24th International Symposium on Automation & Robotics in Construction (ISARC 2007)
Construction Automation Group, I.I.T. Madras

DEVELOPEMENT OF THE GRIPPING CONTROL ALGORITHM FOR WIRE-SUSPENDED OBJECT IN STEEL CONSTRUCTION

Kyungmo Jung
Graduate School of Korea University
5Ga-1, Anam-Dong, Sungbuk-Gu, Seoul, Korea
km904@korea.ac.kr

Kihyun Bae
Graduate School of Korea University
5Ga-1, Anam-Dong, Sungbuk-Gu, Seoul, Korea
luxmit@empal.com

Dongnam Kim
Graduate School of Korea University
5Ga-1, Anam-Dong, Sungbuk-Gu, Seoul, Korea
smileast@korea.ac.kr

Daehie Hong
Dept of Mech. Engr., Korea University
5Ga-1, Anam-Dong, Sungbuk-Gu, Seoul, Korea
dhhong@korea.ac.kr

ABSTRACT

Robot system used in building construction sites can efficiently reduce construction time and increase safety by replacing human in dangerous operations. This paper describes the development of a robotic manipulator control algorithm which provides stable and efficient gripping of a pendulum-like object. The pendulum object mimics the construction materials hanging from tower crane, such as steel beam and column. The robot should be able to handle the heavy objects in order to be used in the building construction sites. This control algorithm requires dynamic modeling of the hanging object. To simplify the analysis, the dynamic modeling was limited to the 2 dimensional pendulum movements in x-y plane. In order to achieve the stable and efficient gripping, a shock isolator is designed using a pre-acting control.

KEYWORDS

Robot, Gripping Control, Pre-Acting Control, Shock Isolator, Steel Construction

1. INTRODUCTION

As social problems like aging of population, falling birth rate, etc, have emerged, it becomes necessary that manpower be replaced with automation equipments such as robots. Especially, construction industry has many dangerous factors and needs a lot of manpower. This paper deals with an automation problem that can arise from the assembly of steel structures in high-rise building construction sites.

The assembly process of steel structures includes handling extremely heavy objects, for example, steel beams, columns, girders, etc., which are usually carried by a tower crane installed at construction site. The steel construction also contains fundamental structure of bolting linkage between H-shaped beams (or girders) and H-shaped columns. For the bolting process, human workers generally climb up on a steel structure, place a new beam or column hanging from tower crane in position, and bolt them directly. This process is very dangerous to the workers, and takes long time to bolt down. Furthermore, this assemble process is seriously influenced by weather, such that it can not be carried out during windy or rainy days. It is a fatal weakness to some countries that have long period of rainy days.

In order to automate the process of steel structure, one of essential requirements is the ability to safely grip the H-beam (beam or column) that weighs from 4 tons to 10 tons. The H-beam hanging from tower crane inevitably generates tremendous amount of impact when it swings due to its heavy weight. So, it is necessary to appropriately control the automation equipments (robot manipulators, for example), which isolates the impact and protects the equipments from the shock caused by the huge mass of the H-beam. This paper presents a strategy to deal with this problem. The strategy contains pre-acting control to protect the manipulator from the shock. It estimates a magnitude of the shock from wire-suspend object by sensor data and generates pre-acting control. If the magnitude of the shock from the hanging beam is under a limit, the pre-acting control is activated and generates control force to opposite side before the impact, so that the robot system can grip the H-beam hanging from tower crane safely.

2. BACKGROUND

2.1 Manipulator Design

Figure1 shows a potential design of the manipulator to grip H-beam. This robot system is connected to another carrier mechanism housed in construction factory (CF). The manipulator can be positioned anywhere by the carrier mechanism.

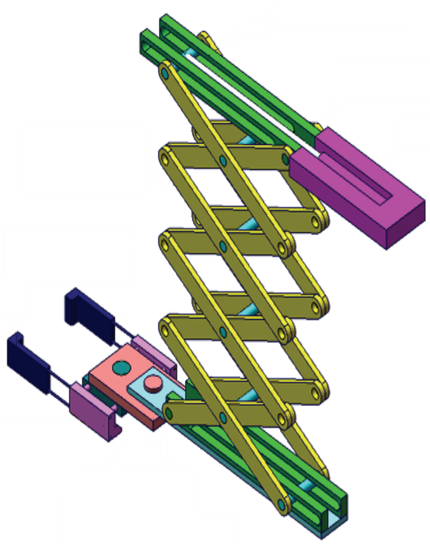

Figure 1 Design of the Manipulator

The manipulator has three degrees of freedom. Among them, one is vertically up and down movement with scissor-jack type joints. The others are the translation in front and backward directions and rotation of the end-effector joint. All actuators are driven by hydraulic systems. There is a space reserved for bolting robot which is used to assemble beams and columns. This manipulator is designed to have a mobility and a capability that can grip the H-beams in all directions.

2.2 Dynamic Model of Pendulum-Like Object

The analysis for the motion of the H-beam hanging from tower crane is performed based on the following assumptions:

1) Pendulum motion of H-beam is restricted to 2-D plane
2) Swing angle is small, 5 degree is chosen as a reference value $(\theta \leq 5^\circ)$

These assumptions are feasible because the cable from the tower crane is long and main impact acts to the normal direction of end-effector plane.

Figure 2 shows 2-D plane motion of the H-beam hanging from crane. The equation of motion is derived using free-body-diagram shown in Fig. 2 and Lagrange-Newton method. First of all, the velocity and acceleration of the object can be figured out from Figure 2.

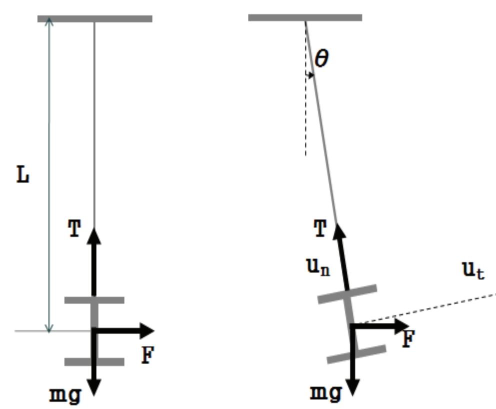

Figure 2 Model of 2-D Plane Motion

$$v = \upsilon_t u_t = l\dot{\theta}u_t \quad (1)$$

$$a = a_t u_t + a_n u_n = l\ddot{\theta}u_t + l\dot{\theta}^2 u_n \quad (2)$$

Also, the kinetic energy, potential energy, and virtual work are found out to apply Lagrange-Newton equation.

$$T = \frac{1}{2}m(\upsilon_t^2 + \upsilon_n^2) = \frac{1}{2}m(l\dot{\theta})^2 \quad (3)$$

$$V = mgl(1 - \cos\theta) \quad (4)$$

$$\overline{\delta W} = F\delta x = F\delta(l\sin\theta) = Fl\cos\theta\delta\theta \quad (5)$$

where,

m : object(beam) mass

l : length of wire

g : gravity acceleration

θ : angular displacement

$\dot{\theta}$: angular velocity

$\ddot{\theta}$: angular acceleration

θ, $\dot{\theta}$, $\ddot{\theta}$ are prescribed functions of time which have sinusoidal form.

And the virtual work is expressed in terms of generalized force and generalized displacement as follow

$$\overline{\delta W} = \Theta\delta\theta \quad (6)$$

Using Eq. (5) and (6),

$$\Theta = Fl\cos\theta \quad (7)$$

$$L = T - V \quad (8)$$

Eq. (3), (4), and (7) are substituted into Eq.(8), the followings are obtained

$$L = \frac{1}{2}m(l\dot{\theta})^2 - mgl(1-\cos\theta) \quad (9)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\theta}}\right) - \frac{\partial L}{\partial\theta} = \Theta \quad (10)$$

Finally, inserting Eq.(7) and (8)

into Eq (9)

$$ml^2\ddot{\theta} + mgl\sin\theta = Fl\cos\theta \quad (11)$$

$$ml\ddot{\theta} + mg\theta = F\cos\theta \quad (12)$$

based on the assumption of small swing angle, such that $\sin\theta \approx \theta$.

$$F = \frac{ml\ddot{\theta} + mg\theta}{\cos\theta} \quad (13)$$

3. CONTROL ALGORITHM

3.1 Pre-Acting Control for Isolator

H-beam has heavy weight ranging from 4 tons to 10 tons but the robot system has light weight under 1 tons and relatively weak due to its structural characteristics.

As such, a shock isolator is required to protect the manipulator from the impact by swinging object. Fig. 3 shows the design concept of the shock isolator. If the magnitude of shock is relatively compared to the strength of the robot arm, the robot system can grip H-beams safely using this isolator.

To design a better isolator, pre-acting control algorithm is used. Using appropriate sensors (camera, for example), the robot system can predict the instant of the shock. Using this data, the control effort is put before the shock is applied and the shock is actively absorbed during the impact.

The problem of limiting performance of shock isolator can be formulated with pre-acting control [3],[4].

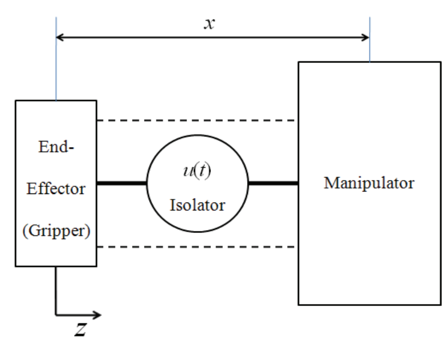

Figure 3 Schematics of Shock Isolator

From Fig. 3, the governing equation can be formulated as,

$$m\ddot{x} + u = -m\ddot{z} \quad (13)$$

where,

m : manipulator mass

x : manipulator displacement relative to end-effector

z : manipulator displacement relative to global frame

u : control force

$\ddot{z}$ is a prescribed function of time and its value is zero during $-t_0 < t < 0$. Its result applies to the initial conditions, which are,

$$x(-t_0) = 0, \quad \dot{x}(-t_0) = 0 \tag{14}$$

It is important to find out pre-acting control $u_0(t)$ defined during $-t_0 < t < \infty$,

$$\min_u \{\max|x - x_0|\} \quad \text{while} \quad \max_t |\ddot{x}| \le U \tag{15}$$

$$\max_t |\ddot{x}| = u_0(t) \tag{16}$$

Where U is defined to minimize the maximum peak absolute value of the relative displacement of the manipulator as Eq. (15) and (16).

Let the shock is instantaneous impact at $t = 0$, then $\ddot{z}(t)$ is expressed by Dirac-Delta function like Eq.(17). That is,

$$\ddot{z}(t) = \ddot{z}_0 \delta(t) \tag{17}$$

Graphical-analytical method is used to solve limiting performance problem. An optimal control force is obtained by assuming unit pre-acting time, $t_0 = 1$ [5]

$$u_0(t) = \begin{cases} -1, & (-1 \le t < -3/4) \\ 1, & (-3/4 \le t < 1/2) \\ 0, & (1/2 \le t \le \infty) \end{cases} \tag{18}$$

Fig. 4 shows the time history of the optimal pre-acting control force by plotting Eq. (18).

From Eq. (17) and (18), Eq. (13) is expressed as

$$m\ddot{x} + u = 0 \tag{19}$$

Subject to the conditions at $t = -t_0$ and $t = 0$

$$x(-t_0) = 0, \quad \dot{x}(-t_0) = 0 \tag{20}$$

$$\dot{x}(-0) + \ddot{z}_0 = \dot{x}(+0) \tag{21}$$

Using Eq. (18) ~ Eq. (21), the velocity and displacement of x during $-t_0 < t < \infty$ can be found, where $m = 1$ and $\ddot{z}_0 = 1$

$$\dot{x}(t) = \begin{cases} t+1, & (-1 \le t < -3/4) \\ -t-1/2, & (-3/4 \le t < 0) \\ 1/2 - t, & (0 \le t < 1/2) \\ 0, & (1/2 \le t < \infty) \end{cases} \tag{22}$$

$$x(t) = \begin{cases} (t+1)^2/2, & (-1 \le t < -3/4) \\ 1/16 - (2t+1)^2/8, & (-3/4 \le t < 0) \\ 1/16 - (2t+1)^2/8 + t, & (0 \le t < 1/2) \\ 1/16, & (1/2 \le t < \infty) \end{cases} \tag{23}$$

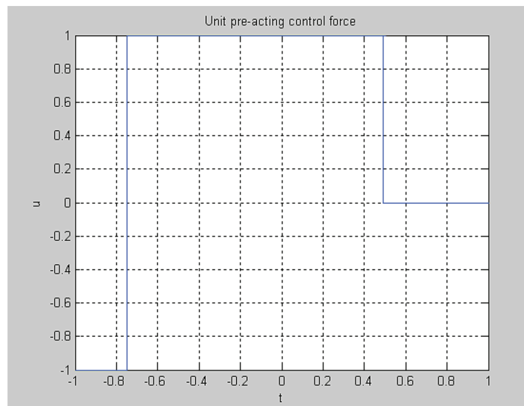

Figure 4 Time History of the Optimal Pre-Acting Control Force

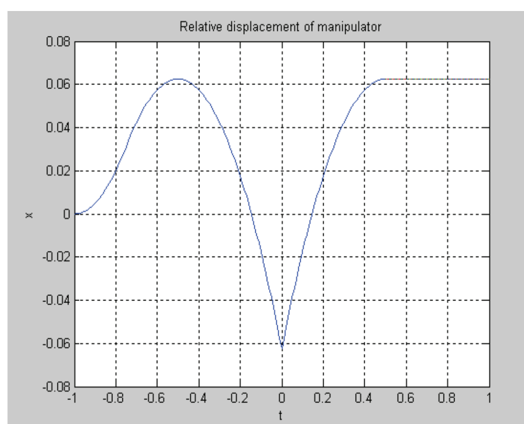

Figure 5 Time History of the Relative Distance of Optimal Pre-Acting Control Force

Figure 5 shows the time history of the relative distance of optimal pre-acting control force.

4. CONCLUSION

In this paper, the dynamics of wire-suspended object was found for estimating the amount of shock and pre-acting control scheme was applied for minimizing the shock from the swinging object, such as H-beams. This topic is very important when using a robot in construction fields, since there are many processes that handle very heavy objects suspended through crane cable. In these cases, the robot should be able to absorb tremendous amount of shock from the swinging object to avoid its damage. The strategy presented in this paper will be valuable components when implementing robotic construction, especially in the assembly of steel beams and columns in high-rise building construction.

5. ACKNOWLEDGMENTS

This research was supported by a grant (code# 06-D01) from Unified and Advanced Construction Technology Program funded by Ministry of Construction & Transportation of Korean government.

6. REFERENCES

[1] Leonard Meirovitch, Elements of Vibration Analysis,McGRAW-HILL, 1986

[2] R. M. Murray, Z. Li, and S. S. Sastry, "A Mathematical Introduction to Robotic Manipulation", Boca Raton, FL: CRC, 1994

[3] D. V. Balandin, N. N. Bolotnik, and W.D. Pilkey, "Pre-acting Control for Shock and Impact Isolation Systems," Shock and Vibration, 12, pp. 49-65, 2005.

[4] E. Sevin and W. D. Pilkey, Optimum Shock and Vibration Isolation, Shock and Vibration Information Analysis Center, Washington DC, 1971.

[5] D. V. Balandin, N. N. Bolotnik, and W.D. Pilkey, "Limiting Performance Analysis of impact Isolation System for injury Prevention" The Shock and Vibration Digest 2001, 33; 453.