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APPLICATION OF MULTI-DIMENSIONAL WIRE CRANES IN CONSTRUCTION

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ABSTRACT

In this paper, we propose a new type of installation, "multi-dimensional wire crane", which can be used for construction of buildings and their facade maintenance. By using wires, the structure of installation becomes simple, and it is easy to install. To prove the effectiveness of the idea, we developed a prototype of 2-dimensional wire crane and a prototype of 3-dimensional wire crane. This paper describes the structure and the control algorithm of 2-dimensional wire crane.The experiment results are also presented here. The structure of 3-dimensional wire crane is also described in this paper.

1. Introduction

In recent years, buildings rising become higher and higher. More and more walls of glass and aluminum, stainless steel or stone are used. In large metropolitan areas the total surface area of these buildings can be measured in square kilometers. By using these materials, buildings can last longer. On the other hand, as air pollution becomes heavy, the task of inspecting, cleaning and maintaining so vast a surface area becomes greater to retain building's original appearance and value for years. Now many facade maintenance installations are used to do this task. An example of facade maintenance installation is shown in Fig.1[Ref.1]. It consists of a hoist mechanism to wind wires, a chassis to maintain smooth wheel rotation along rails, jib arms to let wires run from the hoist mechanism , down to the cage through over pulleys, and a cage from which repairs or inspections are made. But this kind of installation is rather complex and it is uneasy to mount on various kinds of buildings. In this paper we propose a new type of installation, "2-dimensional wire crane", for construction of buildings and their facade maintenance.

As a development of 2-dimensional wire crane, we also made a 3-dimensional wire crane. Equipped with some inspecting sensors it can be used to measure some physical quantities such as temperature, humidity, cleanness, etc. at any position in a test room because the fine(mm order) wires have little influence to the operating space.

2. 2-Dimensional Wire Crane

2.1 System configuration

The prototype of 2-dimensional wire crane is shown in Fig.2 and Fig.3. The cage is suspended and driven by four pairs of wires from the four corners. Each pair of wires is rolled up on one drum through pulleys, and drum is driven by DC servo motor through a pair of spur gears(reduction ratio =1/4). Though the upper two pairs of wires can position cage by themselves due to the existence of the gravity of cage, the lower two pairs of wires are used in order to move cage more fast and control the orientation of cage in operating plane. Using a pair of wires for each drum is effective to reduce the swing of cage vertical to the operating plane.

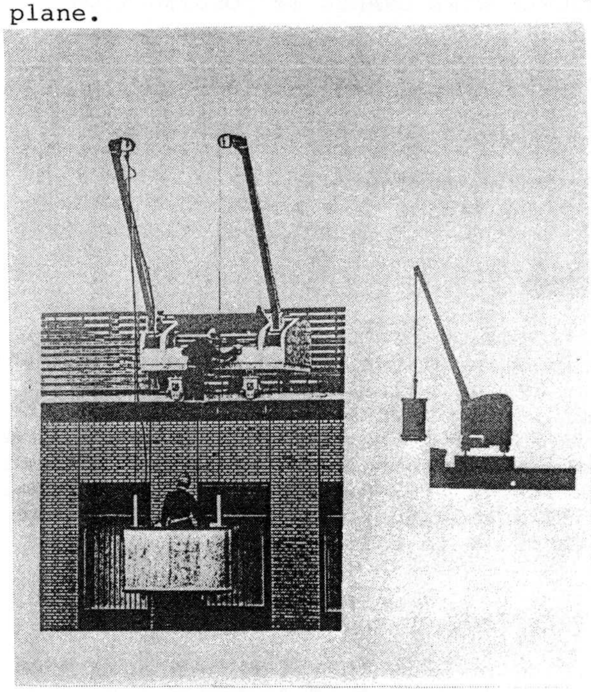

Fig.1 An Example of Facade Maintenance Installation

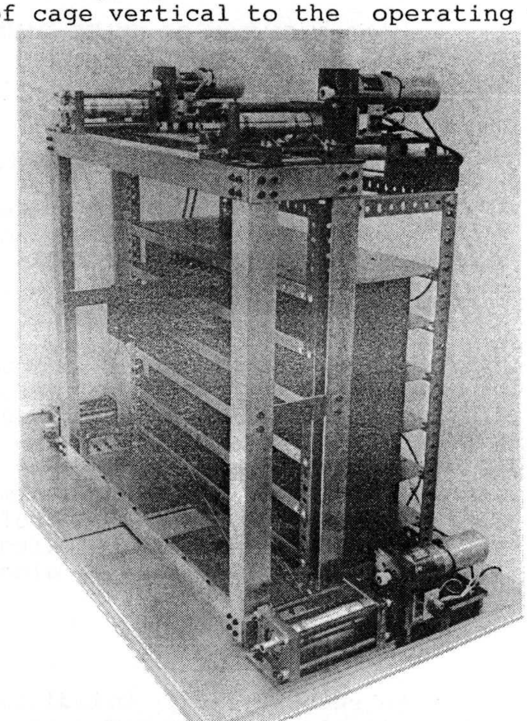

Fig.2 Prototype of 2-Dimensional Wire Crane

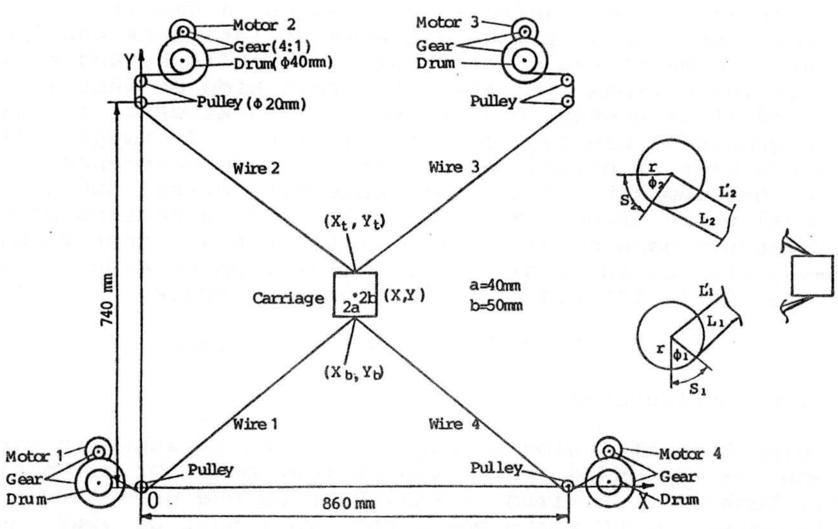

Fig.3 Configuration of 2-Dimensional Wire Crane

2.2 Control Configuration

As mentioned before, to move the cage in high speed and control the orientation of the cage in the operating plane four pairs of wires are used in the 2-dimensional wire crane, and four motors are used for controlling the length of each pair of wires. Because the motion of cage in the operating plane is a 2-dimensional motion and 1-dimensional orientation, the control of each motor is not independent from each other. That is , the four pairs of wires and cage form a complete closed kinematic loop with kinematic redundancy. With the kinematic redundancy the four pairs of wires must move in harmony (synchronized motion) to realize the desired motion and orientation of the cage. The characteristic that the wires can always exert tension to each other is desirable for the control of wire crane, because the tension of each wire must be kept above zero when moving cage.

For such a system, four proportional control configurations can be proposed:

1) position control of four pairs of wires,

2) force (tension) control of four pairs of wires,

3) position control of some pairs of wires and force control of some pairs of wires,

4) position control and force control , hybrid control of each pair of wires.

Control method 1) is a simple control method and it is only necessary to form a control system consisted of four single input (position), proportional feedback control loops. The following section will discuss it in details.

To implement the control method 2), the tension of each wire would be measured with force sensor. And it can be used for the case that the cage does some works for which the control of force is necessary.

About method 3), for instance, we can control the upper two pairs of wires 2 and 3 by position control to position cage , and the lower two pairs of wires 1 and 4 by tension control to prevent the swing of cage.

Method 4) is to form a hybrid feedback loop for each pair of wires and a smooth, rapid motion of cage can be expected by changing the weight factor between position loop and tension loop, and the gains of each loop in one process.

In this paper we investigate method 1) to see how fast cage can move and what positioning accuracy can be obtained by only position control loop. The other methods will be done in our future works.

2.3 Algorithm of position control

2.3.1 Construction of control system

The block diagram of position control is shown in Fig.4. Digtal command from computer (NEC PC9801F) passes through D/A converter, power amplifier and drives DC servo motor(75w for each). Encorder(500pulse/rev, used at four times) attached to motor measures the rotated angle of motor in pulse, and counter counts the number of encorder's pulse. Software servo (see 2.3.3) is performed to make digital command by computer. To detect the home position of cage two potentiometers are attached to the axes of drum 2 and drum 3 respectively.

2.3.2 Implementation of Synchronized Motion

As shown in Fig.3 we define world coordinate as XOY. Suppose that we want to move cage from initial point (X_0,Y_0) to destination point (X_T,Y_T). To implement synchronized motion, we must define a trajectory at first, and then calculate the necessary length of each pair of wires at each control sampling point on this trajectory. Then obtain the rotation angles of each motor from these lengths.

To achieve shortest distance between two points we use a straight line trajectory , and to make cage move smoothly, we select a three order polynomial shown in equation (1)[Ref.2].

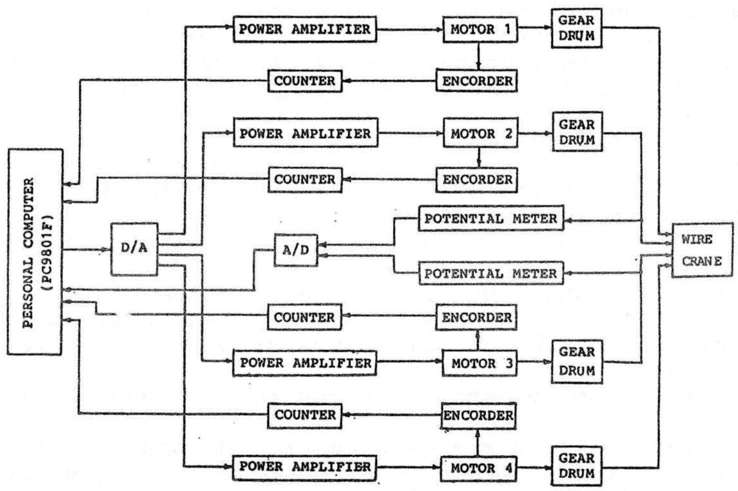

Fig.4 Block Diagram of Position Control

Letting ΔT, DOTS and i denote the sampling time, the number of whole sampling points and the ith sampling point respectively, and substituting $t=i*\Delta T$, $T=\Delta T*DOTS$ into above equation, we can obtain the coordinates (X,Y) of the center point in cage at ith sampling point.

Next, we calculate the coordinates of upper knot point(X_t,Y_t) and the coordinates of lower knot point (X_b,Y_b) from equation (2). Then we calculate each wire's length at ith sampling point by equations (3)-(7).

$$X(t)=X_0+\frac{3\cdot(X_T-X_0)}{T^2}\cdot t^2-\frac{2\cdot(X_T-X_0)}{T^3}\cdot t^3$$
$$Y(t)=Y_0+\frac{3\cdot(Y_T-Y_0)}{T^2}\cdot t^2-\frac{2\cdot(Y_T-Y_0)}{T^3}\cdot t^3 \qquad (1)$$

$$X_t=X,\quad Y_t=Y+b,\quad X_b=X,\quad Y_b=Y-b \qquad (2)$$

$$L'_1=\sqrt{X_b^2+Y_b^2}$$
$$L'_2=\sqrt{X_t^2+(740-Y_t)^2}$$
$$L'_3=\sqrt{(860-X_t)^2+(740-Y_t)^2} \qquad (3)$$
$$L'_4=\sqrt{(860-X_b)^2+Y_b^2}$$

$$L_1=\sqrt{(L'_1)^2-r^2}+S_1$$
$$S_1=r\cdot\varphi_1 \qquad (4)$$
$$\varphi_1=\pi-\tan^{-1}\frac{X_b}{Y_b}-\tan^{-1}\frac{\sqrt{(L'_1)^2-r^2}}{r}$$

$$L_2=\sqrt{(L'_2)^2-r^2}+S_2$$
$$S_2=r\cdot\varphi_2 \qquad (5)$$
$$\varphi_2=\pi-\tan^{-1}\frac{740-Y_t}{X_t}-\tan^{-1}\frac{\sqrt{(L'_2)^2-r^2}}{r}$$

$$L_3=\sqrt{(L'_3)^2-r^2}+S_3$$
$$S_3=r\cdot\varphi_3 \qquad (6)$$
$$\varphi_3=\pi-\tan^{-1}\frac{740-Y_t}{860-X_t}-\tan^{-1}\frac{\sqrt{(L'_3)^2-r^2}}{r}$$

$$L_4=\sqrt{(L'_4)^2-r^2}+S_4$$
$$S_4=r\cdot\varphi_4 \qquad (7)$$
$$\varphi_4=\pi-\tan^{-1}\frac{860-X_b}{Y_b}-\tan^{-1}\frac{\sqrt{(L'_4)^2-r^2}}{r}$$

Then we can obtain the rotation angle (in pulse number) of each motor at ith sampling point from wire's lengths and store these data into the memory of computer. When controlling the wire crane, computer reads these data , uses these data as commanded inputs of software servo at every sampling point, and controls each motor in turn by software servo.

2.3.3 Software servo

In order to design a controller suitable for the 2-dimensional wire crane, we adopted software servo, that is, constituting servo loop by program. By using software servo, we can try various servo algorithms and change servo parameters easily and in low cost.

The conventional PID control is exerted on the error between commanded pulse number and feedbacked pulse number from encorder at each sampling point in each servo loop.

The block diagram of software servo is shown in Fig.5 , and the discrete equation of the control algorithm is shown in equation (8). In order to get a pure integral we used trapezoidal integral instead of rectangular integral. We measured the cycle time of PID program of four motors when moving cage and found that the cycle time is about 2 milisecond. It is generally sufficient for position control loop.

We investigated the range of gain value of each loop within which the control system is stable, and they are as follows: $16<K_{Pi}<128$, $32<K_{Di}<256$, $0.002<K_{Ii}<2$. For the control system of 2-dimensional wire crane, due to the errors of parameters used for calculating, elastic strain of wires, loose of gears etc., interference among four pairs of wires always exists. Therefore, there is a discrepancy between the interference and servo stiffness of each motor(generally by choosing higher proportional gain values). That is, to achieve higher servo stiffness of four motors by higher proportional gain values tends to detract from achieving less interference. The measured error between commanded pulse number and feedbacked pulse number with high proportional gain values and motor current are shown in Fig.6 and Fig.7, respectively. Similarly the error and motor current with low proportional gain values are shown in Fig.8 and Fig.9. As shown in Fig.6 and Fig.7, the maximum value of error of each motor is kept below 20 pulses, but motor current changes so sharply and in high frequency. Also due to the large interference some noise from gears can be heard. Conversely, in Fig.8 and Fig.9 the motor current changes smoothly comparative to Fig.7 with large error existing. So in the position control system of 2-dimensional wire crane, each gain value must be chosen to assure an optimum balance not only to get high servo stiffness of each single motor but also to move cage in high accuracy with minimum interference among four pairs of wires.

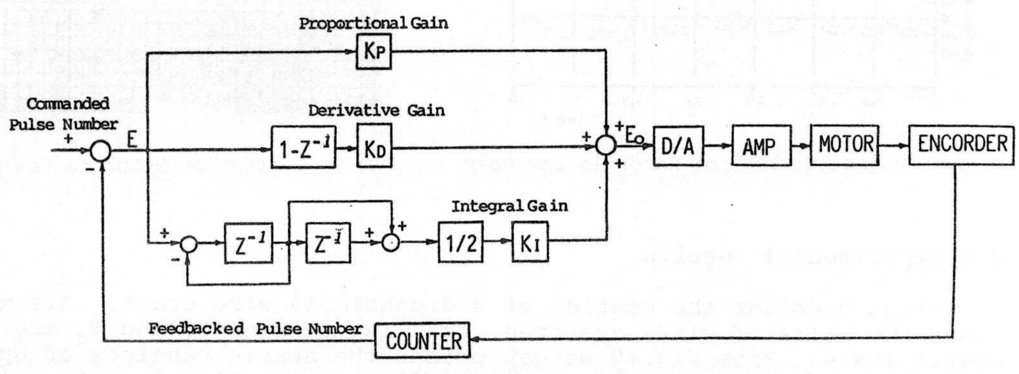

Fig.5 Block diagram of Software Servo

$$E_0 = K_P \cdot E(i) + K_D \cdot [E(i) - E(i-1)] + K_I/2 \cdot \sum_{k=1}^{i} [E(k) + E(k-1)] \qquad (8)$$

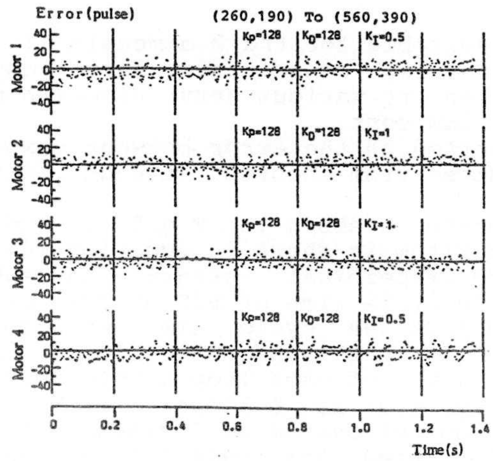

Fig.6 Rotation Error of Motor in High Gain

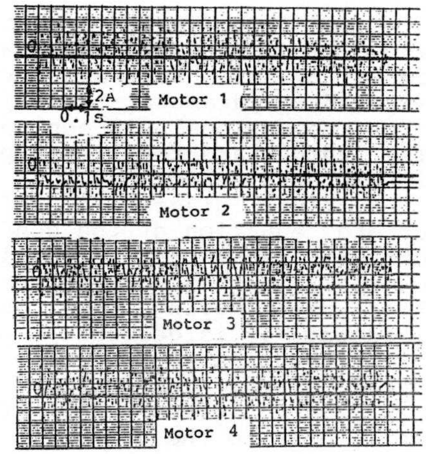

Fig.7 Current of Motor in High Gain

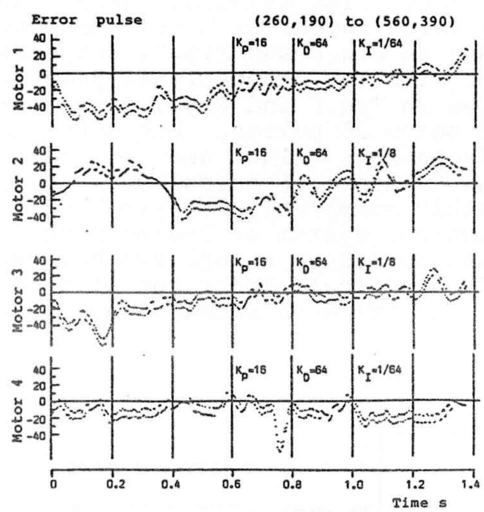

Fig.8 Rotation Error of Motor in Low Gain

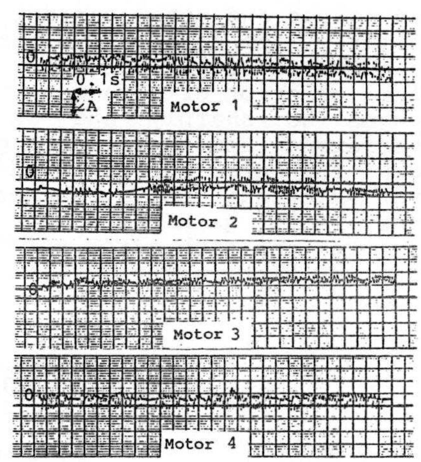

Fig.9 Current of Motor in Low Gain

2.4 Experimental results

Let us consider the statics of 2-dimensional wire crane. Assume that lower two pairs of wires are free, that is, tension T_1 and T_4 are zero in static state. From Fig.10 we can obtain the static tensions of upper two pairs of wires T_2 and T_3 by equation (9). In Fig.11 the contour lines of tension in operating area are shown. In the upper part of operating area the tension increases rapidly. To make the values of static tensions of the upper two wires less than 2Mg we selected Y=580mm as the upper limit line of operating area for experiment. In the lower part of operating area, there is also a limit to lower limit line because if the lower limit line is too low the tensions of wires 1 and 4 cannot be exerted well through pulleys by motor, a lower limit line Y=80mm is decided. With the same reason as above, X=80mm and X=780mm are defined as left and right limit lines of operating area respectively. In this operating area(700mm*500mm), a maximum speed of 0.9m/s of cage is obtained.

To measure the positioning accuracy of cage, we used a electro-optical device called OPT-FOLLOW 7000C. The resolution of this device is about ±2.4mm when measuring a area of 600mm*600mm.

As well known, repeatability is very important for operation because we can compensate for absolute positioning error by teaching method. To measure the repeatability we moved the cage according to a reference course with a rectangle and its diagonal lines for seven times. The measured result is shown in Fig.12. In this course, the maximum velocity is about 0.6m/s and it is at the middle point of each diagonal line. From Fig.12, it can be said that the repeatability of the cage is below the minimum resolution of OPT-FOLLOW 7000C. There is a slight winding in upper line on the trajectory, it may be the effect of large static tensions.

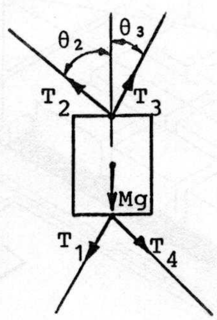

Fig.10 Statics of 2-Dimensional Wire Crane

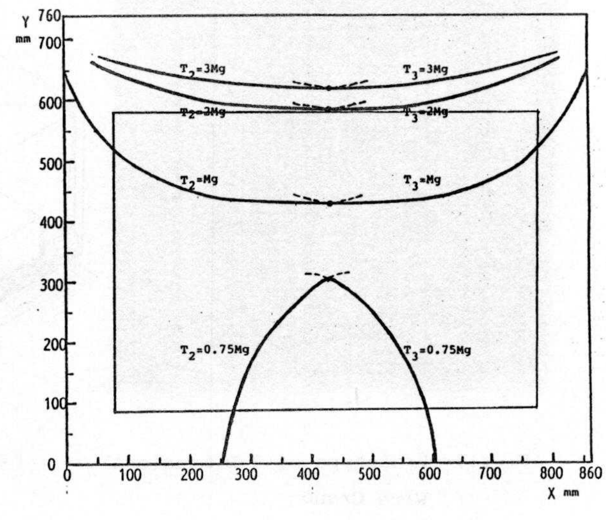

Fig.11 Contour Lines of Tension and Operating Area

$$T_2=\frac{\sin\theta_3}{\sin(\theta_2+\theta_3)}Mg \qquad (9)$$

$$T_3=\frac{\sin\theta_2}{\sin(\theta_2+\theta_3)}Mg$$

where

$$\theta_2=\tan^{-1}\frac{X}{790-Y}$$

$$\theta_3=\tan^{-1}\frac{860-X}{790-Y}$$

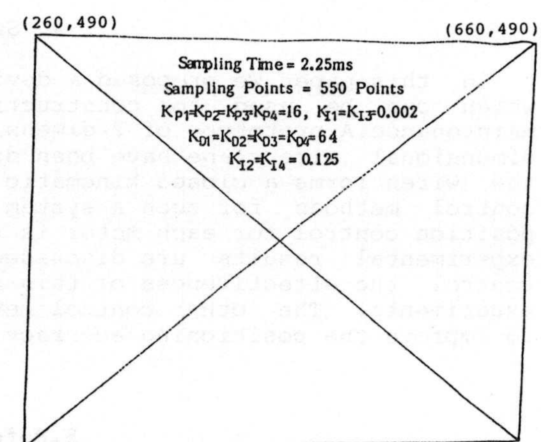

Fig.12 Result of Positioning

3. 3-Dimensional Wire Crane

As shown in FIg.13 and Fig.14, the prototype of 3-dimensional wire crane consists of a gondola suspended by four wires from four corners of a room. As the case of 2-dimensional wire crane, to move the gondola fast and to control the orientation of the gondola, more than four wires are necessary for 3-dimensional wire crane. Also because the motion of each motor is not independent, a concentrated control system for all motors may be necessary.

The 3-dimensional wire crane can be used for operations in a 3-dimensional space, for example inspecting temperature in a test room, handling goods in 3-dimensional space, and so on.

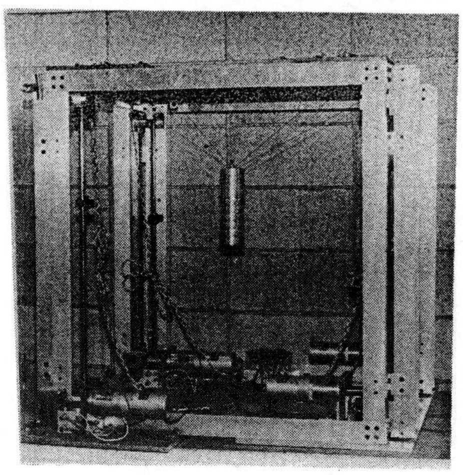

Fig.13 Prototype of 3-Dimensional Wire Crane

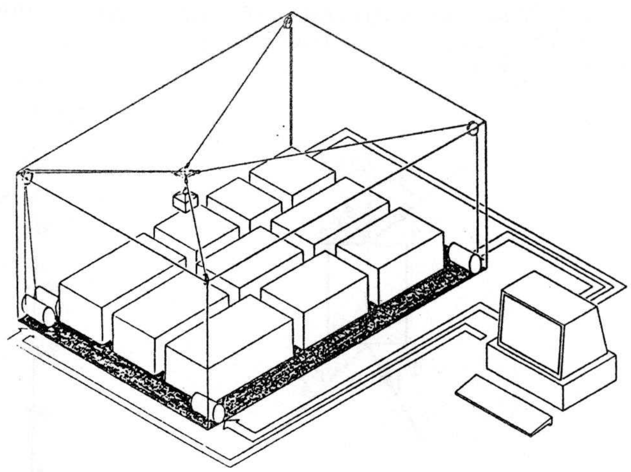

Fig.14 Configuration of 3-Dimensional Wire Crane

4. Summary

In this paper we proposed a device driven by wires called wire crane which can be used for construction of buildings and their facade maintenance.A prototype of 2-dimensional wire crane and a prototype of 3-dimensional wire crane have been developed. In 2-dimensional wire crane the wires forms a closed kinematic loop with kinematic redundancy. The control methods for such a system are discussed. A control system of position control for each motor is realized by using software servo. Some experimental results are discussed, and even under the only position control the effectiveness of this kind of installation is identified by experiments. The other control methods will be done in our future works to improve the positioning accuracy of cage and to move cage more fast.

5.References

1. NIHON BISO CO.,LTD, "The BISO line at a glance", 1987.
2. Y. Jinbo, "A Textbook on Industrial Vibration",Gakukensha.