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Research Article

Intelligent Control of a Novel Hydraulic Forging Manipulator

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The increased demand for large-size forgings has led to developments and innovations of heavy-duty forging manipulators. Besides the huge carrying capacity, some robot features such as force perception, delicacy and flexibility, forging manipulators should also possess. The aim of the work is to develop a heavy-duty forging manipulator with robot features by means of combination of methods in mechanical, hydraulic, and control field. In this paper, through kinematic analysis of a novel forging manipulator, control strategy of the manipulator is proposed considering the function and motion of forging manipulators. Hybrid pressure/position control of hydraulic actuators in forging manipulator is realized. The feasibility of the control method has been verified by the experiments on a real prototype of the novel hydraulic forging manipulator in our institute. The intelligent control of the forging manipulator is performed with programmable logic controller which is suitable for industrial applications.

1. Introduction

The use of manipulators in open die or free forging can be traced back about 60 years when development started in both Europe and the USA. Manipulators for heavy workpieces, that is, those in the region of 200 tons weight, have been developed steadily since that time, and currently there are a number of examples of computer-controlled fully automatic forging manipulators being used [1]. As a result of the practical use of the control system, the operators were released from mental stress, the training period for operators was reduced, the uniformity of forging quality was improved, and a higher production rate was attained [2].

Control of the manipulators involves rotational control in the continuous rotation and incremental angle rotation modes. The manipulator position requires integrated control with the press to achieve inches per press stroke while compensating for workpiece length increase due to cross-section area reduction of workpiece [3]. Vitscheff [4] demonstrates the need for compliance control when robots are used to manipulate the workpiece during forging. Specifically, the external forces exerted on the manipulator through its manipulation of the workpiece during forging steps must be minimized to avoid damage to the robot mechanism.

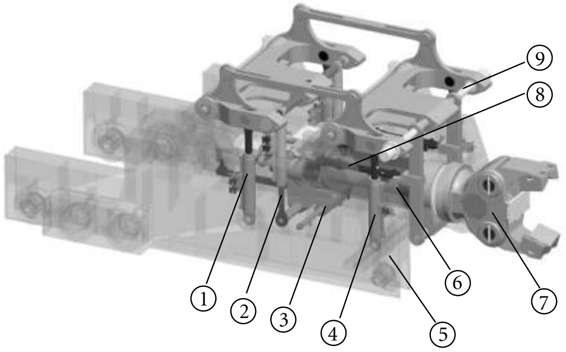
An ASEA robot was used as an open-die forging manipulator. The ASEA robot has an inbuilt Intel microprocessor which controls its arm and gripper movements in five axes. The robot was used in conjunction with a fielding hydraulic press [1, 5, 6]. The application of neural networks for compliance control of the forging robot was investigated. Effectiveness of the neural network-based compliance control module is evaluated through a full dynamic system simulation [7, 8]. An integrated forging plant, 25 MN open die press with 200 kN and 400 kNm manipulators, was built in 1999. The workpiece is put into position by two rail-bound manipulators with rotation and travel movements actuated by closed hydraulic circuits to reduce energy consumption and shocks and to improve positioning [9]. The rail-bound forging manipulator with a carrying capacity of 1600 kN and 4000 kNm load moment started its operation in 2007 at JSW. The manipulator supports a straight line peel movement as well as an accurate and stable positioning which is possible because of the special lever arrangement [10].

The increased demand for large-size forgings has led to developments and innovations all around the improvement of quality and productivity. Many efforts have been undertaken to research and develop heavy-duty forging manipulators. The researches in recent years focus on the mechanisms of forging manipulator, such as kinematic modeling and analysis [11, 12]; dynamic load analysis, dynamic stability, and behavior [13–15]; performance analysis and optimization [16, 17].

The forging manipulator is not only an equipment with huge carrying capacity, but also a robot with delicacy and flexibility, capable of picking up and putting down workpieces gently with force perception. The compliance is another required capability of heavy-duty forging manipulators. It is important of the promotion of quality, protection of manipulator, reduction of impact of heavy load, and energy saving. The overall aim of this work is to develop a heavy-duty forging manipulator with robot features by means of combination of methods in mechanical, hydraulic, and control field. The kinematic analysis of a novel forging manipulator is performed. On this basis, control strategy of the manipulator is proposed considering the function and action of forging manipulators. Hybrid pressure/position control of hydraulic actuators in forging manipulator is realized. The control of a real prototype of the novel hydraulic forging manipulator in our institute reaches the target of intelligent control.

2. Model of Control Object

This work focuses on the novel track-mounted forging manipulator used for heavy-duty manipulations in integrated open-die forging plants. This serial-parallel forging manipulator is newly designed in our institute. Its CAD model is shown in Figure 1.



(1) Rear lifting cylinder
(2) Tilting cylinder
(3) Rear side-shifting cylinder
(4) Front lifting cylinder
(5) Truck frame
(6) Gripper support
(7) Gripper
(8) Damping cylinder
(9) Front side-shifting cylinder

Figure 1: CAD model of the serial-parallel forging manipulator.

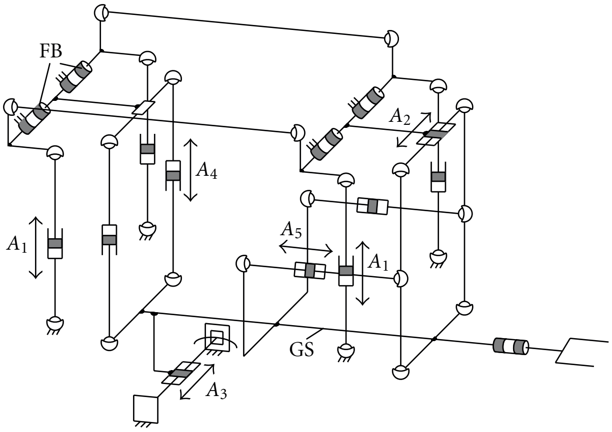


Figure 2: Geometric configuration of the serial-parallel forging manipulator.

The geometric configuration of the serial-parallel forging manipulator is shown in Figure 2. Between the fixed base (FB) and the gripper support (GS), there are three kinematic limbs: lifting mechanism closed loop, tilting limb, and buffer mechanism closed loop. The gripper support (GS) has 5 DOFs (3T2R). While the gripper obtains another DOF by a serially articulated rotation joint which connects the gripper with the gripper support, then the whole system has 6 DOFs in total. The active joints are five prism joints and a rotation joint, other joints are all passive. The five prism joints consist of front/rear lifting cylinder (A_1), front side-shifting cylinder (A_2), rear side-shifting cylinder (A_3), tilting cylinder (A_4), and damping cylinder (A_5). Rear lifting cylinders are used to improve mechanical properties and always keep synchronization with front lifting cylinders.

The major motion of the forging manipulator as shown in Figure 3 comprises of lifting T_a, tilting θ_a, and horizontal damping T_b.

Gripper lifting motion is driven by lifting cylinders

$$T_a = l_1\varphi, \tag{1}$$

where l_1 is the length of the lifting arm (O_2E), and φ is the rotation angle of the lifting arm. The relationship between φ and the displacement of lifting cylinders d_l is as follows:

$$d_l = \sqrt{\left[l_1(1-\cos\varphi)\right]^2 + \left(l_1\sin\varphi + d_{l0}\right)^2}, \tag{2}$$

where d_{l0} is the original length of the lifting cylinder.

Gripper tilting motion is driven by tilting cylinders

$$\theta_a = \alpha, \tag{3}$$

where α is the rotation angle of the gripper support. The relationship between α and the displacement of tilting cylinders d_t is as follows:

$$d_t = l_2\tan\alpha + d_{t0}, \tag{4}$$

where l_2 is the length of the gripper support (JK), and d_{t0} is the original length of the tilting cylinder.

Gripper horizontal damping motion is driven by damping cylinders

$$T_b = l_3\beta, \tag{5}$$

where l_3 is the length of the suspender (EJ), and β is the rotation angle of the suspender. The relationship between β and the displacement of damping cylinder d_d is as follows:

$$d_d = \sqrt{\left(d_{d0} - l_4\sin\beta\right)^2 + \left(l_4 - l_4\cos\beta\right)^2}, \tag{6}$$

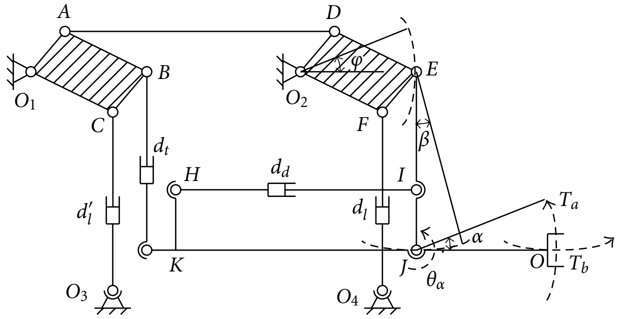


Figure 3: Geometric configuration of the major motion mechanism.

where l_4 is the length of the suspender (EI), and d_{d0} is the original length of the damping cylinder.

Define the output of the mechanism as T_a, θ_a, and T_b based on the realistic working condition, then for the input d_l, d_t, and d_d, each of the output variables are only related to one of the input elements. The input-output relationships are considered independently for each main motion. The major motion mechanism of the forging manipulator is decoupled. The control of the forging manipulator is simplified.

3. Control Strategy

The whole forging process can be divided into three stages of prepress, inpress, and afterpress. During the periods of prepress and afterpress, operations of the forging manipulator are the same: the gripper grasps the workpiece then places it on the lower die. During the period of inpress, the forging manipulator complies with the deformation of the workpiece. The control strategy of forging manipulator in these three conditions is discussed as follows.

(a) *Grasp the Workpiece.* Firstly, the horizontal and vertical position of the gripper is adjusted, and the workpiece on the bench is clamped by the gripper. Then the workpiece is lifted up by lifting cylinders with a constant lifting force which is greater than the total weight of the workpiece, gripper, and its support. When the expected height is exceeded, the position error will feed back to the constant force servosystem of lifting cylinders. This negative feedback of position makes the actual lifting force smaller than the setting value. In equilibrium, the actual lifting force equals the total weight of the workpiece, gripper, and its support, and the error of force equals the error of position multiplied a coefficient.

(b) *Place the Workpiece.* The workpiece is fed to the forging press, right over the lower die by the forging manipulator. Then decreasing the height setting value, the balance of force and position of lifting cylinders is broken. The actual lifting force is smaller than the total weight of the workpiece, gripper, and its support. So the workpiece moves down with the gripper. The decent velocity of the workpiece is determined by the change rate of the height setting value. When the workpiece touches the lower die, the pressure in lifting cylinders will change greatly for the workpiece begins to be supported by the lower die. At this moment, keeping the height setting value constant, then the force and position of lifting cylinders comes to a new balance.

(c) *Comply with the Workpiece.* During forging, when the workpiece is pressed by the upper die, extra force is applied on the gripper by the deformed workpiece. The force causes an increase of the load in lifting cylinders. Meanwhile, the servosystem is trying to keep the lifting force constant. As a result, the gripper moves down with the workpiece and applies the minimum reaction force on the deformed workpiece. When press is over, the upper die rises, and the external force exerted on the gripper disappears. The workpiece is lifted up to the original position by a constant lifting force. Then the manipulator carries the workpiece to feed. The next press is ready.

As discussed above, hybrid force/position control is the core principle in forging manipulator control. Figure 4 illustrates the hybrid control system that incorporates these ideas. Force control is the base of the control loop. In the balanced state, expect that the actual lifting force is equal to the weight of the workpiece, gripper, and its support, smaller than the force setting value. The error of force should be compensated by another control variable. The negative feedback of error of position is added to the control loop. When the actual lifting position is lower than the height setting value, the feedback of error of position is zero, and the gripper moves up under a constant lifting force. When the actual lifting position is higher than the height setting value, the negative feedback of error of position works, and the actual lifting force decreases until force and position tends to balance.

Owing to the newly designed mechanism of the forging manipulator which is decoupled as discussed in Section 2, the motions of side shifting, tilting, damping, and lifting are independent, and any one of the motions has no effect on the others. The control of the forging manipulator is simplified and only related to lifting cylinders. During the whole period of forging process, front side-shifting cylinders, rear side-shifting cylinders, and tilting cylinders keep their positions all the time. The deformation of workpiece in horizontal direction is absorbed by damping cylinders during the process of inpress. The compliance happens when the deformation resistance is larger than the setting value of pressure relief valve in damping hydraulic circuit. The reaction force in horizontal direction almost keeps constant that depends on the property of the relief valve.

4. Pressure/Position Control Method of Hydraulic Servosystem

A block diagram of the overall control scheme is shown in Figure 5. The system is composed of controller, power amplifier, servovalve, cylinder, pressure sensor, and position sensor. The PID controller equation is

$$u = K_p e + K_i \int e\,dt + K_d \frac{de}{dt}, \tag{7}$$

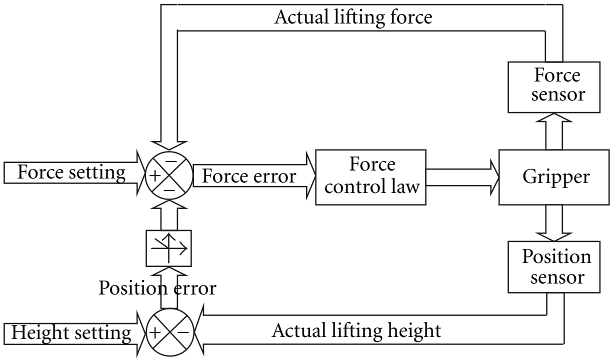


Figure 4: Construct of the hybrid control system.

where u is the output of controller, K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, $e = u_{p0} - u_p - K(u_{x0} - u_x)$ is the error signal, u_{p0} is the pressure command signal, u_p is the pressure detected by sensor, u_{x0} is the position command signal, u_x is the position detected by sensor, and K is the position error gain.

Because amplifier and sensors have negligible dynamics compared with the hydromechanical components, they can be described by their steady-state gain constants. The power amplifier equation is

$$i = K_a u, \tag{8}$$

where i is the power amplifier output current, K_a is the power amplifier gain, and u is the power amplifier input voltage. The pressure sensor equation is

$$u_p = K_{Fp} p, \tag{9}$$

where K_{Fp} is the pressure sensor coefficient and p is the pressure in cylinder. The position sensor equation is

$$u_x = K_{Fx} x, \tag{10}$$

where K_{Fx} is the position sensor coefficient and x is the position of cylinder piston.

The transfer function from input current to servovalve spool position can be approximated to

$$\frac{X_v}{I} = \frac{K_v}{T_v s + 1}, \tag{11}$$

where K_v is the servovalve gain and T_v is the servovalve time constant.

The linearized servovalve flow equation is

$$Q_L = K_q x_v - K_c P_L, \tag{12}$$

where Q_L is the load flow which represents the average of the flows in the lines, P_L is the load pressure difference, x_v is the valve displacement from neutral, K_q is the valve flow gain, and K_c is the valve flow-pressure coefficient.

Assume that the pressure in each chamber is everywhere the same and does not saturate or cavitate, fluid velocities in the chambers are small so that minor losses are negligible, line phenomena are absent, and temperature and density are constant. The load flow is consumed by leakage, flow to displace the actuator, and flow stored due to compressibility. The continuity equation for actuator is

$$Q_L = A\dot{y} + C_{tc} P_L + \frac{V_t}{4\beta_e} \dot{P}_L, \tag{13}$$

where A is the effective area of piston, y is the piston displacement developed by load, $C_{tc} = C_{ic} + C_{ec}$ is the total leakage coefficient of cylinder, C_{ic} is the internal leakage coefficient, C_{ec} is the external leakage coefficient, β_e is the effective bulk modulus of system, and V_t is the total volume of cylinder

As static and coulomb friction loads are neglected in a linearized analysis, the force balance equation for actuator can be presented as follows:

$$P_L = \frac{1}{A}\left(m_t \ddot{y} + B_c \dot{y} + K_L y\right) + \frac{F_L}{A}, \tag{14}$$

where m_t is the total mass of cylinder and load, B_c is the viscous damping coefficient of load, K_L is the spring gradient of load, and F_L is the arbitrary load on cylinder.

There are two command signals u_{p0} and u_{x0} in the control loop. If the actual position detected by the position sensor is less than u_{x0}, then the negative feedback of position error does not work. It is a pure pressure control loop. If the actual position is more than u_{x0}, then the error of position feeds back to compensate the difference between u_{p0} and balance pressure of workpiece weight. Thus, the workpiece can stay at a position with equilibrium of forces

$$u_{p0} - u_p - K(u_{x0} - u_x) = 0, \quad (K < 0). \tag{15}$$

Hybrid pressure/position control is very useful in manipulator lifting control where plunger cylinders are used. Based on this method, the intelligent control of forging manipulator is realized.

5. Analysis of Intelligent Control

5.1. Automatic Identification of Pressure Value Settings. As shown in Figure 6, when the workpiece is grasped by the manipulator, the hybrid pressure/position control method is used, and the pressure and position command values are set with original ones of p_0 and x_0. The workpiece is lifted up with a constant force created by hybrid control loop with command pressure p_0. When the position command value x_0 is exceeded, the negative position error feeds back to the pressure control loop, the actual pressure in system begins to decrease and will stop decreasing at the weight balance pressure. In equilibrium, the workpiece stops moving, and the actual lifting force equals the total weight of the workpiece, gripper, and its support. Record this actual balance pressure and use it as the pressure value settings in compliance control in forging process.

5.2. Automatic Identification of the Placement Height of Workpiece. As shown in Figure 7, supposing the workpiece is

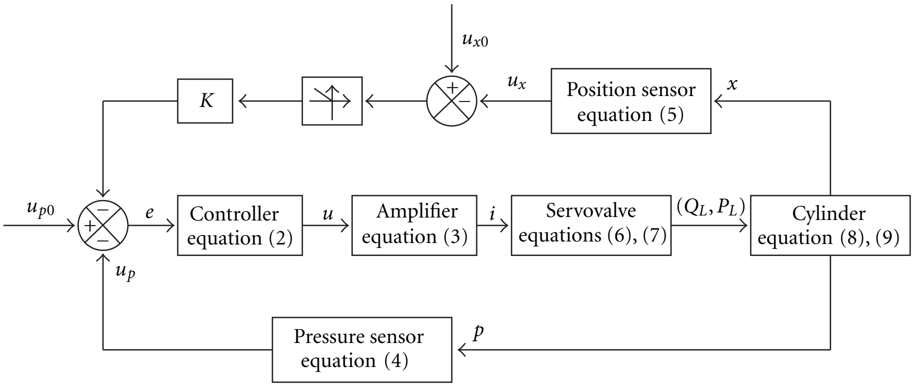


FIGURE 5: Block diagram of hybrid pressure/position control system.

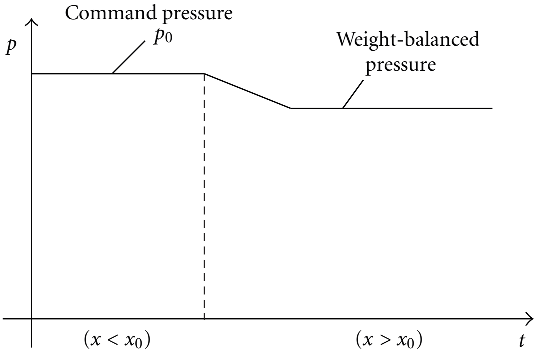


FIGURE 6: Illustration of the measurement of workpiece.

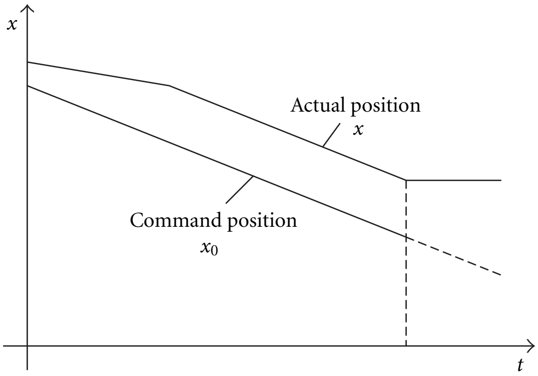


FIGURE 7: Illustration of the placement of workpiece.

staying at a position with equilibrium of forces, decrease the command position x_0 in a constant rate, then the balance has been broken. For the feedback of error of position increasing, the actual pressure will become smaller and try to go to another equilibrium state. The actual lifting force is less than the weight of the workpiece, gripper, and its support now. So the workpiece moves down until touching the lower die. At this moment, the actual pressure drops rapidly. According to the change rate of pressure, the workpiece placement state can be identified automatically. Keep the command position x_0 with the height value of workpiece position placed on the lower die. The pressure and position of lifting cylinders goes to a new balance.

5.3. Compliance in Vertical Direction and Move Up Automatically. As shown in Figure 8, when the workpiece is pressed by the upper die, the load on cylinder will increase for the deformation of workpiece; this process is called "inpress." In the mode of pressure/position control, the increased load makes the workpiece move down, and when $x < x_0$, the position error feed back does not work. During this period, the force acting on the workpiece by manipulator increases from weight balance pressure to the command pressure p_0, while it is still much smaller than the press force. Thus, the compliance in vertical direction is realized. When press is finished and upper die moves up, this process is called "afterpress," the load on cylinder decreases. The lifting force makes the workpiece move up until the pressure and position of lifting cylinders goes to a new balance.

6. Experiment Results

The experiments were executed on a real prototype of the novel hydraulic forging manipulator in our institute, as shown in Figure 9. The mechanism and hydraulic system of the manipulator is identical with a rail-bound forging manipulator with a carrying capacity of 2000 kN and 4000 kNm load moment which is designed by our institute. The main characteristics of this prototype are carrying capacity 60 kN, load moment 150 kNm, and installed power 130 kW. The hydraulic actuators are supplied by a constant pressure pump source and controlled by servoproportional valves with position transducer. A programmable logic controller performs all control actions.

Figure 10 demonstrates the measurement of the weight and the gravitational torque of workpiece. The controller attempts to maintain a constant pressure 4.2 MPa, and while the height of the workpiece position exceeds the preset command position 400 mm, the negative feedback of position works. When lifting cylinders stop moving, control returns to a stable steady state. The weight-balanced pressure can be identified from the curve, which is 3.55 MPa.

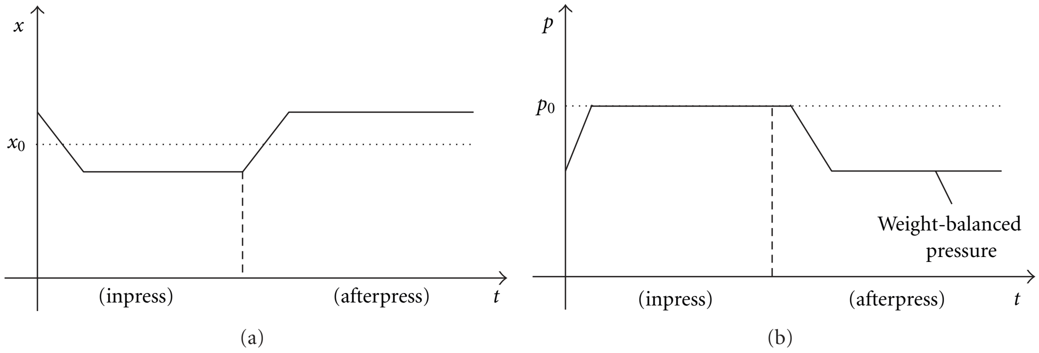


Figure 8: Illustration of the compliance during forging steps.

Figure 9: Prototype of the novel hydraulic forging manipulator.

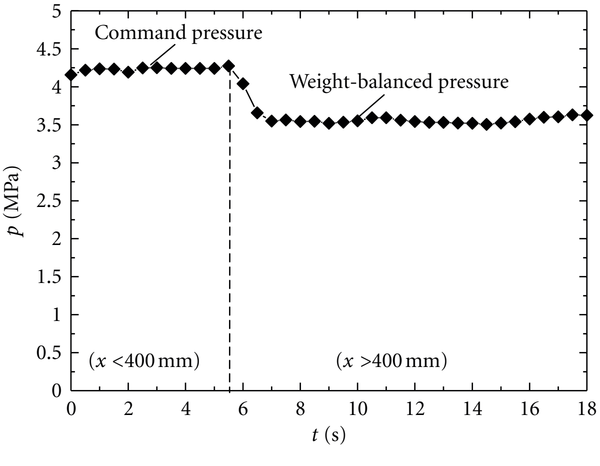


Figure 10: Pressure curve in lifting cylinder.

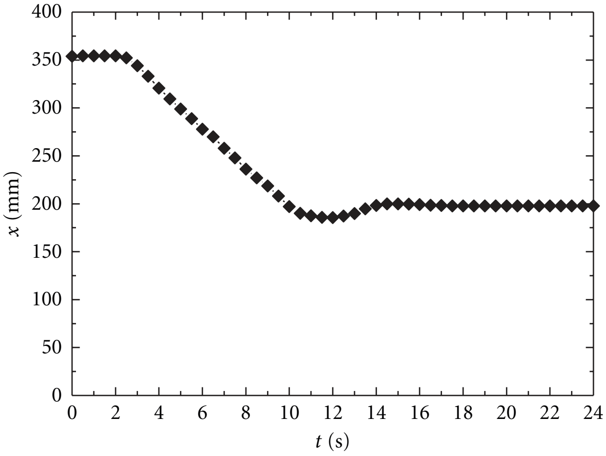


Figure 11: Position curve in lifting cylinder.

Figure 11 depicts the process of placing the workpiece on the lower die. While the command position signal diminished at a constant rate, the workpiece moved down trying to catch the rate. The touch of workpiece on the lower die can be detected by pressure changes in lifting cylinders. Lifting cylinders stayed on this position. The height of the workpiece placement can be found from the curve.

The experiment results show that the technique is straightforward and feasible. All the supposed control methods have been realized on the prototype of the forging manipulator. The experimental datum forms the base of further research on intelligent control of heavy-duty forging manipulators.

7. Conclusions

A novel hydraulic forging manipulator is proposed, with newly designed mechanism, intelligent control strategy, and improved hydraulic control method. The major motion mechanism is decoupled, thus the control of the forging manipulator is greatly simplified. Workpieces can be picked up and put down gently by forging manipulators with force perception. Moreover, the forging manipulator can comply with the external forces exerted on it by workpiece during forging steps. These are based on a new pressure control method and a hybrid pressure/position control method of hydraulic servosystem presented in this paper. All of the hydraulic control methods and intelligent control strategies have been verified by experiments on the prototype forging manipulator. This work provides the theoretical and practical foundation for further development of intelligent heavy-duty forging manipulators.

Acknowledgments

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