The adaptive robust tracking control of deep-sea hydraulic manipulator based on backstepping design

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***Abstract*—In this paper, design and experiments of the 4500m deep-sea manipulator are introduced. With the extreme working condition, the deep-sea manipulator is more complex and the study is more challenging. The design highlight is stressed, including the double screw pairs elbow joint which could transmit large torque with a compact size, principle of pressure compensator which could balance the water pressure and so on. To achieve high tracking performance, the adaptive robust tracking control based on backstepping algorithm is proposed. The unknown parameters are estimated to enhance the tracking precision. Simulations and experiments based on this algorithm has been performed to verify the controller, the results show that the joint tracking control is fast and smooth, the overshot is small.**

Keywords—Deep-sea hydraulic manipulator; Joint tracking control; Adaptive robust control; Backstepping control

I. INTRODUCTION

A deep-sea hydraulic manipulator is widely used in underwater task, such as sediment sampling, pipeline maintenance and other works. The hydraulic system is extensively used in the deep-sea work condition for some reasons, for example, the power density is much higher than the electrical driven system[1],[2], and electrical manipulator require heavy protection shell or auxiliary system to resist the high sea pressure[3], while in the hydraulic manipulator system, a pressure compensator could be used to balance the sea pressure. Most of the deep-sea manipulators are master-slave type, the slave hand is installed in front of the ROV, shown in Fig. 1(a), it's controlled by the master hand, and the master hand is handled by the on deck operator[4]. The control signal is transferred though the long cable connecting the boat and ROV. The video signal is obtained by an underwater camera on the ROV and sent to the monitor through the optical fiber, so the operator could see the position and posture instantly.

Some companies like Schilling Robotics, Hydro-Lek, they have made some underwater manipulators, most of the high precision manipulators are controlled by the servo valves, they have a high precision and fast response, however, servo systems have a rigorous oil cleanliness requirement, servo valves often get jammed because of the small metal particles. In this paper, the proportional valves are adopted, they need a lower level of cleanliness, and lager size of metal particles are allowed. But the proportional valves control are more complex, the performance of the proportional valves system with traditional controller is inferior to the servo system, so effective control algorithms should be studied to improve the system performance[5]-[9].

In this paper, the integral design process of the manipulator is discussed. In section 2, the hardware of the manipulator is studied, including the mechanical and hydraulic part, electronic design. In the next part, the adaptive robust control algorithm is specified, the controller stability is also proved in this part. In the last part, the control algorithm is applied, simulation on MATLAB and field experiment are carried out to verify the proposed algorithm.

II. DEVELOPNENT OF DEEP-SEA HYDRAULIC MANIPULATOR

A. *Design Objective*

According to the requirement of a scientific exploration ROV, design objective is specified. As shown in , the manipulator is designed to work under 4500m deep sea, considering the load capacity of the ROV, the weight should be less than 75Kg, and in the meantime, the load capacity of the manipulator when fully extended is expected to be larger than 100Kg. Other design inputs are shown in TABLE Ⅰ.

TABLE I. DESIGN OBJECTIVE

Depth Rating	4500m	Maximum Reach	1.6m
Functions	7	Lift at Full Reach	100Kg
Weight in Air	75Kg	Weight in Water	60Kg
Shoulder Rotation	120°	Big arm Rotation	120°
Fore arm Rotation	120°	Elbow Rotation	270°
Wrist Swing	104°	Wrist Rotation	360°

B. *Mechanical and Hydraulic System Design*

The slave hand is mainly made of aluminum alloy, 6061T6 is selected because the alloy can resist corrosion in seawater, and the density is lower than stainless steel. The slave hand is

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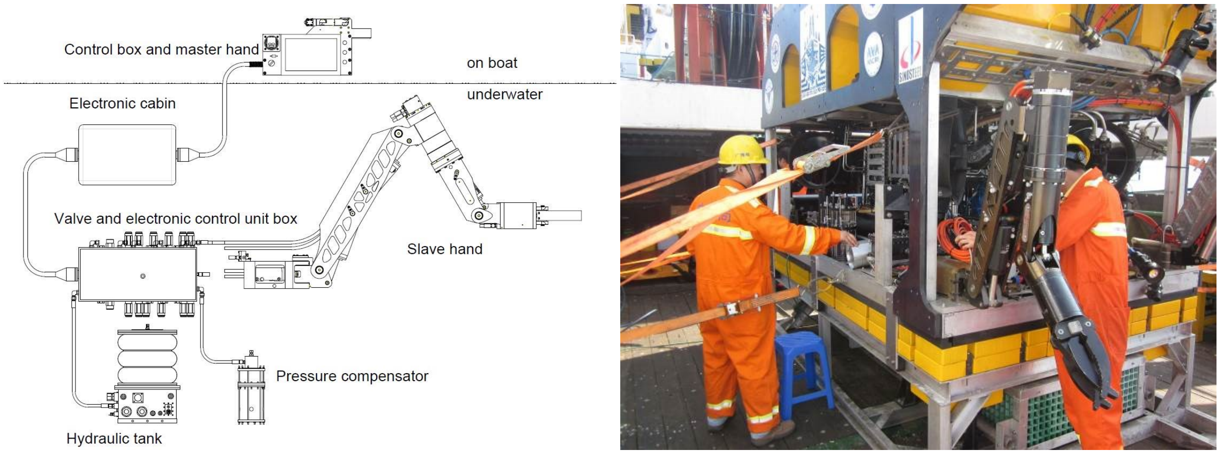

(a) (b)

Fig. 1 Overall system of the manipulator. (a) schematic diagram of the manipulator and auxiliary equipment (b) manipulator installed in front of the ROV

made of 6 joints and 1 claw, as shown in Fig. 1, the 6 joints correspond to the human arm joints. They are the shoulder, big arm joint, fore arm joint, elbow joint, wrist swing and wrist rotation. The shoulder, big arm, fore arm, wrist swing and claw are actuated by hydraulic cylinders, these cylinders are specially designed to miniaturize the manipulator. For example, the claw is driven by a specially designed cylinder which is actually installed inside the wrist rotation joint. The elbow joint and wrist rotation are designed based on other transmission principles to guarantee high torque output and reduce the overall size at the same time. The hydraulic double-cycloid wrist rotation joint could output larger and more stable torque, the frequent working direction switching is acceptable. Also the hollow axis is used as the cylinder of the claw actuation, make the overall structure more compact.

The elbow joint is specially designed so that the joint could transmit high torque even the dimension is small[10]. The output torque can reach 450Nm with 3 rpm rated speed. Double screw pairs are applied to reduce the leakage and friction. In the complex underwater environment, the exposed pipeline and wire are potential dangers, it is a terrible situation if they get hooked. So the unique hollow axis is designed, it could be used as the channel for oil pipeline and signal wire, although the joint could rotate continuously more than 360°, the pipeline and wire wouldn't twisted together.

Fig. 2 is the section view of the elbow joint, a and b are hydraulic chambers, hydraulic oil go through the tunnel inside the axis. If a is in high pressure, the piston (blue part) is pushed to the right end, the outer screw makes the piston rotating along the central axis when it's moving axially. The inverse direction screw pair inside the piston could mesh with the shaft axis (golden color), the rotating piston force the shaft axis to rotate, so the torque is generated.

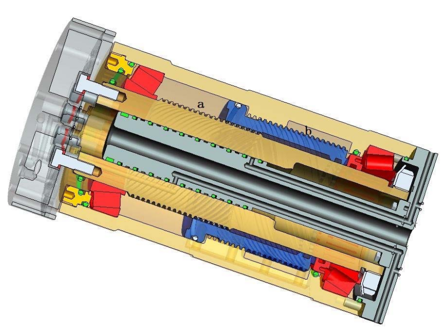

Fig. 2 Structure of the elbow joint

Caused by the unbalanced hydraulic force, the axially force on the central axis increases with the pressure rising. It will result in friction increasing, reducing the torque transmission efficiency. Compensation ring is applied to solve this problem. High pressure oil is introduced to the end of the shaft axis to balance the axially force. For example, if the chamber a is in high pressure, the compensation ring in the right end is in high pressure to reduce the axially force.

Fig. 3 is the hydraulic circuit of the whole system, each joint is controlled separately by a proportional valve. The control valve is used to regulate the flow rate, the actuator's velocity is proportional to the flow rate, so the joint speed is precisely controlled by the proportional solenoid valve. The valves selected in this project are Wandfluh NG3-mini type, which have small size and large flow rate capacity, also the proportional electromagnet can work under high oil pressure.

In Fig. 3, relief valves can drain oil to tank when pressure is higher than the warning level. The relief valves work in case of emergency, if the manipulator hit on some hard stone, the rapid

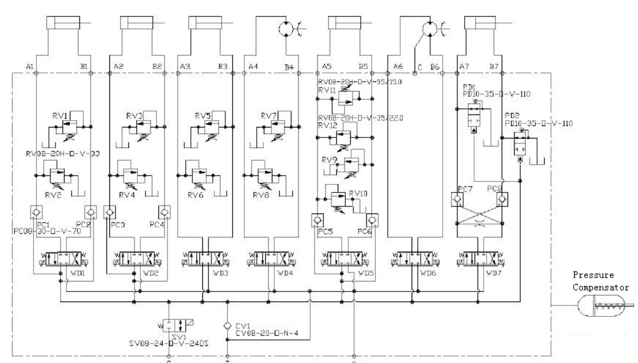

Fig. 3 Hydraulic circuit of the manipulator

change of the joint speed might lead to a sharp increase of chamber pressure, the extreme pressure could break pipeline without relief valves, it's fatal for an underwater hydraulic system, salt water could corrode the pump in a short time, also the sand will abrade the internal surface of the hydraulic parts, so the relief valves are critical in this system.

The check valve are used to lock the joint when manipulator stop working. The oil is trapped in the chamber so it could keep the posture even the power supply is shut down.

The pressure compensator is adopted in the system to balance the sea pressure, as shown in the Fig. 4, the chamber is divided into 2 parts, they are separated by the rubber membrane, one chamber is filled with hydraulic oil, this side connects to the valve and electronic control unit (ECU) box, and another side is open to the seawater, a coil spring can be seen in the Fig. 4, it's used to press the rubber chamber, that will guarantee the oil chamber pressure always a little higher than the sea pressure. So even if there are unnoticeable cracks in the system, the seawater can't penetrate into the system, only small amount of oil could leak out through the cracks.

C. Electronic Design

When working under 4500m sea, the pressure in the valve and ECU box could reach 45MPa, electronic components might be damaged in such circumstance. Some components have been processed to fit the high pressure.

In proportional valve control system, to avoid the spool jamming problem, the oscillation signal with small amplitude is added to power amplifier output signal. The oscillation signal frequencies are different for different valves, some tests have be done, and finally the frequency is set to be 200Hz.

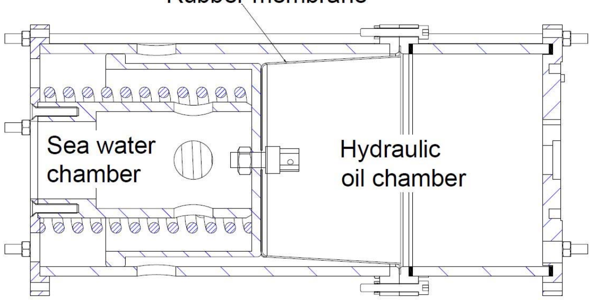

Fig. 4 Structure of the pressure compensator

Fig. 5 Control box. It's a multifunctional control box, in the left the handle with red buttons is used to control a 5 functional manipulator, the right handle is used to control the 7 functional manipulator.

As shown in Fig. 5, it's the control box, the master hand joints are corresponding to the slave hand joints. The operator handle the master hand, the joints signals generated by the angle sensor embedded in the master hand are transferred to the ECU, then the slave hand is controlled to track the joints angle. Core computer SIEMENS CPU315-2PD/DP in the control box is equipped with Profibus and Profinet whose baud rate could reach 100Mb/s. Profinet transfer data from the core computer to the touch screen. The master hand joint signal is sent to the core computer through the Profibus. After data processing, the computed control signal is sent to peripheral equipment which can transfer the signal to the optical fiber signal.

After long distance travel, optical fiber signal goes into the electronic cabin directly, seen in fig, then signal is processed and sent to the valve and ECU box. The valve and ECU box consisting of all the valve in fig and their power amplifiers can control the pressure and flow rate. This electronic control network could achieve the real-time control of the manipulator.

III. Modeling and Algorithm

A. Modeling

The manipulator's performance mostly depends on joint control efficiency. It will be easy for operator to control the system if the joint response is fast and accurate. So a lot of algorithms are come up with. Before the controller design, the system model should be studied first.

The manipulator's dynamic equation is:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau(u) + \Delta \tag{1}$$

$M(q)$ represents the inertia matrix, $C(q,\dot{q})\dot{q}$ is the centripetal and Coriolis torques term, and $G(q)$ represents gravitational effects. The manipulator equation has a special property: $\zeta^T\left[\dot{M} - 2C(x_1,x_2)\right]\zeta = 0$. $\tau(u)$ is the control torque generated by cylinder, Δ is lumped uncertain external disturbances, for example the friction forces. In this paper, the big arm and fore arm are studied, so the specific model of the two joints system can be described as:

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & 0 \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \tag{2}$$

Because of the unknown load, the second link parameters, such as I_2, m_2, are unknown, so they are the predicted items in the linearization form.

$$\theta_1 = m_2, \theta_2 = m_2 l_{c2}, \theta_3 = m_2 l_{c2}^2, \theta_4 = I_2 \tag{3}$$

So the linearization model of the manipulator is described as follow:

$$Y(q,\dot{q},\ddot{q})\Theta = \tau + \Delta \tag{4}$$

$$Y(q,\dot{q},\ddot{q}) = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{15} \\ m_{21} & m_{22} & m_{23} & m_{24} & m_{25} \end{bmatrix} \tag{5}$$

$$\Theta = [1 \quad \theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4]^T \tag{6}$$

$Y(q,\dot{q},\ddot{q})$ is the linearized coefficient, the term $m_{11}\cdots m_{25}$ are determined by the specific model of the two link manipulator. Θ is the unknown parameter, which is assumed to be in a convex set Ω_Θ , also can be expressed as: $\Theta_{i\min} \le \Theta_i \le \Theta_{i\max}$, for $i = 1...n$.

Define the following symbol descriptions:

$$x_1 = q, x_2 = \dot{q} \tag{7}$$

The following are hydraulic chamber dynamic equations:

$$\frac{V_1(x)}{\beta_e}\dot{P}_1 = -A_1\dot{y} + Q_1 = -A_1\frac{\partial y}{\partial q}\dot{q} + Q_1 \tag{8}$$

$$\frac{V_2(x)}{\beta_e}\dot{P}_2 = A_2\dot{y} - Q_2 = A_2\frac{\partial y}{\partial q}\dot{q} - Q_2 \tag{9}$$

y is the piston displacement, the partial differential $\frac{\partial y}{\partial q}$ depends on the mechanical structure; Q_1, Q_2 are the flow rates of the cylinder end and rod end; $V_1(x)$ is the cylinder end chamber volume, and the $V_2(x)$ is the rod end chamber volume; β_e is the effective bulk modulus, it's assumed to be a constant in this paper. A_1 is the area of cylinder end, and A_2 is the area of rod end.

Proportional valves are used to control the pressure and flow rate of the chamber. The relationship between flow rate and valve opening can be determined by the following equation:

$$Q_1 = K_{q1} g_1(P_1, \mathrm{sgn}(x_v)) x_v \tag{10}$$

$$Q_2 = K_{q2} g_2(P_2, \mathrm{sgn}(x_v)) x_v \tag{11}$$

$g(P_1, \mathrm{sgn}(x_v))$ is a nonlinear term, it's related to the pressure drop across the valve, it can be describe as follow:

$$g_1(P_1, \mathrm{sgn}(x_v)) = \begin{cases} \sqrt{P_s - P_1} & x_v \ge 0 \\ \sqrt{P_1 - P_r} & x_v < 0 \end{cases} \tag{12}$$

$$g_2(P_2, \mathrm{sgn}(x_v)) = \begin{cases} \sqrt{P_2 - P_r} & x_v \ge 0 \\ \sqrt{P_s - P_2} & x_v < 0 \end{cases} \tag{13}$$

K_{q1}, K_{q2} are the flow gain coefficients of the proportional valve. P_s is the supply pressure, and P_r is the vent pressure. P_1 is the pressure of cylinder end, and P_2 is the pressure of rod end.

The link between input voltage u and valve opening x_v is:

$$x_v = K_u u \tag{14}$$

K_u is the proportional amplifier gain.

B. *Controller design*

The manipulator can be treated as cascade system, so the backstepping control method is adopted. The manipulator dynamics are the main system, in this part, the hydraulic dynamics are neglected, only the desired torque is designed. The hydraulic dynamics are the subsystem, in this part the valve control voltage is computed to realize the desired torque.

The position error is:

$$\tilde{q} = x_1 - q_d \tag{15}$$

The reference velocity and reference acceleration:

$$\dot{z} = \dot{q}_d - \Lambda\tilde{q} \tag{16}$$

$$\ddot{z} = \ddot{q}_d - \Lambda\dot{\tilde{q}} \tag{17}$$

The reference velocity error:

$$s = x_2 - \dot{z} = \dot{\tilde{q}} + \Lambda\tilde{q} \tag{18}$$

The desired torque can be expressed as:

$$\tau_d = Y(x_1, x_2, \dot{z}, \ddot{z})\hat{\Theta} - K_D s - K_s \,\mathrm{sgn}(s) \tag{19}$$

In this expression, $Y(x_1, x_2, \dot{z}, \ddot{z})\hat{\theta}$ is the predicted part, it's applied to eliminate the dynamic torque of the manipulator, the expression is:

$$Y(x_1, x_2, \dot{z}, \ddot{z})\hat{\Theta} = \hat{M}(x_1)\ddot{z} + \hat{C}(x_1, x_2)\dot{z} + \hat{G}(x_1) \tag{20}$$

Where $\hat{M}(x_1), \hat{C}(x_1, x_2), \hat{G}(x_1)$ are the predictions of $M(x_1), C(x_1, x_2), G(x_1)$

According to (20)(19), manipulator's dynamic equation can be written as:

$$M(x_1)\dot{s} + C(x_1, x_2)s = Y(x_1, x_2, \dot{z}, \ddot{z})\tilde{\Theta} - K_D s - K_s \,\mathrm{sgn}(s) + \Delta \tag{21}$$

$$\dot{s} = M(x_1)^{-1}\left[Y(x_1, x_2, \dot{z}, \ddot{z})\tilde{\Theta} - C(x_1, x_2)s - K_D s - K_s \,\mathrm{sgn}(s) + \Delta\right] \tag{22}$$

Assuming that the parameters to be predicted are constant or varies slowly, the adaption law is design as:

$$\dot{\tilde{\Theta}} = \dot{\hat{\Theta}} = -\Gamma Y(x_1, x_2, \dot{z}, \ddot{z})\mathrm{s} \tag{23}$$

To guarantee the controller can be achieved, all the parameter in this paper are bounded, the projection constrain the estimated parameter into a domain

$$\mathrm{Proj}(\bullet_i) = \begin{cases} 0 & \text{if } \hat{\Theta}_i = \Theta_{i\max} \text{ and } \bullet_i > 0 \\ 0 & \text{if } \hat{\Theta}_i = \Theta_{i\min} \text{ and } \bullet_i < 0 \\ \bullet_i & \text{otherwise} \end{cases} \tag{24}$$

Define the positive Lyapunov function:

$$V_1 = \frac{1}{2}\left[s^T M(x_1)s + \tilde{\Theta}^T\Gamma^{-1}\tilde{\Theta}\right] \tag{25}$$

Then:

$$\begin{aligned} \dot{V}_1 &= s^T M\dot{s} + \frac{1}{2}s^T\dot{M}s + \tilde{\Theta}^T\Gamma^{-1}\dot{\tilde{\Theta}} \\ &= s^T\left[Y(x_1, x_2, \dot{z}, \ddot{z})\tilde{\Theta} - K_D s - K_s \,\mathrm{sgn}(s) + \Delta\right] \\ &+ \frac{1}{2}s^T\left[\dot{M} - 2C(x_1, x_2)\right]s +^T \Gamma^{-1}\dot{\tilde{\Theta}} \end{aligned} \tag{26}$$

Because of the property $\zeta^T\left[\dot{M}-2C(x_1,x_2)\right]\zeta=0$, and replace the $\dot{\tilde{\Theta}}$ with (23),

$$\begin{aligned}\dot{V}_1&=s^TY(x_1,x_2,\dot{z},\ddot{z})\tilde{\Theta}-\tilde{\Theta}^TY(x_1,x_2,\dot{z},\ddot{z})s\\&+s^T\left[-K_s\,\mathrm{sgn}(s)+\Delta\right]-s^TK_Ds\\&=s^T\left[-K_s\,\mathrm{sgn}(s)+\Delta\right]-s^TK_Ds\end{aligned}\tag{27}$$

In the controller, if $K_s>|\Delta|$ is guaranteed, then $\dot{V}_1$ is negative definite, then $s\to 0$. According to (18), the asymptotically stable is obtained, and $q\to q_d$.

In the last step, the hydraulic dynamics are neglected, in this step, the hydraulic actuator's output torque is controlled to achieve the asymptotically stable goal.

$$F_L=A_1P_1-A_2P_2\tag{28}$$

$$F_{Ld}=d(q)^{-1}\tau_d\tag{29}$$

Then the force error is:

$$\dot{\tilde{F}}_L=\dot{F}_L-\dot{F}_{Ld}=A_1\dot{P}_1-A_2\dot{P}_2-\dot{F}_{Ld}\tag{30}$$

According to the hydraulic chamber equation(8)(9), $\dot{\tilde{F}}_L$ is expressed as:

$$\begin{aligned}\dot{\tilde{F}}_L&=\beta_e\left[-(A_1V_1^{-1}(y)A_1\frac{\partial x}{\partial q}\dot{q}-A_2V_2^{-1}(y)A_2\frac{\partial x}{\partial q}\dot{q}\right]\\&+\beta_e\left[A_1V_1^{-1}(y)Q_1+A_2V_2^{-1}(y)Q_2\right]-\dot{F}_{Ld}\end{aligned}\tag{31}$$

In the equation, the part $Q_L=A_1V_1^{-1}(y)Q_1+A_2V_2^{-1}(y)Q_2$ is designed:

$$Q_{Ld}=A_1V_1^{-1}(y)A_1\frac{\partial x}{\partial q}\dot{q}+A_2V_2^{-1}(y)A_2\frac{\partial x}{\partial q}\dot{q}+\frac{1}{\beta_e}(\dot{F}_{Ld}-K_{pL}\tilde{F}_L)\tag{32}$$

To achieve the Q_{Ld}, according to the property of the valve, the proportional valve's opening is:

$$x_v=\left[A_1V_1^{-1}K_{q1}g_1(P_1,\mathrm{sgn}(Q_{Ld}))+A_2V_2^{-1}K_{q2}g_2(P_2,\mathrm{sgn}(Q_{Ld}))\right]^{-1}Q_{Ld}\tag{33}$$

Replace the $A_1V_1^{-1}(y)Q_1+A_2V_2^{-1}(y)Q_2$ in (31) with (32)

$$\dot{\tilde{F}}_L=-K_{pL}\tilde{F}_L\tag{34}$$

Define the Lyapunov function:

$$V_2=\frac{1}{2}\tilde{F}_L^T\tilde{F}_L\tag{35}$$

$$\begin{aligned}\dot{V}_2&=\tilde{F}_L^T\dot{\tilde{F}}_L\\&=-\tilde{F}_L^TK_{pL}\tilde{F}_L<0\end{aligned}\tag{36}$$

So the force tracking error $\dot{\tilde{F}}_L$ will reach 0 asymptotically.

Lyapunov function of the whole system $V=V_1+V_2>0$ is positive define, and the derivate $\dot{V}=\dot{V}_1+\dot{V}_2<0$ is negative define, so the whole system could track the reference signal asymptotically.

IV. SIMULATION AND EXPERIMENTS

To verify the proposed controller, simulations and experiments are carried out. The MATLAB/Simulink is used in the simulation, the proposed algorithm is converted to MATLAB scripting language, and the manipulator model is expressed in the SimMechanics package.

In the simulation, the sample rate is 10kHz, and the supply pressure is set to be 7MPa, bulk modulus of the hydraulic oil is 70MPa. Other parameters obtained from the actual manipulator are list in TABLE Ⅱ.

TABLE II. PARAMETERS OF THE MANIPULATOR

Parameter Description	***Big Arm***	***Forearm***
Mass(Kg)	9.5	30~45
Mass center(m)	0.39	0.4~1
Inertia(Kg•m^2)	1.91	10~30
Piston area(m^2)	2.626×10^{-3}	2.626×10^{-3}
Rod end area(m^2)	2.022×10^{-3}	2.022×10^{-3}

The reference signal is defined as:

$$q_{1d}=\frac{\pi}{4}+\frac{\pi}{12}\sin\left(\frac{\pi}{6}t\right),q_{2d}=-\frac{\pi}{4}-\frac{\pi}{12}\sin\left(\frac{\pi}{6}t\right)\tag{37}$$

The controller parameters in the simulations and the experiments are set to be the same:

$$\begin{aligned}&\Gamma=diag\{1,10,10,100,100\},K_D=diag\{500,800\},K_{pL}=diag\{200,300\}\\&\Lambda=diag\{20,20\},K_s=diag\{30,30\}\end{aligned}$$

The simulation results is shown in Fig. 6, the joint angle could reach the desired trajectory in a short time, and the tracking error reach 0 asymptotically. The simulation results shows that the controller is effective for the manipulator control.

Then field test is carried out in the lab. To deploy the experiment system expediently, the xPC system is used in the experiments. There are host PC, target PC in the system, the data acquisition card (DAQ) is embedded in the target PC. The feedback joint angle signals are sent to the DAQ in the target PC. Then the target PC, sends the joint angle signal to host PC, then host PC running the MATLAB/Simulink software transfer the control signal to the power amplifier through the target PC, finally actuate the proportional valve.

The controller parameters remain unchanged, and the reference signal is same as the in （37）.

Experiments results is seen in Fig. 7, the amplitude and frequency are same with the simulation. Joint angle could quickly reach the desired trajectory even the initial error is

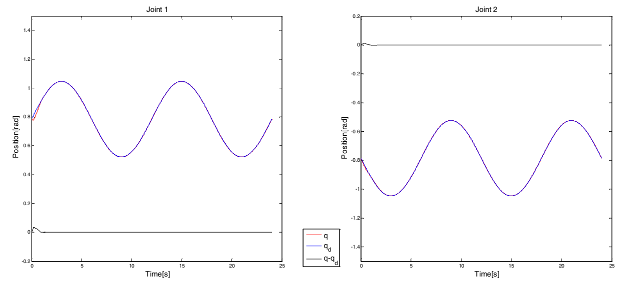

Fig. 6 The simulation results of the joint tracking control.

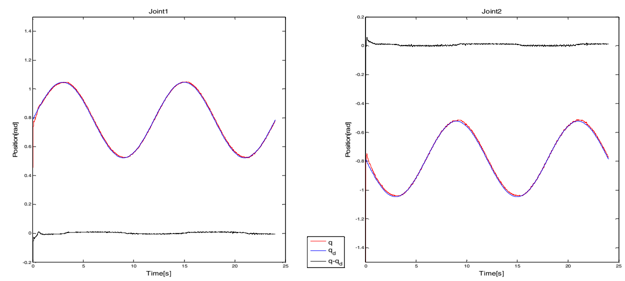

Fig. 7 the experiment results of the joint tracking control

large, no exceeding overshoot is observed, and the tracking error is small, within ±0.02 rad. Small amplitude oscillations can be seen in some parts of the curve, it's the character of the sliding mode control, the sliding term lead to the oscillations. The error can't be totally eliminated, the reasons are various, like nonlinear friction, transducer white noise, but most of the disturbances have been eliminated with the proposed controller.

V. Conclusion

In this paper, the overall system of the deep sea manipulator is studied, to realize the design objective, hydraulic actuators are redesigned to minimize the size, and improve the output torque, also pipeline and wire deploying problem is considered when design the actuators structure. Simulations and experiments are conducted on the manipulator to test its performance as well as the control algorithm, results show that the manipulator could tracking the reference signal rapidly, and the tracking error is negligible, so it could also be applied to track the reference signal provided by the master hand. The experiments results show that the preliminary task has been fulfilled, further study should be focused on the algorithm optimization.

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