Design and Experiments of a Deep-sea Hydraulic Manipulator System

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***Abstract*—Deep-sea master-slave hydraulic manipulator is among most commonly tools equipped on remotely-operated vehicles or human occupied vehicles. The design and realization of a 7-function master-slave hydraulic manipulator can be used in 7000 meters depth is proposed, and the design and control experiments of the salve arm are described in detail. Linear actuator, rotary actuator and cycloid motor are the three basic modules of the slave arm. The rotary actuator is the most difficult module to realize, a double-screw-pair swing rotary actuator is designed in this paper, which realized rotary driving, multi-path oil and electric cable passing through and rotary angle measuring. To achieve smooth control result, PI control algorithm with variable gains is applied on the control of the slave arm. Running experiments show the reliability of the manipulator system. The control algorithm is also certified effective in alleviating the movement delay and overshoot jitter of slave-arm.**

Keywords—Deep-sea hydraulic manipulator; Design and experiments; Double-screw-pair swing rotary; PI control algorithm.

I. INTRODUCTION

It has been decades since underwater vehicles applied in underwater exploring and research, and have been considered as efficient tools in the field of marine science and engineering. However an underwater vehicle can only take survey tasks unless equipped with a underwater operation tool. Underwater manipulator is a typical underwater operation tool which is widely used for performing underwater tasks[1]. Recently, autonomous manipulation has been a hot research field in underwater-vehicle manipulator system(UVMS)[2], but master-slave manipulators mounted on remotely-operated vehicles and human occupied vehicles are still important tools, because of their irreplaceable performance in unstructured and complicated environment[3].

A main difference between underwater and land is that pressure increases with water depth at a rate of one bar per 10 meters, which is a crucial factor of hindering development of deep-sea underwater vehicles and manipulators. From materials, manufacture, power supply to communication, the design of deep-sea manipulator is far different from that operated on land, and more difficult. Some industrial companies such as Schilling Robotics[4], Hydro-Lek[5] and ISE Ltd.[6], have already realized manipulator productization, the normally designed depth rating is 6000 meters or less. However oceans deeper than 6000 meters account for the bottom 45 percent of the full ocean depth range, where we barely know about. It is clear that deep-sea manipulator system is an important research field. Published literatures of manipulator mainly concentrates their studies on controller design[7-10] or dynamic analysis[11,12]. Reference [13] describes a 7-function hydraulic underwater manipulator which working depth is 3000 meters, including the system configuration, main components, control system and fault and error diagnosis scheme.

This paper systemically presents the whole system of 7000 meters depth-rating hydraulic manipulator which was supported by the China national 863 plan, and organized as follows. The system design is described in section 2, where mechanical, electronic and software design is separately represented in detail. Slave arm controller using PI algorithm with variable gains is studied in section 3. In section 4, results of simulation and field experiment are presented to demonstrate the proposed control algorithm and system performance.

II. THE 7-FUNCTION MANIPULATOR SYSTEM DESIGN

A. System Overview

The 7-function manipulator system could be mounted on remotely-operated vehicles or human occupied vehicles to perform underwater tasks, and normally works in a master-slave mode. The system is divided into surface part and underwater part, the former is composed of a surface control box and a power supply junction box, while the latter is composed of a hydraulic control valve pack, a slave arm, a hydraulic power unit and a pressure compensator, and linked to the surface part with a cable. The whole system configuration is shown in Fig. 1. The slave arm is the system's actual actuator which is powered by hydraulic force with 6-DOFs movement joints and a gripper, each joint equipped with a displacement sensor to achieve servo control. The slave arm is controlled by the master arm, besides automatic extension and recovery functions are included.

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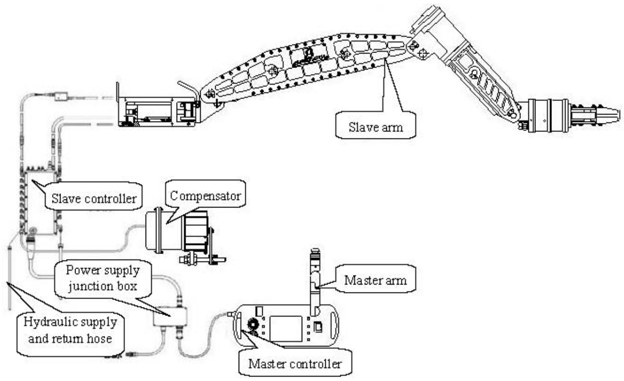


Fig. 1. System configuration of the 7-function manipulator

Surface control box is the control terminal of the system, consisting of a master controller, a control panel and a master arm. Operators can choose control mode and set parameters of the system through the function keys on the control panel, an LED monitor is used for visualized human-machine interaction. The master arm is a small scaled model of the slave arm.

Hydraulic control valve pack is an underwater sealed container, and filled with compensation oil in order to work stably without variation of water depth. A slave controller and seven servo valve blocks are contained inside the valve pack. The slave controller receives the command from the master controller to drive the motion of the slave arm, and returns the real-time work state of the underwater part. The servo valve block is integrated electro-hydraulic servo valve, relief valve and locking valve.

The power supply junction box is connected to the 220VAC power source and links the surface part with underwater part through a cable. The hydraulic supply and return hoses transport hydraulic oil between the hydraulic power unit and other hydraulic components. A pressure compensator is used to compensate the variation of pressure caused by water depth for the valve pack and other housing sealed components so as to prevent seawater from entering the system.

B. Mechanical Design

1) The 7-function hydraulic slave arm

The 7-function hydraulic slave arm is the system's actual actuator to perform underwater tasks, in addition to completing the appropriate action, having sufficient strength and stiffness, but also to facilitate the installation, testing, maintenance and repair, so mechanism design of the slave arm is the emphasis and difficulty of the entire system realization.

Structural configuration of the slave arm includes a stationary base, a shoulder joint, a main arm, an elbow joint, a forearm, a wrist joint and a gripper, each joint has two DOFs, thus makes the slave arm with six DOFs in total. Seven functions are composed of 6-DOFs motion and a grip function. The main performance specification of the slave arm is shown in TABLE I. The hydraulically powered 7-function slave arm is driven by linear cylinder, rotary actuator or cycloid motor. Displacement sensors integrated inside movement joints and electro-hydraulic servo valve are used to achieve close-loop position control. The joint function configuration, actuator type and nominal range of the slave arm are shown in TABLE II.

TABLE I. PERFORMANCE SPECIFICATION OF THE SLAVE ARM

Item	Value
Depth rating	7000 m
Weight in air	85 kg
Lift at full extension	65 kg
Maximum reach	1.9 m
Working pressure	21 MPa
Elbow torque	340 Nm
Wrist torque	290 Nm
Wrist rotate	7~32 rpm

TABLE II. JOINT FUNCTION CONFIGURATION, ACTUATOR TYPE AND NOMINAL RANGE

Joint function	Actuator type	Motion range
Shoulder yaw	Linear	120 degree
Shoulder pitch	Linear	120 degree
Elbow pitch	Linear	120 degree
Elbow yaw	Rotary	180 degree
Wrist pitch	Linear	120 degree
Wrist rotate	Gerotor	360 degree
Gripper	Linear	140 mm

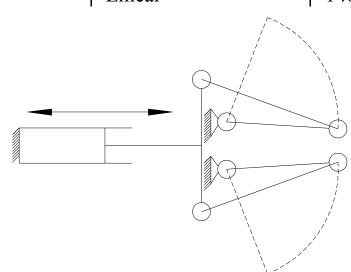


Fig. 2. Diagram of the gripper drive mechanism

Linear motion of cylinder's piston could be converted into rotation through joint transmission, thus is used to drive the motion of shoulder yaw and pitch, elbow pitch, and wrist pitch. Since angular displacement of joint motion can be measured directly or by calculating conversion from piston displacement, integrating the displacement sensor inside linear cylinder would simplify structural design and improve the system stability and modularity. A short linear cylinder driving a linkage mechanism is designed to realize gripper close and open. The diagram of gripper driven mechanism is shown in Fig. 2.

Rotary actuator which typically used to drive elbow yaw is a compact module to achieve rotary motion of the 7-function slave arm, and is the most difficult module to realize because of high torque-to-volume ratio and multi-path oil passing through mechanism. A double-screw-pair swing rotary actuator is designed to realize rotary driving, multi-path oil and electric cable passing through and rotary angle measuring. As shown in Fig. 3 is the internal mechanism design of multi-path oil and electric cable passing through, path A-A and B-B is an example of oil passing through, path L-L is an electric cable passing through. The design keeps oil hoses remaining state of rest while rotary actuator rotating, thus avoiding hoses wound.

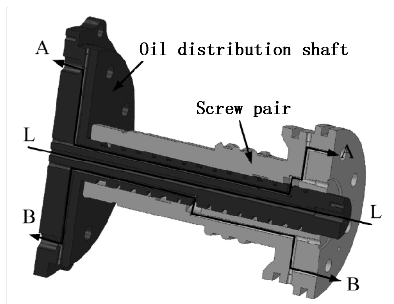


Fig. 3. Internal structure diagram of the swing rotary actuator

Cycloid motor is a core component to achieve continuous rotation. A White Motor is chose for its compactness. Restructuring has been carried out to minimize the dimension of wrist and gripper module, which using the cycloid motor directly drives the rotation of the short linear cylinder.

2) Pressure compensator

Pressure compensator is a widely used hydraulic component in underwater engineering, which could compensate the pressure of hydraulic system caused by variation of ambient seawater pressure at different depths, thus pressure difference would be constant. The structural diagram of pressure compensator is shown in Fig. 4. Assuming P_c is the internal pressure of compensator. A_c and A_s is effective active area of two sides of the isolation diaphragm separately. P_s is ambient seawater pressure. K_s is spring stiffness. The amount of spring pre-compression is x_0, while x_c is the amount of compression relative to pre-compression position. Ignoring deformation resistance of the isolation diaphragm, force equilibrium equation of the piston becomes:

$$P_c A_c = P_s A_s + K_s \left(x_0 + x_c \right) \tag{1}$$

It's clearly that internal pressure of the compensator is slightly higher than ambient seawater pressure. In addition, pressure fluctuation is only related to spring stiffness and compression, which can be limited within a certain range as long as a reasonable choice of related parameters.

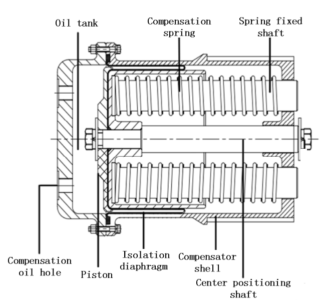


Fig. 4. Structural diagram of pressure compensator

C. Electronic Design

Electronic system contains surface part and underwater part, which is the master controller and slave controller of the 7-function manipulator separately. The whole architecture diagram of the electronic system is shown in Fig. 5.

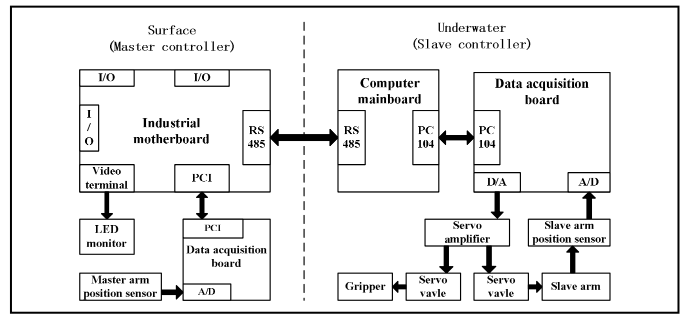


Fig. 5. Architecture diagram of electronic design

The surface part adopts industrial motherboard as main controller, which is powered by 220 VAC. An LED monitor is connected to the motherboard through video terminal interface, which achieved friendly human-machine interaction. A data acquisition board is used to acquire displacement sensor signal of the master arm, which connected to the motherboard through PCI bus. Since the displacement sensor signal is analog, thus an analog to digital module is possessed on the data acquisition board.

A small and stable computer mainboard powered by 12 VDC is used as the slave controller in underwater part, communicating with the surface part through RS-485 serial interface. A data acquisition board with an analog to digital module and an digital to analog module is connected to the mainboard through PC104 bus. The analog to digital module acquires the displacement sensor signal of slave arm, while the digital to analog module converts control signal to analog one exported to servo amplifier. Servo amplifier is a key component of a electro-hydraulic servo control system which drives and controls electro-mechanical conversion device. With the action of servo amplifier, weak signal of controller is amplified to strong signal to drive electro-hydraulic servo valve. The underwater electronic subsystem is designed to oil-proofing and pressure resistance, so could be directly submerged in compensating oil of hydraulic control valve pack.

D. Software Design

Special system software designed for master computer and slave computer is presented separately in this section. The master computer is responsible for control of the whole system, dealing with operator's command, managing system, communicating with slave computer, monitoring real-time status of the slave arm. To achieve visualization of human-machine interface, an MFC procedure is programmed. The master computer software mainly contains four blocks: initialization block, master arm sensor data acquiring block, function keys monitoring and executing block, communication block and slave computer information processing block. The flowchart diagram of master computer software is shown in Fig. 6.

Control software of slave computer is written in C language, and mainly deals with commands from master computer, including command analyzing, task decomposing, and control algorithm realizing in real-time. The procedure processes communication, command analysis, strategy making, sensor data acquiring and system managing in a single machine cycle.

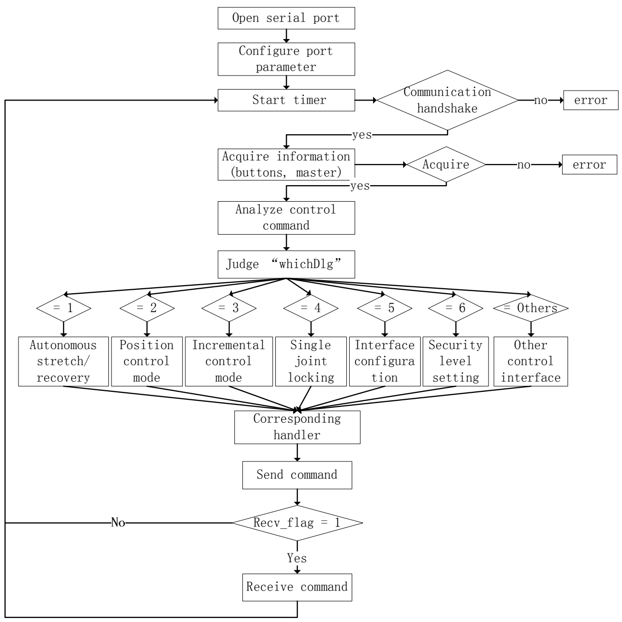


Fig. 6. Flowchat diagram of master computer software

III. Slave Arm Controller Design

Variability of underwater environment, floating behavior of fixed platform, kinematic and dynamic coupling between vehicle and manipulator make the control problem of underwater manipulator more challenging. The 7-function hydraulic manipulator system works in a master-slave control mode. Slave arm follows the motion of master arm, thus the accuracy of following motion determines the system performance and task execution efficiency.

PID control algorithm is widely used in robotic control schemes for its simplicity and practicality. However control parameters of traditional PID algorithm remain constant, resulting the contradiction between control accuracy and stability difficult to balance. To improve the performance of traditional PID algorithm, a PI control algorithm with variable gains is presented in this section, which achieving a smooth control result with high accuracy and strong stability.

Assuming e is control error, while $\dot{e}$ is the differential of control error. PI control algorithm with variable gains is described as follows:

Rule 1: if $e \cdot \dot{e} < 0$, then $U(k) = k_p \cdot e$;

Rule 2: if $e \cdot \dot{e} \geq 0$, then $U(k) = k_p \cdot e + k_i \int e$;

where k_p is proportional coefficient, $k_p = k_1 + k_2 \cdot |e|$,k_1 and k_2 is a small positive number, k_i is integral coefficient.

The proportional coefficient k_p is a function of e. It approaches k_1 when e approaching zero, thus proportional control action reduced. As a result, controlled object keeps rising, which helpful to reduce overshoot without increasing rise-time. If the system output pass over a given value, leading to a larger control error, so the integral part is activated that the system returns to a steady state quickly.

In order to verify the effectiveness of the proposed algorithm, motion control experiment of shoulder pitch which is driven by a linear cylinder and bears the largest load variation is conducted. The servo control model of this joint is described in [14]. The open-loop transfer function of piston output displacement relative to servo amplifier input voltage of shoulder pitch becomes (2):

$$\frac{Y(s)}{U(s)} = \frac{\omega_h^2 K_a K_{sv} K_x / A_m}{s^3 + 2x_h \omega_h s^2 + \omega_h^2 s} \tag{2}$$

where w_h=352Hz, is hydraulic natural frequency; x_h=0.76, is hydraulic damping ratio; K_a=1, is transfer function of servo amplifier; K_{sv}=5.18×10^{-3}, is transfer function of servo valve; K_x=2.5, is gain coefficient of servo valve flow; A_m=1.264×10^{-3}, is average area of piston;

Applying the value into (2), yields (3):

$$\frac{Y(s)}{U(s)} = \frac{1.27 \times 10^6}{s^3 + 535s^2 + 123904s} \tag{3}$$

IV. Experiments Reserach

A. Simulation

Simulation results of proposed PI algorithm with variable gains based on Matlab simulation platform is presented in this section. The contrast diagram of step response is shown in Fig. 7.

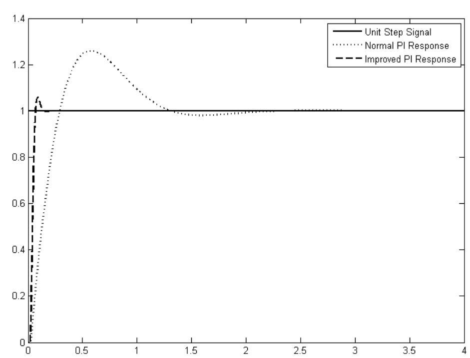


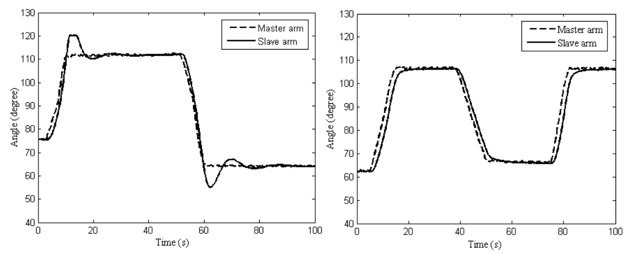
Fig. 7. Contrast diagram of step response

In traditional PI control algorithm, integral part is activated to eliminate the steady-state error, but a large overshoot and long rise-time occurs. The PI algorithm with variable gains only introduces integral part when output deviating from the target value, and increases the proportional coefficient to reduce settling time, thus improving the system real-time performance.

B. Slave arm control contrast experiment

The proposed algorithm is applied in the motion control of shoulder pitch of actual 7-function hydraulic manipulator system. Working hydraulic pressure is set at 10 MPa, and control period time is 0.2 s. The experiment result is shown in Fig. 8.

In traditional PI algorithm, k_p=0.4, k_i=0.1; while k_p=0.4+0.03×|e|, k_i=0.1 in proposed algorithm. The result shows that the proposed algorithm doesn't have overshoot, but a little hysteresis occurs. This is because the control is weak when output close to the target value, and integral part is not obvious. To improve the control performance, a larger k_p and k_i is applied to the system. The experiment result is shown in Fig. 9.



(a) (b)

Fig. 8. Contrast experiment of (a) traditional PI algorithm and (b) PI algorithm with variable gains

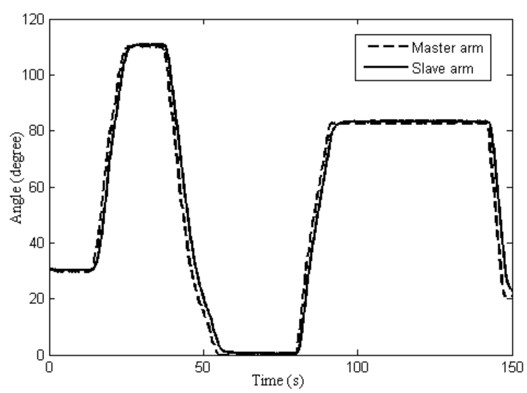


Fig. 9. PI algorithm with variable gains of increased coefficients

V. CONCLUSION

The paper presents the development of a 7-function deep-sea manipulator system which is powered by hydraulic and works in a master-slave mode. The system mainly consists of surface part including surface control box and a power supply junction box, and underwater part including a hydraulic control valve pack, a slave arm, a hydraulic power unit and a pressure compensator. A detailed describe of system design including mechanical structure, electronic subsystem and software is represented subsequently. The internal mechanism of rotary actuator that realized multi-path oil and electric cable passing through is developed, which is the most difficult part of mechanical design. To achieve position close-loop control in master-slave mode, every joint except gripper of the master and slave arm equipped with a displacement sensor. A PI algorithm with variable gains based control scheme is proposed to improve control accuracy and stability. Simulation and physical experiment on 7-function manipulator system results demonstrate the excellent performance of the proposed control algorithm.

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