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Development of Tele-operation System for a Crane without Overshoot in Positioning

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Abstract— **A tele-operation system for a crane is developed. The crane consists of a small actuator and a large actuator in x and y direction respectively. The large actuators are controlled by input signals from an operator and the small actuators are used as a regulator and feedback controlled by a wire angle sensor. Since a motion of the suspended object can be approximated as a second order system, overshoots of the object inevitably happen at the moment when the operator give a stop command to the system. To avoid this overshoots, a novel user interface is developed where operators indicate via points or target point of the object on a monitor screen from the camera imaging the scene below the crane. The system interpolates the via points by using four order functions and give the velocity commands to the crane until the inputs of the via points are stopped. The final point is regarded as the target point. From experimental results, the effectiveness of the developed control system and its control algorithm is verified.**

I. Introduction

TO tele-operate second order systems such as cranes or flexible arms like Canada Arm mounted on a space shuttle, vibration becomes a problem because of their natural property, which degrades control performance of the system, such as positioning accuracy or takt time. Moreover, in such tele-operation systems for the second order systems, overshoots of the object inevitably happen at the moment the operator give a stop command to the system. To develop tele-operation systems for the second order systems, these two problems should be overcome.

In this paper a tele-operation system for a 2 dimensional crane is developed. There are many studies for crane control in most of which open loop control commands are calculated based on crane mathematical models and feedback control are also installed[1],[2]. These systems work well when the crane model is accurate and the effect of disturbance on the system is very small. However, these open loop commands can not be used in tele-operation systems because the control commands are given by operators. Installation of a regulator by feedback control is a practical solution for the reduction of swinging motions of the suspended object[3], but time constant of large cranes are usually very large, which causes the difficulty of the installation of feedback control to the crane. In addition, even if the installed regulator works well, overshoots of the suspended object inevitably happen at the moment when the operator gives a stop command to the controller at a target point. Therefore, it is very difficult to position suspended objects by walls. There are also many studies about tele-operation of cranes[4],[5]. However, the problem of overshoot hasn't been dealt with until now.

In this paper, a new crane control system using macro-micro servo concept is developed and installed into the crane mechanism in x and y driving directions in horizontal plane. The driving mechanism in each direction consists of a large actuator and a small actuator. These are connected serially. The large actuator is controlled by operator's command and the small actuator is controlled by feedback signals obtained by wire angle sensors.

To solve the problem of overshoot, a novel user interface is developed. A scene below the crane obtained by a CCD camera is displayed on a monitor screen in front of the operator. When the operator clicks a point on the screen, the point is regarded as the target point of the suspended object and the crane starts to the point. If the operator clicks other points continuously, the latest clicked point is regarded as the target point and other points are regarded as via points.

First, the abstract of the developed crane system is overviewed in Section II. Then a control algorithm for macro-micro servo system is designed in Section III. In Section IV, the details of the system are illustrated and some fundamental experiments are done for the verification of the effectiveness of the developed system. The results are summarized in Section V.

II. Developed Crane System

A. Abstract of System

The configuration of the developed tele-operation system for the crane is shown in Fig.1. The system consists of a crane, user interface with a monitor screen and a controller of the crane. A CCD camera is fixed downward at the upper end of the wire which takes scenes below the crane as shown in Fig.2. The operator gives a series of target points to the controller by clicking on the monitor screen where the scene below the crane is displayed(Fig.3(a)). The controller regards the latest point as the target point and other points as via points. The desired path is designed by connecting adjacent points with a straight line(Fig.3(b)). Then the crane controller calculates the desired time trajectory of the suspended object by using a constant velocity and four order functions, and moves the object to the target point via

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other points(Fig.3(c)). The trajectory is modified whenever the new target point is sent to the controller from the operator(Fig.3(d)).

B. Structure of Crane System

The schematic view of the crane system is shown in Fig.4. The crane moves in x and y direction in a horizontal plane and also has a wire feed mechanism. Ball screw mechanisms driven by DC servo motors are used as cranes in x and y directions respectively. In each direction, the crane has two degrees of freedom which consists of a large ball screw and a small ball screw connected serially.

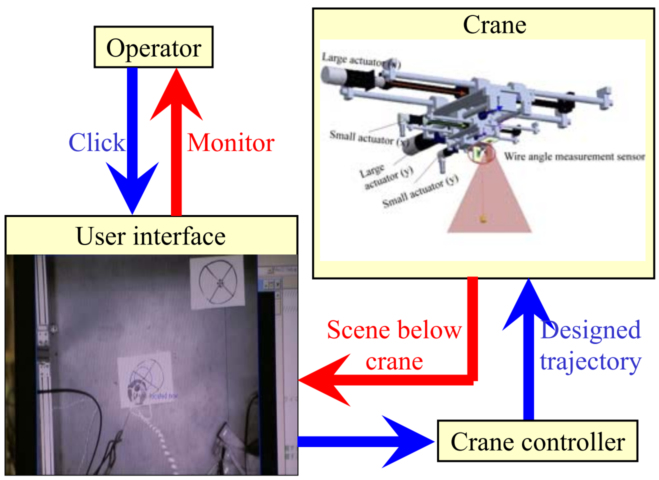


Fig.1 Configuration of tele-operation system

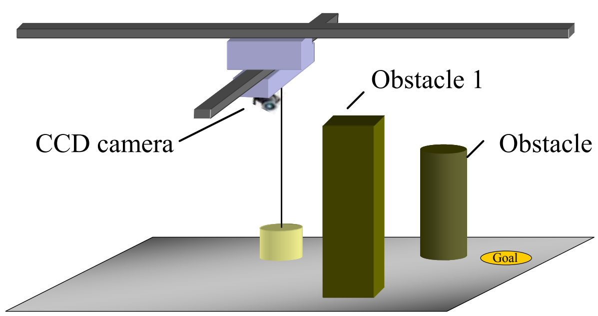


Fig.2 Schematic view of crane and environment

C. Wire angle measurement sensor

A wire angle measurement system developed in [6] is installed at the top of the wire feed mechanism which can measure the wire angle in two dimensional directions with an accuracy of 0.1 degree.

Figure 5 shows a schematic view of the sensor system using two CCD cameras. The sensor coordinate system is defined as shown in Fig.6. The x and y axes of the sensor coordinate are set on a horizontal plane near the upper end of a wire, and the z axis is aligned to the wire at the equilibrium point. Two cameras are placed on the x and y axis respectively. From the simultaneously obtained two images of the wire, the wire angles are calculated.

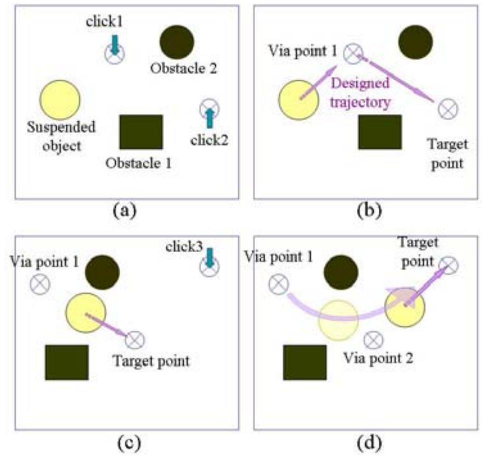


Fig.3 Operation procedure

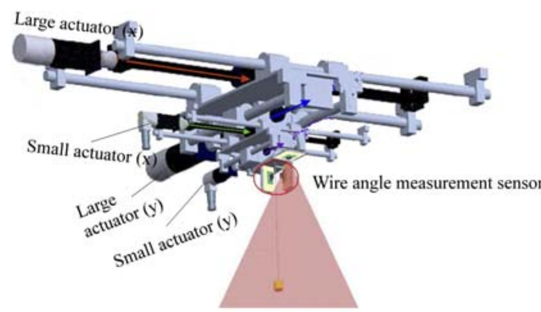


Fig.4 Structure of crane with large and small crane

The principle of measuring wire angles is shown in Fig.6. Two image coordinate systems Σ_1 and Σ_2 are fixed at each center of the CCD image plane whose z axis is the same as the optical axis of each lens. The upper and lower ends of the projected wire image in each CCD image are expressed as $({}^iu_u, {}^iv_u)$ and $({}^iu_l, {}^iv_l)$ in the image coordinate Σ_i(i=1,2). From $({}^iu_u, {}^iv_u), ({}^iu_l, {}^iv_l)$ and the lens centers, two planes including the wire are derived. The wire angle can be obtained as the cross line of these two planes.

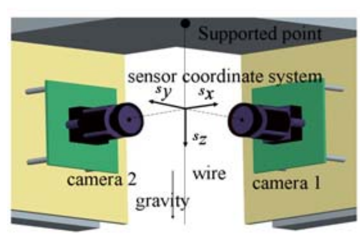


Fig.5 Schematic view of the sensor system

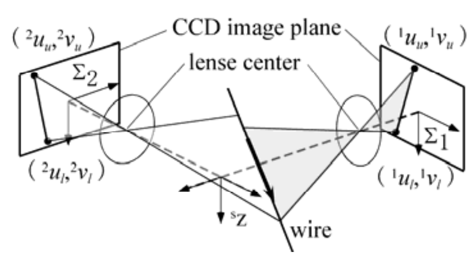


Fig.6 Principle of measuring wire angle

III. DESIGN OF CONTROLLER

A. Dynamic model of crane

Many algorithms for motion control of a redundant manipulator consisting of a macro manipulator and a micro manipulator connected serially have been proposed. Macro-micro manipulator systems can be seen in various applications, such as space robotics, human interface systems and accurate positioning[7]-[10]. In these applications, macro-micro manipulators are used for improving dynamics of manipulator systems, vibration control of long arms and positioning accuracy. Here, the concept of the macro-micro system is used for achieving high frequency response and high resolution of positioning. The large actuator is used for tracking desired trajectories and the small actuator is used as a servo regulator for reducing swinging motion of the suspended object. Since the swinging motions due to disturbance are reduced by the small actuators, the suspended object can be positioned without overshoot by controlling the object considering dynamics.

It is assumed that the swinging motion of the suspended mass is small enough for neglecting the coupling effect between x and y direction, the dynamic model of x and y direction can be modeled as shown in Fig.7 and the dynamics of the system in x direction can be expressed as Eq.(1),

$$\begin{aligned} F_{2x} &= M_{2x}\ddot{x}_c + m(\ddot{x}_c + l\ddot{\phi}_x \cos\phi - l\dot{\phi}_x^{\,2}\sin\phi) \\ F_{1x} &= M_{1x}\ddot{x}_1 + F_{2x} \\ ml^2\ddot{\phi}_x &= -ml\cos\phi_x \ddot{x}_c - mlg\sin\phi_x \\ x_c &= x_1 + x_2 \end{aligned} \quad . \qquad (1)$$

The parameters in Eq.(1) are shown in Fig.7 and as follows: x_1: position of the large actuator, x_2: displacement of small actuator w.r.t. large actuator table, x_c: position of the crane(pulley), x: position of the suspended object, ϕ_x: tilt angle of wire, F_{1x}: large actuator force, F_{2x}: small actuator force, m: mass of suspended object, l: wire length, and g: acceleration of gravity. The masses M_{ix} and M_{iy} (i=1,2) of the moving tables in x and y directions are different because the driven mechanism in y direction is mounted on the moving table in x direction.

B. Desired trajectory of the object

As explained in Section II, the series of the input points from the operator are transformed into the desired trajectory of the suspended object.

When the i+1th clicked point is given by the operator as shown in Fig.8, the distance between the i-th and i+1th points are decomposed into x and y components, d_{xi}, d_{yi}, and the desired trajectories are designed in x and y direction respectively. Since the dynamics in the both directions can be regarded as independent of each other, the trajectory can be designed respectively. So, the trajectory in x direction will be explained below. The required trajectory in y direction can also be obtained in the same manner.

In order to accelerate or decelerate the object suspended by a wire, it is necessary to tilt the wire which is proportional to the desired acceleration of the suspended object $\ddot{x}_d(t)$. Therefore, the required trajectory of the crane (the upper end of the wire) $x_{cd}(t)$ should be shifted by $\ddot{x}_d(t)$ as expressed in Eq.(2).

$$x_{cd}(t) = x_d(t) + \frac{l}{g}\ddot{x}_d(t) \qquad (2)$$

Since the velocity of the crane $\dot{x}_c(t)$ can not be changed discontinuously, the differentiation of the acceleration of the desired trajectory $\ddot{x}_d(t)$ must be continuous. If $\ddot{x}_d(t)$ is continuous, the object can be positioned at the target position without overshoot because feed forward terms for compensating the object dynamics can be calculated. Otherwise the overshoot is inevitable. The desired trajectory of the suspended object between two adjacent points should be designed so as to satisfy the above condition.

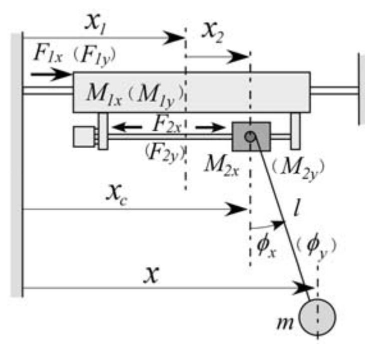


Fig.7 Model of crane system (x direction)

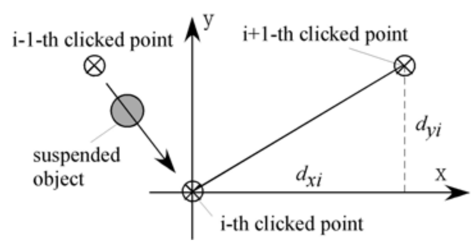
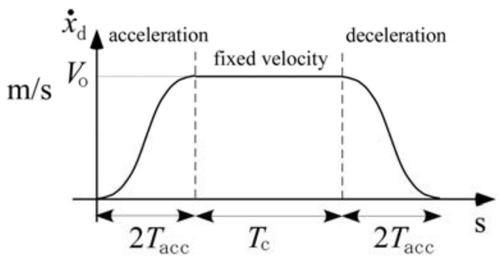


Fig.8 Design of target trajectory of suspended object

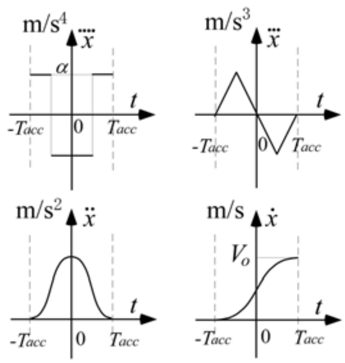
The desired trajectory is designed as follows.

First, the time $2T_{acc}$ for acceleration or deceleration is determined in advance, and a fixed velocity V_o is used in the rest of the section as shown in Fig.9(a). V_o is determined considering the actuator power and the length between two adjacent points. A four order function shown in Fig.9(b) is used for interpolation during $2T_{acc}$. The time optimal control input can also be used for interpolation instead, but it is not useful because it is time-consuming and it can not be adapted for the change of target points.

If an additional point is given like Fig.8, the trajectory between the former latest point and the additional point is calculated in the same manner. Then, by adding these two trajectories as shown in Fig.10, the trajectory is revised. Just by adding two velocity trajectories, the object can be positioned at the final target point without positioning error.

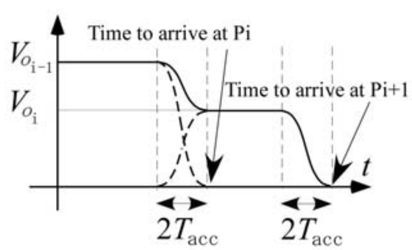


(a) Desired velocity of suspended object
by using a fixed velocity and interporation



(b) Fourth order function for interpolation

Fig.9 Desired velocity between two adjacent points



V_{oi} is the fixed velocity between the i-th and i+1-th points.

Fig.10 Superposition of two target trajectories

The velocity between two points and the acceleration time T_{acc} is calculated considering the maximum force and velocity of the crane. The procedure of calculating T_{acc} and the fixed velocity V_o is shown below.

The desired trajectory of the crane $x_{cd}(t)$ achieving the trajectory in Fig.9 is expressed as Eq.(3) by using V_o. The origin of the time t=0 below is the midpoint of the acceleration or deceleration period for simplicity, but it can easily be modified to the actual control time.

$$\begin{cases} -T_{acc} \le t \le -\frac{T_{acc}}{2} : \ddot{x}_{cd} = \frac{\alpha}{2}(t+T_{acc})^2 + \frac{\alpha l}{g} \\ -\frac{T_{acc}}{2} < t \le \frac{T_{acc}}{2} : \dot{x}_{cd} = -\frac{\alpha}{2}t^2 + \frac{\alpha}{4}T_{acc}^2 - \frac{\alpha l}{g} \\ \frac{T_{acc}}{2} < t \le T_{acc} : \dot{x}_{cd} = \frac{\alpha}{2}(t-T_{acc})^2 + \frac{\alpha l}{g} \end{cases}$$

$$\begin{cases} -T_{acc} \le t \le -\frac{T_{acc}}{2} : \dot{x}_{cd} = \frac{\alpha}{6}(t+T_{acc})^3 + \frac{\alpha l}{g}(t+T_{acc}) \\ -\frac{T_{acc}}{2} < t \le \frac{T_{acc}}{2} : \dot{x}_{cd} = -\frac{\alpha}{6}t^3 + (\frac{\alpha}{4}T_{acc}^2 - \frac{\alpha l}{g})t + \frac{\alpha}{8}T_{acc}^3 \\ \frac{T_{acc}}{2} < t \le T_{acc} : \dot{x}_{cd} = \frac{\alpha}{6}(t-T_{acc})^3 + V_o + \frac{\alpha l}{g}(t-T_{acc}) \end{cases} \quad (3)$$

$$\alpha = \frac{4V_o}{T_{acc}^3} \quad g: acceleration\ of\ gravity$$

From Eq.(3), the maximum values of the required force and velocity for the crane during $2T_{acc}$ are obtained as Eq.(4) and Eq.(5).

$$\begin{aligned} F_{2x\max} &= (m+M_{2x})\ddot{x}_{c\max} \\ F_{1x\max} &= M_{1x}\ddot{x}_{c\max} + F_{2x\max} \end{aligned} \quad (4)$$

$\ddot{x}_{c\max}$ is the maximum acceleration required for the crane in x direction and obtained as follows.

$$\begin{cases} 4\sqrt{\frac{l}{g}} \le T_{acc} : \quad \ddot{x}_{c\max} = \frac{V_o}{T_{acc}} - \frac{4V_o l}{gT_{acc}^3} \\ T_{acc} < 4\sqrt{\frac{l}{g}} : \quad \ddot{x}_{c\max} = \frac{V_o}{2T_{acc}} + \frac{4V_o l}{gT_{acc}^3} \end{cases}$$

The maximum velocity $\dot{x}_{c\max}$ required for the crane in x direction is calculated as follows.

$$\begin{cases} \sqrt{\frac{24l}{11g}} \le T_{acc} : \quad \dot{x}_{c\max} = V_o \\ T_{acc} < \sqrt{\frac{24l}{11g}} : \quad \dot{x}_{c\max} = V_o(\frac{1}{12} + \frac{2l}{gT_{acc}^2}) \end{cases} \quad (5)$$

In the lower case of Eq.(5), the maximum velocity appears at $t = -T_{acc}/2$, and the upper case at $t = T_{acc}$. The moving distance d_{acc}, during the acceleration or deceleration is calculated as Eq.(6).

$$d_{acc} = T_{acc}V_o \quad (6)$$

The shorter the moving distance d_{acc} during the acceleration or deceleration is, the more flexible the tele-operation system becomes. So, the acceleration time T_{acc} should be as short as possible. On the other hand, the maximum velocity required for the crane becomes larger almost inversely proportional to the square of T_{acc} as shown in Eq.(5). Since the required velocity for the crane should not be too large, T_{acc} is determined as Eq.(7).

$$T_{acc} = \sqrt{\frac{24l}{11g}} \tag{7}$$

This is the shortest acceleration time among the trajectory whose maximum velocity doesn't exceed V_o. The maximum acceleration required for the crane in this case is obtained as Eq.(8).

$$\ddot{x}_{c\max} = \frac{7V}{2T_{acc}} \approx \frac{3V_o}{T_p} \quad , T_p = 2\pi\sqrt{\frac{l}{g}} \tag{8}$$

From Eq.(5) and Eq.(8), the relationship between maximum forces required for the actuators and the velocity V_o can be obtained. The velocity V_o must be determined so that the maximum force required for the actuators should not exceed the capability of actuators.

The relationship among T_{acc}, V_o, time for the fixed velocity section T_c, and the distance between the adjacent points d_x, is expressed as $V_o(2T_{acc} + T_c) = d_x$. The desired values of T_{acc} and T_c may change according to the wire length or applications as shown in Eq.(7), therefore, the preferable V_o should be determined considering the property of the target applications.

The procedure of determining the above parameters is as follows:

1) T_{acc} is determined by Eq(7) in advance. Once the value of T_{acc} is determined, it isn't allowed to change the value so that the superposition shown in Fig.10 should always be satisfied.
2) V_o is determined according to the velocity and forces capability of the crane, the distance between two adjacent points, and applications.
3) If the distance d_x between the adjacent points is smaller than the value $2T_{acc}V_o$, V_o is modified as Eq.(9).

$$V_o = \frac{d_x}{2T_{acc}} \tag{9}$$

C. Servo systems for large and small actuators

The small actuator is used just for reducing the swinging motions of the suspended object caused by disturbance. Moreover, since the working range of the small actuator is very narrow, it is desirable to keep its position as near to the origin of the working range as possible. Therefore, the desired target trajectory of the large and the small actuators x_{1d}, x_{2d}, are determined as Eq.(10).

$$\begin{aligned} x_{1d}(t) &= x_{cd}(t) \\ x_{2d}(t) &= 0 \end{aligned} \tag{10}$$

The large actuator can be controlled by the input torque expressed by Eq.(11):

$$F_{1x} = (M_{1x} + M_{2x} + m)\ddot{x}_{cd} + k_v(\dot{x}_{cd} - \dot{x}_1) + k_p(x_{cd} - x_1), \tag{11}$$

where k_v and k_p are velocity feedback gain and position feedback gain respectively. They are determined so that the position error of the large actuator converges to zero as soon as possible.

To reduce the swinging motion of the object, a servo regulator is installed into the small actuator controller. The state equation of the small actuator and the object is expressed as Eq.(12).

$$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & mg/M_{2x} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -(m+M_{2x})g/M_{2x}l & 0 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 1/M_{2x} \\ 0 \\ -1/M_{2x}l \end{bmatrix} F_{2x} + \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{bmatrix} \ddot{x}_1 \tag{12}$$
$$\mathbf{x} = \begin{bmatrix} x_2 & \dot{x}_2 & \phi_x & \dot{\phi}_x \end{bmatrix}^T$$

The force command to the small actuator is calculated as Eq.(13).

$$\begin{aligned} F_{2x} &= \mathbf{k}\begin{bmatrix} x_2 & \dot{x}_2 & \phi_x - \phi_{xd} & \dot{\phi}_x - \dot{\phi}_{xd} \end{bmatrix}^T + (M_{2x} + m)\ddot{x}_1 \\ \phi_{xd} &= -\frac{M_{2x}}{M_{2x} + m}\frac{\ddot{x}_d}{l} \\ \mathbf{k} &= \begin{bmatrix} k_{x1} & k_{x2} & k_{\phi x1} & k_{\phi x2} \end{bmatrix} \end{aligned} \tag{13}$$

k is the feedback gain vector of the regulator of the small actuator. Since the wire should tilt according to the acceleration or deceleration of the object, the equilibrium point of the regulator is shifted as shown by Eq.(13) using the required acceleration or deceleration of the object.

The force commands and the regulator in y direction can also be obtained in the same manner.

IV. EXPERIMENT

A. Experimental System

The size of the crane is about 2m(W)x1.5m(D)x2m(H) and the parameters of the experimental system are shown in Table1 and Table2. In the experimental system, the velocity of the crane is limited very small in comparison with the force capability of the system because the moving ranges of the experimental system are too narrow. T_{acc} obtained by Eq.(7) is about 0.5[s], but the actual value used in experiments is 1[s] for safety. All actuators are controlled by high gain velocity controllers instead of torque controllers in practice because unknown large friction forces can not be compensated. The commanded forces calculated by Eq.(13) are converted into velocity commands.

B. Experimental condition

As described in Section II, the operator clicks a series of points by a mouse on the monitor screen where the scene below the crane is projected. It is assumed that the height of the crane and the wire length are known in advance, and the length of the wire is not changed during the experiments.

The clicked points are regarded as the points on the ground, and they are converted to the target points on the same height of the object. The calibration of the camera parameter should carefully be compensated for this conversion.

Table 1 Parameters of crane system

	Large actuator		Small actuator	
	x	y	x	y
Mass of actuators [kg]	22.5	3.95	2.94	3.51
Working distance [mm]	1200	900	200	200
Positioning resolution [μm]	12.5	8.0	1.5	1.5
Velocity resolution [mm/s]	0.42	0.27	0.05	0.05
Maximum Velocity [m/s]	1.66	2.18	0.27	0.27
Angle resolution: 0.002 [rad]		Wire length: 0.99 [m]		
Pos. res. of mass: 2.0 [mm]		Suspended mass:1.0 [kg]		
Sampling time: 10 [ms]				

Table 2 Designed parameters for control

T_{acc}: 1.0 s	V_o: 0.3 m/s
Poles of regulator	-2.57±1.87j, -1.0±2.59j

C. *Experiments*

The following four experiments are done.

1) Trajectory control of the large actuator by using the function shown in Fig.9(a) for the verification of the designed trajectory.

2) Feedback control by only using the small actuator is done for the verification of the regulator.

3) Motion control of the suspended object by using both actuators is done with initial disturbance for the verification of the macro-micro servo system.

4) Tele-operation experiment is done for the verification of effectiveness of the system.

1) Trajectory control of large actuator

First, an open loop control just by using the large actuator and the pre-designed trajectory is done in x direction. The parameters of the trajectory are shown in Table 2. The results are shown in Fig.11 and Fig.12.

Figure 11 shows the position of the object and the planned trajectory. These two lines almost coincide. Figure 12 shows the measured and designed velocities of the large actuator. They also coincide. From these results the validity of the designed trajectory is proved.

2) Feedback control of small actuator by regulator

The small actuator is feedback controlled by Eq.(11). The poles of the regulator are shown in Table 2. An impulsive force is given to the suspended object at 0 [s]. The results are shown in Fig.13. These two lines are the positions of the object and the small actuator respectively. The swinging motion of the object is reduced in 6 seconds and the motion range of the small actuator is about 0.05m which is within the working space. From this result, the effectiveness of the regulator is verified.

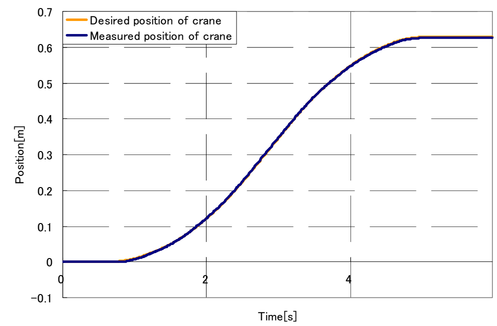


Fig.11 Position of suspended object and crane(large actuator) in motion

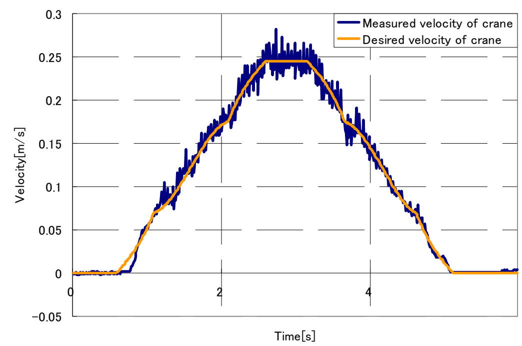


Fig.12 Velocity of crane(large actuator)

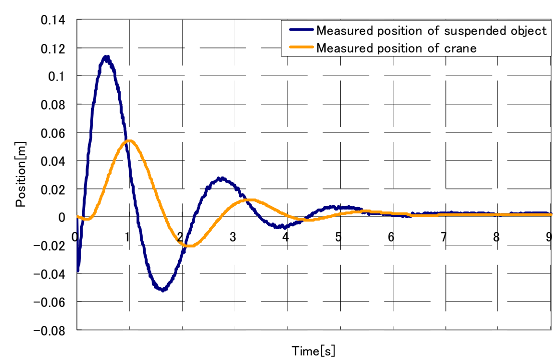


Fig.13 Position of suspended object and crane(small actuator)

3) Motion control of suspended object by large and small actuators

The designed trajectory of the large actuator and the regulator by the small actuator are combined, and a motion control of the suspended object is done. The experimental results are shown in Fig.14 and Fig.15. To verify the effectiveness of both controllers, an impulsive force is given to the object as an initial disturbance at the beginning of the experiment. The suspended object shown in Fig.14 has tracking error at first due to the initial disturbance, but the error is converged almost in 2 seconds, and the object follows the designed trajectory precisely after the convergence. Figure 15 shows the wire angle during the experiment. The behavior of the measured angles is almost the same as the position error shown in Fig.14. From these results, it can be seen that the combination of the large actuator and the small actuator works very effectively.

4) Tele-operation experiment

Tele-operation experiment is done. The scene below the crane is shown in Fig.16. The initial position and the goal position are fixed in advance. The operator clicks via points in sequence while the crane moves.

The result is shown in Fig.17. The number of via points is 4. The initial position of the object is (0,0) in the coordinate and the target point is (-1.2, -0.2). The operator clicked four via points before the object arrived at the goal. The line in the figure is the locus of the object measured by the encoders of all the actuators and the wire angle sensor. From the result, the object can be positioned at the target point accurately and overshoot does not appear at the target position, which means that the concept of the system is correctly achieved.

V. Conclusion

A tele-operation system for a two dimensional crane was developed by using which operators can easily position the suspended object at a target position without swinging motion and overshoot in positioning. The following technologies are developed for achieving the tele-operation system.

- Macro-micro servo system was designed. A large actuator and a small actuator are connected serially. The large actuator is used for moving the suspended object along the designed trajectory and the small actuator is used for reducing swinging motions of the object with a servo regulator. The equilibrium point of the regulator is modified by the acceleration trajectory of the large crane.
- A novel user interface was developed. According to the series of points clicked by the operator, each section between two adjacent points is interpolated by a velocity profile consisting of a fixed velocity and four order functions. Just by adding each interpolation functions, the desired trajectory of the object is easily revised.

From the results obtained by some fundamental experiments, the validity of the designed control algorithm and the effectiveness of the proposed system was verified.

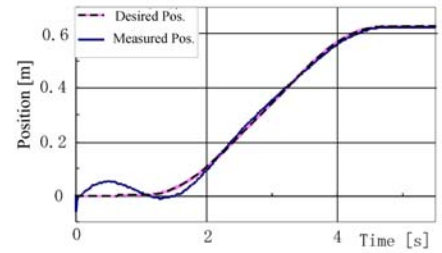


Fig.14 Measured position of object with initial disturbance

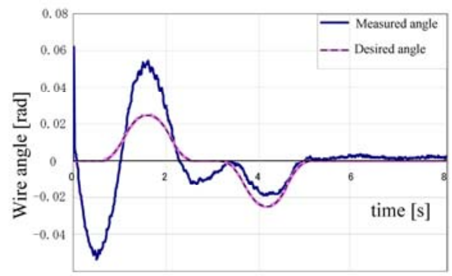


Fig.15 Measured wire angle with initial disturbance

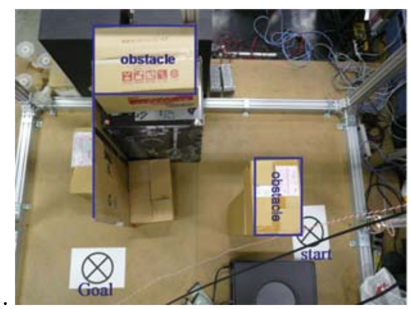


Fig.16 Scene below crane

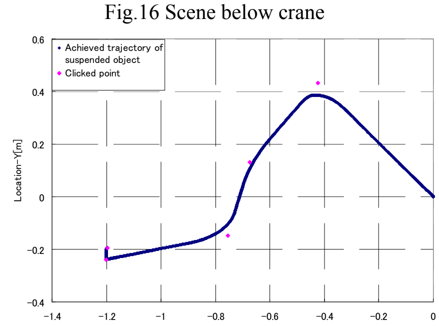


Fig.17 Locus of object during tele-operation

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