CRANE CONTROL SYSTEM WITH AN INDUSTRIAL ROBOT

Tamio ARAI, Hisashi OSUMI, Jun OHTA

Dept. of Precision Machinery Engineering
Fac. of Engineering, Univ. of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan

ABSTRACT

Most of existing industrial robots have much smaller load capacity than their own weight. Therefore it is very difficult for a robot to handle a heavy work such as a steel frame in a construction site. The purpose of this research is to develop a crane control system which can operate heavy works with a small-size robot. In this system a heavy work is suspended by a crane and a robot handles the work. A flexible arm is attached to the robot to avoid impulsive force on grasping the vibrating work. In this system, the robot is position-controlled, while the crane is velocity-controlled by the feedback signal from a strain gauge pasted on the flexible arm. Experiments with an industrial robot proved that this system is very efficient in the utilizing of robots for handling heavy works.

1. INTRODUCTION

Nowadays hundreds of robots are introduced in production lines in factories, but few in construction sites. The reason lies in the small payload of the robots. Most of industrial robots have much smaller payload comparing to their own weight.

We developed a crane control system which can operate heavy works with an industrial robot. The idea of compensating the gravity of a heavy work by a crane originates in the research on elevator assembly line[1]. A flexible arm is attached to the end point of an industrial robot in order to obtain compliance[2]-[5]. In this paper, we discuss the structure of the system, the control strategy, and the results of experiments.

2. STRUCTURE OF THE SYSTEM

In order to handle a heavy work suspended by a crane with a robot, we have to solve the problem of impulsive force applied to the robot on grasping a moving work. Compliance is required for robots to avoid the problem. The compliance can be obtained by the following ways:

1) decreasing servo stiffness of a robot,
2) using a flexible robot.

In the former, quick response is essential for a robot controller in comparison with the vibration period of the robot. Generally speaking, the vibration period of an industrial robot is very short and a robot controller has long time delay. Therefore, it is impossible to adopt the former way. In this system, the latter is introduced by means of a flexible arm attached to the rigid industrial robot, so that the robot may obtain passive compliance.

The schematic view of this system is shown in Fig.1. The work is suspended by a wire of the crane and is fixed to the robot through the flexible arm. The crane consists of a moving table and a wire-feed mechanism. In this system a part of the mechanical closed-loop includes flexibility.

The configuration of the system is shown in Fig.2. The signal from the strain gauge on the flexible arm is sent to personal computer PC9801F2 through a 12 bit A/D converter. The position of the crane is obtained by the encoder of the motor which drives the moving table. The computer is connected to the robot controller with a serial line, RS232C(9600 baud). The movement data of the robot in next 24 msec are sent to the controller. The crane is velocity-controlled by voltage command from the computer through a 12 bit D/A converter.

The specifications of the robot and the crane are indicated in Table.1 and Table.2. The crane is set at 3000 mm height from the floor and the length of the wire is 1800 mm. The length of the flexible arm is 1000 mm and the diameter is 10 mm. The spring constant measured at the tip is 98.0 N/m. The mass of the work is 3.89 kg. The vibration frequency of the work along a horizontal line is 0.8 Hz.

3. CONTROL STRATEGY

In this system it is necessary to reduce the vibration of the work in positioning. On the assumption that the wire, which suspends the work, is rigid in the vertical direction, we study the control strategy of reducing the vibration along the horizontal line.

3.1 Modeling of the control system

The work is modeled as a lumped mass. Additionally, both the flexible arm and the pendulum of the crane are respectively modeled as a spring shown in Fig.3. The work is supported by two springs, namely, the pendulum and the flexible arm. The block diagram is indicated in Fig.4. The parameters in the diagram are as follows:

u : position of the robot,
x_c : position of the crane,
x_m : position of the work,
e_r : input voltage of the robot,
e_c : input voltage of the crane,
M : mass of the work,
K : spring constant of the flexible arm and
K_c : spring constant of the pendulum.

3.2 Design of the control system

This system consists of three sub-systems, that is, a robot sub-system, a crane sub-system and a spring-mass sub-system. The state equation of the total system is expressed as Eq.(1).

$$\frac{d}{dt}\mathbf{x} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_r} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_c} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{K}{M} & 0 & \frac{K_c}{M} & 0 & -\frac{K+K_c}{M} & 0 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 & 0 \\ \frac{K_{ar}}{T_r} & 0 \\ 0 & 0 \\ 0 & \frac{K_{ac}}{T_c} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \mathbf{e} \tag{1}$$

where

$$\mathbf{x} = [\, u \quad \dot{u} \quad x_c \quad \dot{x}_c \quad x_m \quad \dot{x}_m \,]^T, \qquad \mathbf{e} = [\, e_r \quad e_c \,]^T,$$

T_r : time constant of the robot controller,
T_c : time constant of the crane controller,
K_{ar} : ratio of the robot velocity to input voltage, and
K_{ac} : ratio of the crane velocity to input voltage.

DC motors are utilized in both the crane and the robot. Each motor is velocity-controlled by voltage input. The reaction force from the vibrating work to the motors are neglected.

Single but complicated servo system can be designed which makes all the factors of $\mathbf{x}$ follow the desired states. But it is more agreeable to design two separated control systems because the accuracy and control performance of each control system are different from each other. Consequently, cooperative control is introduced. In order to simplify the control strategy, we regard two systems as a master and a follower.

When a task requires quick response, it is desirable to utilize the crane, which has larger torque limit, for reducing vibration of the work. Moreover, considering the accuracy of a robot and a crane, we conclude that it is preferable to use a robot as a master and a crane as a follower. We design a control system of the crane which can follow the robot motion without the vibration of the work. The total system can be divided into the following two control systems.

$$\frac{d}{dt}\begin{bmatrix} u \\ \dot{u} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{T_r} \end{bmatrix} \begin{bmatrix} u \\ \dot{u} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_{ar}}{T_r} \end{bmatrix} e_r \tag{2}$$

$$\frac{d}{dt}\begin{bmatrix} x_c \\ \dot{x}_c \\ x_m \\ \dot{x}_m \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{1}{T_c} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{K_c}{M} & 0 & -\frac{K+K_c}{M} & 0 \end{bmatrix} \begin{bmatrix} x_c \\ \dot{x}_c \\ x_m \\ \dot{x}_m \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_{ac}}{T_c} \end{bmatrix} e_c + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K}{M} \end{bmatrix} u \tag{3}$$

Since the robot is position-controlled, position feedback loop is added to the former system, Eq.(2). The latter system, Eq.(3), consists of a crane sub-system and a spring-mass sub-system, and the position of the robot is understood as a disturbance. In this system a strain gauge pasted on the flexible arm is employed as a sensor. The crane is controlled by both the deflection of the arm and the states of the crane. The transfer function of the position of the work, $X_m(s)$, against the position of the robot, U(s), has two zeroes. Using the pole placement method, a feedforward signal based on the velocity and acceleration of the robot is provided. In this system the acceleration of the deflection of the arm is also used instead of the position of the crane. The block diagram is shown in Fig.5 and the transfer function is expressed as follows:

$$G(s) = \frac{b_2 s^2 + b_1 s + b_0}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{4}$$

$$\begin{aligned}
a_4 &= T_c M \\
a_3 &= M(K_{ac} k_4 + 1) \\
a_2 &= T_c (K + K_c) + K_{ac} K_c k_3 \\
a_1 &= (K + K_c)(K_{ac} k_4 + 1) + K_{ac} K_c k_2 \\
a_0 &= K_{ac} K_c k_1
\end{aligned}$$

$$\begin{aligned}
b_2 &= T_c K + K_{ac} K_c (k_3 + k_6) \\
b_1 &= K(K_{ac} k_4 + 1) + K_{ac} K_c (k_2 + k_5) \\
b_0 &= K_{ac} K_c k_1
\end{aligned}$$

where

k_1 : feedback gain of the arm deflection,
k_2 : feedback gain of the velocity of the arm deflection,
k_3 : feedback gain of the acceleration of the arm deflection,
k_4 : feedback gain of the crane velocity,
k_5 : gain of the robot velocity and
k_6 : gain of the robot acceleration.

In the design of the crane control system, the poles of the transfer function must be arranged so as not to occur the overshooting of the work at a destination. The feedback gains, therefore, should be determined so that the system may provide critical damping in handling the heaviest work in a construction site. In using these poles, the offset of the deflection occurs inevitably in the moving of the robot. For example, on condition that the robot moves at a fixed speed of v, the offset, d, is represented by Eq.(5).

$$d = \left(\frac{k_4 - k_5}{k_1} + \frac{1}{K_{ac} k_1} \right) v \tag{5}$$

The velocity and acceleration of the deflection of the arm are calculated as the difference between the two sequential sampling data. Therefore the phase shift is produced among the feedback factors. The feedback gains are determined by making reference to the results of simulations.

4. THE EXPERIMENTAL RESULTS

The robot is moved along the direction of the crane. The velocity of the robot is 100 mm/s and the move distance is 400 mm. This system is designed as a second order system through the gains, k1, k2, k3, k4, k5 and k6. The two poles of the system are located at -4.0 and -8.0. The result of a simulation in the transporting and positioning processes is shown in Fig.6(a).

The vertical axis means the deflection of the arm and the horizontal axis means time. The robot begins to move at time 0 sec and stops at 4 sec. A small vibration is observed in both processes. It is caused by the phase shift between the feedback factors. The offset of the deflection of the arm is confirmed in the transporting process. The offset accords with the theoretical result, 3.75 cm. The positioning of the work is completed in one second after the robot stops.

The experimental result is shown in Fig.6(b). The larger vibration than that of the simulation is observed because of the error of the model. But the settling time and the offset of the arm are similar to those of the simulation. The work doesn't overshoot at the destination.

5. CONCLUSIONS

In this research we develop a crane control system to utilize a popular industrial robot for heavy works. This system has the following characteristics.

1) The work operated by a robot is suspended by a crane.
2) Flexibility is employed in a robot.

As for the control strategy, the deflection of the arm and the velocity of the crane are fed back to the velocity command of the crane. The motion of the robot is fed forward to the command. By determining the feedback gains so as not to occur the overshooting of the work, the transporting and positioning of the work was achieved without vibration.

From the results of the experiments, it becomes clear that this system is very efficient in operating heavy work with a small-sized industrial robot. This idea is applicable in a construction site.

References

[1] Matsui,T.,Amiya,S., Kobashi,S., Kikuchi,K., Tokoro,Y., Niinomi,T.: "Application of Robots to Assembly Lines", THE HITACHI HYORON, Vol. 64, No. 12, pp.33-38 (Dec. 1982). (in Japanese)

[2] Osumi,H., Arai,T.: "Heavy Work Assembly with a Small Robot", Proc. 3rd Meet. Robotics Soc. Jpn., pp.69-70 (Nov. 1985). (in Japanese)

[3] Osumi,H., Arai,T., Ohta,J.: "Heavy Work Assembly with a Flexible Arm Robot", Proc. Spring Meet. Jpn. Soc. Precis. Eng., pp.711-712 (Mar. 1987). (in Japanese)

[4] Osumi,H., Ohta,J., Arai,T.: "Development of Heavy Work Assembly System with a Small-size Robot (1st report)", Proc. 5th Meet. Robotics Soc. Jpn., pp.487-488 (Nov. 1987). (in Japanese)

[5] Ohta,J., Osumi,H., Arai,T.: "Development of Heavy Work Assembly System with a Small-size Robot (2nd report)", Proc. 5th Meet. Robotics Soc. Jpn., pp.489-490 (Nov. 1987). (in Japanese)

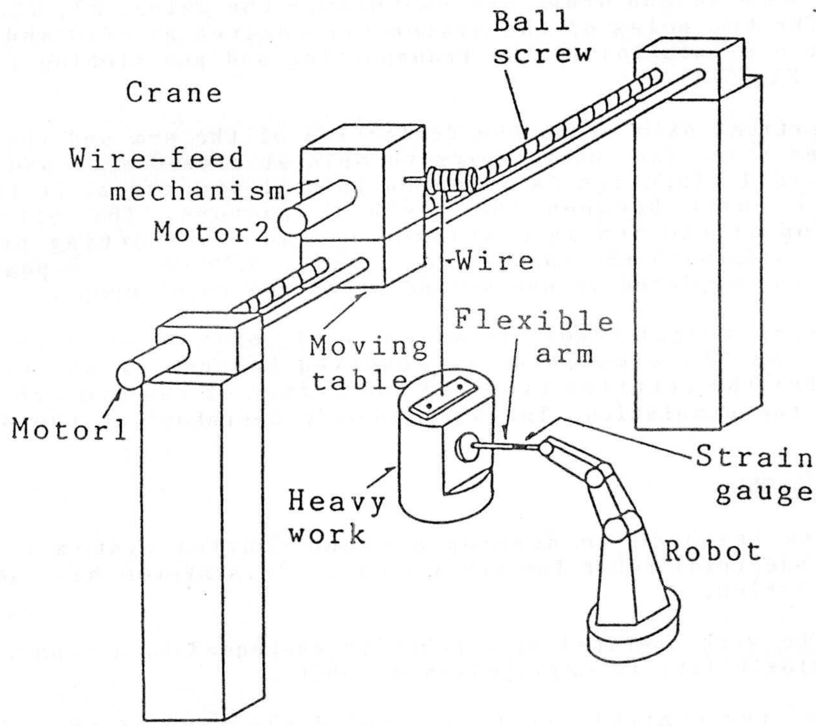


Fig. 1. Schematic view of the crane control system

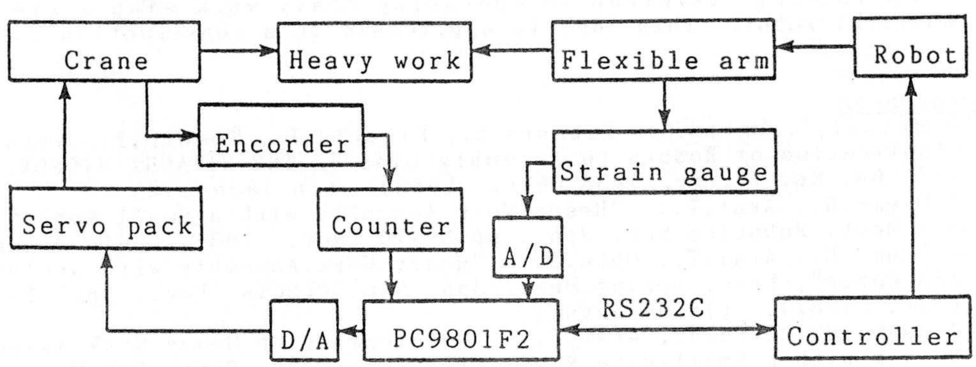


Fig. 2. Configuration of the crane control system

Table 1. Specification of the robot

d. o. f.	5
load capacity	3 kg
body weight	110 kg
repeatability	± 0.1 mm

Table 2. Specification of the crane(moving table)

working distance	1000 mm
maximum velocity	500 mm/sec
minimum step	0.05mm

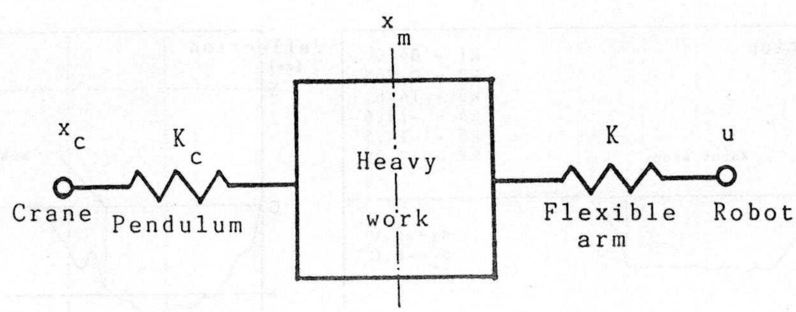


Fig. 3. Dynamic model of the spring-mass system

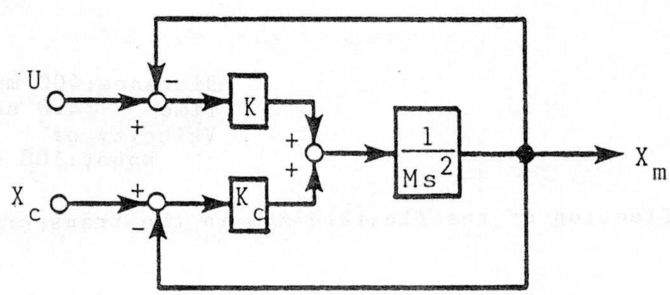


Fig. 4. Block diagram of the spring-mass system

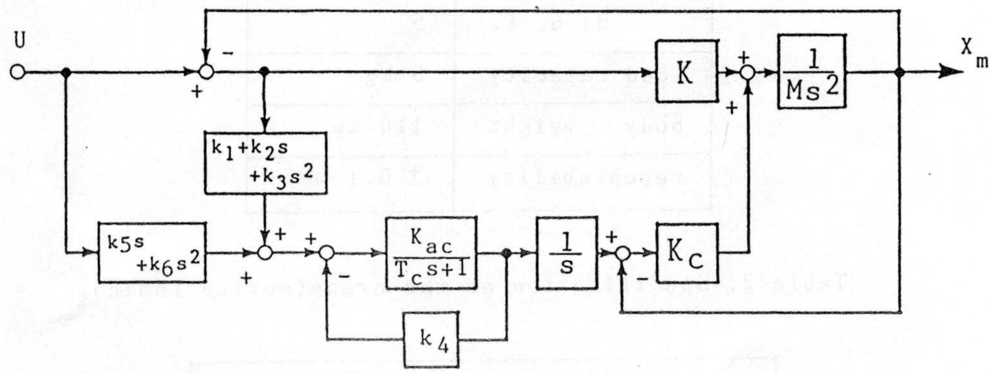
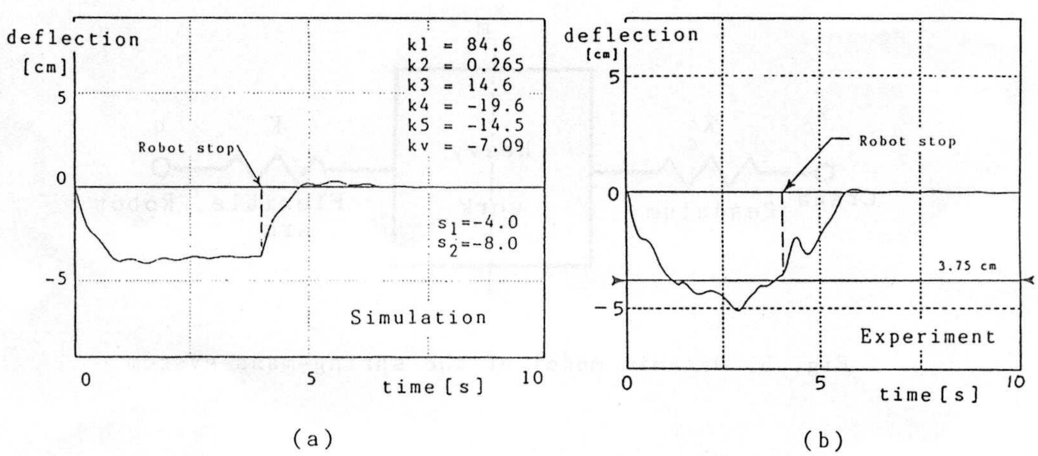


Fig. 5. Block diagram of the crane control system



(a) (b)

Distance:400 mm
Time :4.0 sec
Velocity of
Robot:100 mm/sec

Fig. 6. Deflection of the flexible arm in the transporting process