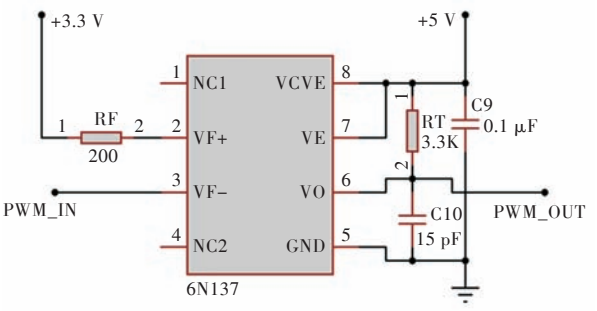

Fig.6 The external circuit of 6N137

2.4 Serial communication and simulation interface circuit

TMS320F2812 chip has asynchronous serial communication interface SCI which can circumscribe MAX3232 chip and realize the serial communication with upper computer. With high integration level and low power dissipation, MAX3232 is a drive chip which conforms to RS-232 standard, adopts +3.3V power supply, has two reception and transmission channels and realizes the connection between control system and upper computer through standard DB9 interface[10]. The serial communication interface principle of MAX3232 is shown in Fig. 7.

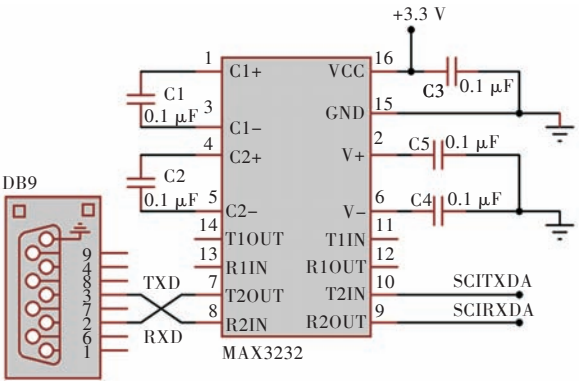

Fig.7 Principle of the serial interface

The interface of Joint Test Action Group (JTAG) is mainly used for downloading and debugging program, supports online debugging simulation and significantly reduces the difficulty in developing DSP system hardware. The connection between TMS320F2812 chip and outer JTAG cable is realized through standard 14 pin simulation interface. The port provides 5 standard JTAG debugging signals (TRST, TCK, TMS, TDI and TDO) and 2 simulation nodes (EMU0 and EMU1)[11]. The peripheral circuit of JTAG interface is shown in Fig. 8.

3 Software design of control system

Code Composer Studio (CCS) is the most extensive

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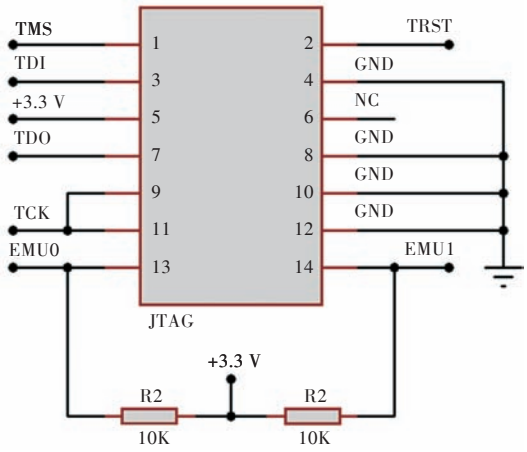

Fig.8 The JTAG circuit

DSP integrated development environment of system. TMS320F2812 program design by utilizing it is the core of control system software design. The control system software of brushless DC motor adopts modularized design idea, mainly including system initialization module, timer interrupt response module, acquisition and processing module of feedback signal and generating and controlling module of PWM waveform. The design procedure of system software is shown in Fig. 9.

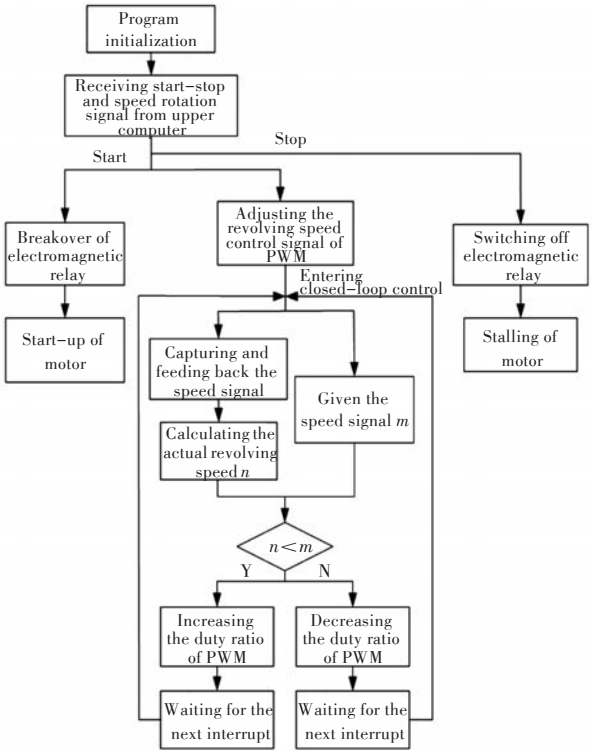

Fig.9 The software flowchart of motor control system

When the system is restored and powered on, the main program firstly completes the system's initialized task, including closing watchdog, deploying PLL clock, setting GPIO operating mode and initializing DSP event manager module. Then it waits for the coming of the upper computer's control instruction and the interrupt of system period. The system has two levels of interrupt, namely event manager interrupt and serial port interrupt. The serial port interrupt is divided into transmission interrupt and reception interrupt which are in charge of sending system information to upper computer and receiving control instruction from upper computer. The event manager interrupt is generated by universal timer DSP. Whenever the values of universal timer's counter register (TxCON) and period register (TxPR) are equal, the event manager breaks off. The system enters the subprogram of interrupt disposition. The actual revolving speed data of motor required in capture unit (CAP) are compared with the revolving speed data given by upper computer. If the given speed is not reached, it needs to increase the duty ratio of PWM in order to improve the motor's revolving speed and wait for the next timer interruption. If the motor's revolving speed reaches the given speed, the duty ratio of PWM should remain unchanged and the motor should operate steadily.

4 Test results

The drive control schemes of brushless DC gyro motor and worm gear reducer motor system were design ahead. Based on the above hardware circuit principle and software design procedure, the peripheral circuit is made. The control program is written into main control chip named TMS320F2812. The control test of driving CMGs by DC motor is carried out.

The rated voltage of brushless DC motor is 24 V. The rated revolving speed is 10 000 r/min. The duty ratio of motor speed control signal named PWM increases 0.2% every other second until the motor reaches the targeted speed and operates steadily. The targeted revolving speed is set as 4 000 r/min. The acceleration process of motor from zero-speed start to the targeted revolving speed and the steady speed curve are shown in Fig. 10. When the speed is stable, the corresponding speed-regulation control input PWM waveform is shown in Fig. 11. It can be seen from the test result that the start-up procedure of brushless DC gyro motor is steady. When the duty ratio of PWM signal which is imposed on speed-regulation voltage input end of motor actuator increases to 40%, the motor reaches the targeted revolving speed and steadily operates at the speed of about 4 000 r/min. It has the system control with high pre-

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cision and good dynamic property. The rated operating voltage of worm gear reducer motor is 12 V. The rated revolving speed is 6 r/min. The output response curve when giving the sine speed and inputting the control signal is shown in Fig. 12. It can be seen that the worm gear reducer motor's start-stop and forward and reverse inversion response speed can change the operative condition of gyro gimbal in real time.

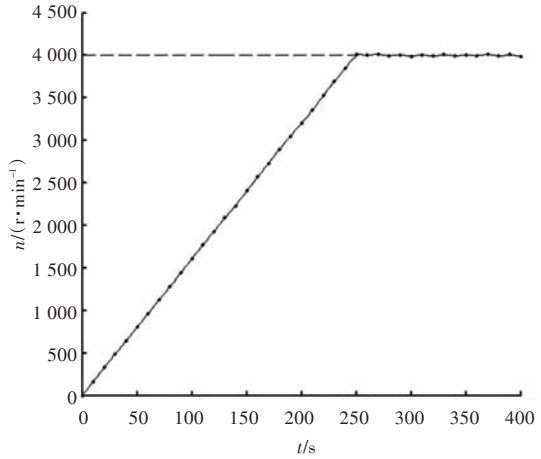

Fig.10 The acceleration and steady velocity curve of DC motor

Fig.11 The PWM control signal of motors in steady velocity

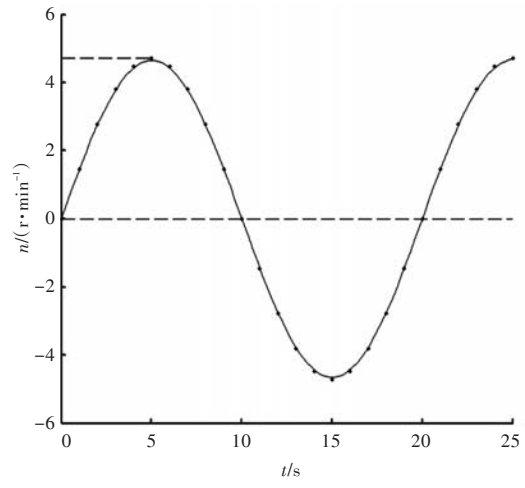

Fig.12 The speed response curve of worm gear reducer motor

In the lab, the attitude maneuver principle is tested on the AUV. The AUV is horizontally hung in the air. The gyro gimbal and gyro rotor operate according to the given rules of speed change. Then it is needed to observe the AUV's attitude maneuver effect in the horizontal plane. The attitude conversion process of hull is shown in Fig. 13. It can be seen from the figure that the attitude sensor detects out that the AUV rotates 70° along the counterclockwise direction in the horizontal plane within about 10 s. The attitude angle changes obviously. The designed DSP control system of CMGs can satisfy the requirements of AUV's attitude control in principle.

Fig.13 Attitude changes of the AUV

5 Conclusions

The present study took TMS320F2812DSP chip as the control core, designed the drive control system of AUV CMGs and completed system hardware circuit design and software development. On this basis, it set up test platform, conducted tests of CMGs's drive control and AUV's attitude maneuver. The results indicated that the start-up procedure of gyro wheel generated by brushless DC motor was stable and it can operate steadily in the expected speed. The large moment output by worm gear reducer motor and rapid dynamic response of gyro gimbal satisfied the requirements of system control. The CMGs' DSP con-

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trol system was stable and the AUV's attitude maneuver effect was obvious in air environment, which fully showed the validity and feasibility of CMGs which was taken as AUV attitude control actuator.

References

[1] THORNTON B. The development of zero-G class underwater robots: unrestricted attitude control using control moment gyros [D]. Southampton: University of Southampton, 2006.

[2] LIU Cheng, LIU Xiangdong, LI Li. Design and application of the control system of SGCMG based on DSP [J]. Electric Drive, 2006, 36(9): 29-31, 43(in Chinese).

[3] TANG Guoyuan, XU Zhengwu, HUANG Daomin, et al. Research on the modeling approach for underwater craft's motion based on control moment gyros[J]. Shipbuilding of China, 2014, 55(2): 18-27(in Chinese).

[4] WANG Can, TANG Guoyuan, HUANG Daomin. The design of control moment gyro system based on integrated circuit [J]. Machinery & Electronics, 2015(6): 47-50(in Chinese).

[5] KIM D K, LEE K W, KWON B L. Commutation torque ripple reduction in a position sensorless brushless dc motor drive [J]. IEEE Transaction on Power Electronics, 2006, 21(6): 1762-1768.

[6] WANG Yan. Design and realization of brushless DC motor control system based on MCU [D]. Nanjing: Nanjing University of Posts and Telecommunications, 2013(in Chinese).

[7] NI Fei. Quasi-sine wave brushless DC motor control and system implementation based on FPGA [D]. Chongqing: Chongqing University, 2013(in Chinese).

[8] LIU Zhaoqing, WANG Xitai, WANG Miao. The research of DSP-based brushless DC motor control system and simulation [J]. Microcomputer Information, 2011, 27(9): 102-104(in Chinese).

[9] LEI Hongmiao, CHENG Yaoyu. Design of DC motor drive circuit based on L298N [J]. Digital Technology and Application, 2012(2): 118, 120(in Chinese).

[10] HE Suqin. DSP system with experimental tutorial[M]. Beijing: Electronics Industry Publishing House, 2013 (in Chinese).

[11] QI Xingming, HU Xiaodong, ZHOU Huojin. Getting started and typical examples of dsp embedded development [M]. Beijing: Posts & Telecom Press, 2011 (in Chinese).

自主潜航器姿态控制力矩陀螺群的DSP控制系统设计

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摘　要: 传统舵面执行机构在自主潜航器低速或零速状态时对其进行姿态控制舵效不足,为改善其操纵性能,引入框架控制力矩陀螺(CMG)作为自主潜航器的姿态控制执行机构,其中驱动系统由4台高速无刷直流电机及4台减速电机组成。考虑到自主潜航器对控制力矩陀螺电机的性能要求,设计了以数字信号处理器(DSP)TMS320F2812为核心的永磁无刷直流电机与蜗轮蜗杆减速电机调速控制系统,包括DSP主控模块、PWM光电隔离模块、驱动模块、JTAG接口模块、RS-232串行通信模块等硬件电路及系统上、下位机的控制软件程序。设计并制作了外围电路板,实现了对无刷直流电机驱动的陀螺转子进行启动停止、转速给定、转速测量等控制任务,以及蜗轮蜗杆减速电机驱动的陀螺框架启停及正反转响应迅速。试验表明,所设计的DSP控制系统能较好地满足自主潜航器姿态控制需求。

关键词: 潜航器; 控制力矩陀螺; 姿态控制; 数字信号处理器; 无刷直流电机

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