Fuzzy Control of a Sway and Skew of a Spreader by Using Four Auxiliary Cables

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Abstract: This article describes the fuzzy control of the 3-dimensional motion of the container cranes used in dockside container terminals. The container is suspended by four flexible cables via spreader, and due to the disturbances such as the wind and acceleration of cranes, the container undergoes translational(sway) and rotational position errors. And due to the uncertainty of weight and rotational inertia, accurate position control of container crane is difficult to realize. This paper, based on the analysis of 3-dimensional dynamics of container moving systems, describes the design of the fuzzy controller, which does not require the computation time to optimize the distribution of cable tension. The developed controller is shown effective in controlling the container position in the presence of gust and parameter uncertainties.

Keywords: container cranes, fuzzy control, motion control, sway, skew

1. Introduction

The mobile gantry crane is widely used in dockside container base or railway freight terminal to pick up and move containers. The gantry crane is composed of three main parts. The first one is gantry whose structure supports all equipment and moves along one direction. The second one is the trolley which is on the longitudinal structure of gantry and moves along longitudinal direction(perpendicular to gantry motion) of gantry. The last one is spreader which is suspended by, typically, four flexible cables from trolley. The spreader is equipped with container pick up mechanisms, and holds the container. By controlling the length of cables, the container is moved upward or downward. The construction of container crane is well illustrated in [1] and [2]. Because the spreader is connected by flexible cables with trolley, acceleration of trolley and gantry induce sway of spreader. And disturbances such as wind or asymmetric loading of container induce sway and rotation(the rotation will be called skew, hereafter) of spreader. Because the sway and skew is not desirable in positioning of container, the four cables are widely spaced to reduce sway and skew. On the contrary, factory crane possesses single or close running parallel cables. Because of the widely spaced cables, the problem is slightly different in that the spreader of mobile gantry crane possesses rather complex dynamics than factory crane [3]. In previous papers by authors [4–6], the 3-dimensional kinematics and dynamics are investigated in detail. In this paper, based on the dynamic equations derived in [6], effective control algorithm for positioning of container is investigated.

This paper is constructed as follows. In next section(section 2.kinematics and dynamics of gantry crane is reviewed and in section 3.the control of the gantry crane system is described. In section 4, fuzzy control algorithm is analysed in detail. In section 5, some simulations are shown. In last section, conclusions and discussions of this paper are summarized.

This work is partly supported by Hyundai Heavy Industry, MOMAF(Development of Automatic Transfer Crane).

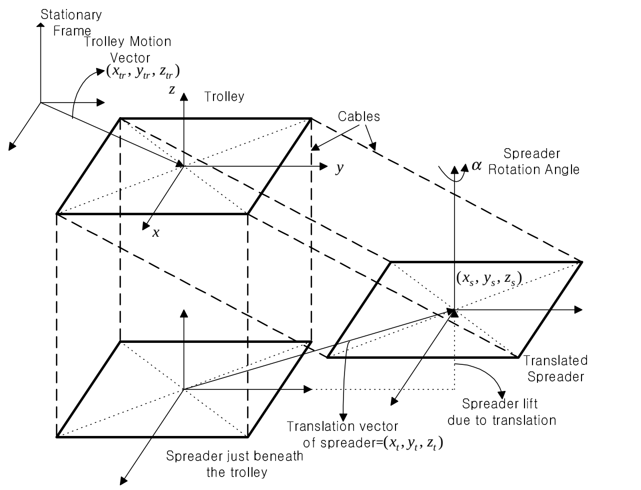

Fig. 1. Schematic diagram to show motion vector of trolley and spreader.

2. Kinematics and Dynamics of Container Cranes

Many researches are devoted to the control of three dimensional position of gantry cranes, for example [7–15]. But most of them treat gantry crane as a point mass and multiple cables as single cable. As a result, their control problem becomes the problem of motion control of a simple pendulum. But as mentioned earlier, three dimensional analysis of spreader are expected to yield more accurate results and shed some insights on the control of sway and skew of spreader. On this subject, paper by Cartmel et. al. [16] is the only one in authors' paper review. The schematic diagram of typical gantry crane is shown in Fig. 1.

In the authors previous research [4–6], the 3-dimensional kinematics and dynamics of container crane is derived and the equations are shown for the completeness of the paper.

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{B}\mathbf{G} \tag{1}$$

where,

$$A = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{0} & -\mathbf{M^{-1}V} \end{bmatrix} \quad (2)$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & -\mathbf{M^{-1}} \end{bmatrix} \quad (3)$$

$$\mathbf{M^{-1}} = \frac{1}{I_s(l^2+y_t^2+x_t^2)+mr^4\alpha^2} \cdot \begin{bmatrix} l^2+y_t^2+x_t^2 & -r^2\alpha x_t & -r^2\alpha y_t \\ -r^2\alpha x_t & \frac{Is(l^2+y_t^2)+mr^4\alpha^2}{m} & -\frac{x_t y_t I_s}{m} \\ -r^2\alpha y_t & -\frac{x_t y_t I_s}{m} & \frac{Is(l^2+x_t^2)+mr^4\alpha^2}{m} \end{bmatrix}$$

$$\mathbf{V(q,\dot{q})} = \begin{bmatrix} v_{11} & v_{12} & v_{13} \\ v_{21} & v_{22} & v_{23} \\ v_{31} & v_{32} & v_{33} \end{bmatrix} \quad (4)$$

$$\begin{aligned}
v_{11} &= C_\alpha + \frac{mr^4\alpha\dot{\alpha}}{l^2} - \frac{2mr^4\alpha^2\dot{l}}{l^3} \\
v_{12} &= \frac{mr^2\alpha\dot{x}_t}{l^2} - \frac{2mr^2\alpha x_t\dot{l}}{l^3} \\
v_{13} &= \frac{mr^2\alpha\dot{y}_t}{l^2} - \frac{2mr^2\alpha y_t\dot{l}}{l^3} \\
v_{21} &= \frac{mr^2\dot{\alpha}x_t}{l^2} - \frac{2mr^2\alpha\dot{l}x_t}{l^3} \\
v_{22} &= C_x + (\frac{m\dot{x}_t}{l} - \frac{2mx_t\dot{l}}{l^2})\frac{x_t}{l} \\
v_{23} &= (\frac{m\dot{y}_t}{l} - \frac{2my_t\dot{l}}{l^2})\frac{x_t}{l} \\
v_{31} &= \frac{mr^2\dot{\alpha}y_t}{l^2} - \frac{2mr^2\alpha\dot{l}y_t}{l^3} \\
v_{32} &= (\frac{m\dot{x}_t}{l} - \frac{2mx_t\dot{l}}{l^2})\frac{y_t}{l} \\
v_{33} &= C_y + (\frac{m\dot{y}_t}{l} - \frac{2my_t\dot{l}}{l^2})\frac{y_t}{l}
\end{aligned}$$

$$\mathbf{g(q)} = [\mathbf{g_1} \quad \mathbf{g_2} \quad \mathbf{g_3}]^{\mathbf{T}} \quad (5)$$

$$\begin{aligned}
g_1 &= \frac{mgr^2\alpha}{l} + \frac{(mgrl)^2\alpha}{4k(l^2-r^2\alpha^2)^2} + \frac{mr^2\alpha(r^2\alpha^2+x_t^2+y_t^2)\dot{l}^2}{l^4} \\
&\quad -\frac{m\ddot{l}r^2\alpha(2l^2+r^2\alpha^2+x_t^2+y_t^2)}{2l^3} \\
g_2 &= \frac{mgx_t}{l} + \frac{(mgl)^2x_t}{4k(l^2-x_t^2-y_t^2)^2} + \frac{m(r^2\alpha^2+x_t^2+y_t^2)\dot{l}^2x_t}{l^4} \\
&\quad -\frac{m\ddot{l}x_t(2l^2+r^2\alpha^2+x_t^2+y_t^2)}{2l^3} \\
g_3 &= \frac{mgy_t}{l} + \frac{(mgl)^2y_t}{4k(l^2-x_t^2-y_t^2)^2} + \frac{m(r^2\alpha^2+x_t^2+y_t^2)\dot{l}^2y_t}{l^4} \\
&\quad -\frac{m\ddot{l}y_t(2l^2+r^2\alpha^2+x_t^2+y_t^2)}{2l^3}
\end{aligned}$$

$$\mathbf{f} = \begin{bmatrix} F_\alpha \\ F_x - m\ddot{x}_{tr} \\ F_y - m\ddot{y}_{tr} \end{bmatrix} \quad (6)$$

g_i : $i-th$ element of vector $\mathbf{g}$
$\mathbf{g}$: $[\ 0\ \ 0\ \ 0\ \ g_1\ \ g_2\ \ g_3]^T$
I_s: moment of inertia of spreader about z-axis
k : spring constant of one set of suspension cables
l : length of cable
m : mass of spreader set
$\mathbf{M}$: mass matrix
M_{ij} : $(i,j)-th$ element of M matrix
$\mathbf{q}$: generalized coordinate vector in Lagrange equation, $[\ \alpha\ \ x_t\ \ y_t]^T$
$\dot{\mathbf{q}}$: time derivative of $\mathbf{q}$
$\ddot{\mathbf{q}}$: time derivative of $\dot{\mathbf{q}}$
q_i : generalized coordinates used in Lagrange equation
r : half of the diagonal length of spreader
$\mathbf{V}$: matrix related to centrifugal and Coriolis force
$\mathbf{u}$: control force vector. $\mathbf{u} = [\ \mathbf{0\ \ 0\ \ 0\ \ f_\alpha\ \ f_x\ \ f_y}]^{\mathbf{T}}$
v_{ij} : $(i,j)-th$ element in $\mathbf{V}$ matrix
$\mathbf{x}$, $\dot{\mathbf{x}}$: system state vector and its time derivatives. $\mathbf{x} = [\ \alpha\ \ \mathbf{x_t}\ \ \mathbf{y_t}\ \ \dot{\alpha}\ \ \dot{\mathbf{x}}_\mathbf{t}\ \ \dot{\mathbf{y}}_\mathbf{t}]^{\mathbf{T}}$
x_s, y_s, z_s : translation of spreader center along x, y and z-axis with respect to stationary frame, respectively
x_t, y_t : translation of spreader center along x and y-axis, respectively, with respect to the coordinate system attached on trolley center.
x_{tr}, y_{tr} : position of trolley along x and y-axis with respect to stationary frame, respectively
$z_t|_{approx}$: approximate spreader lift due to spreader rotation or translation
α : rotation of spreader with respect to z-axis
θ : angle between a cable and the z-axis

The dynamic equations are a lightly coupled in three directions(x-y-α). These equations are the starting block of control algorithm design.

3. Kinematic Configuration of Trolley and Sprerader

To suppress the unwanted motion of container crane and to move it in short time, the four auxiliary cables are installed as shown in Fig. 3. The installation of four auxiliary cables enables independent control of trolley motion and control of sway(planar motion) and skew(rotational motion) of container assembly.

To control the spreader positional offset due to external disturbance such as wind and trolley acceleration, four auxiliary cables are additionally placed between trolley and spreader. The cables arrangement is shown in Fig. 2, and the coordinates of pulleys for cables are shown in Fig. 3. We assume that the spreader is rotated by angle α and then translated in planar direction by $(x_t,\ y_t)$ during trolley motion. And we use the following notations.

$$\begin{aligned}
Rot(\alpha) &= \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} && (7) \\
T_r &= [x_t\ \ y_t\ \ \Delta z]^T && (8)
\end{aligned}$$

where Δz denotes spreader lift that is caused by three components, namely spreader translation(sway), rotation(skew) and the elastic deformation of cables. (Superscript '^{T}' denotes transpose of vector or matrix, hereafter.) And x_t and

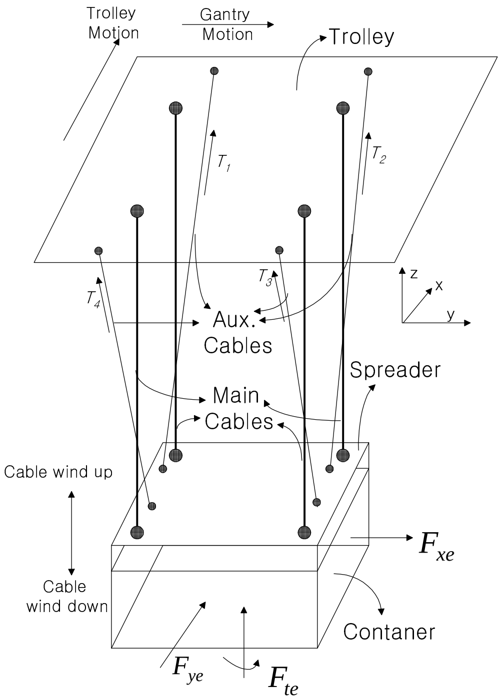

Fig. 2. Schematic diagram to show cables arrangement.

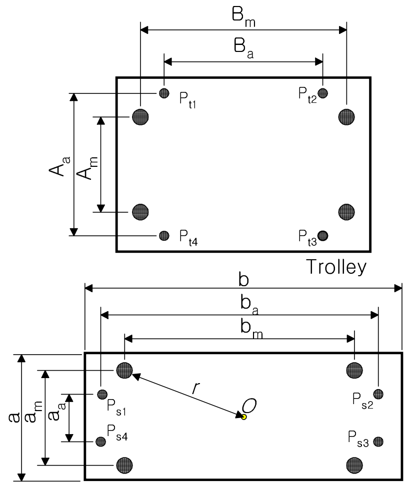

Fig. 3. Schematic diagram to show cabling position of main and auxiliary cables on spreader and trolley.

y_t are translation of spreader center in x and y direction with respect to trolley center. In the above equation, T_r denotes displacement of spreader center from its equilibrium position with respect to coordinate system attached at trolley center. From the results in authors' previous paper [5] and [6],

$$\Delta z \approx -\frac{mg}{4k} + \frac{x_t^2 + y_t^2 + r^2\alpha^2}{2l} \tag{9}$$

where r denotes approximately the half of the diagonal length of spreader(see Fig. 3). Referring Figs. 2 and 3, the coordinates of sheeves at trolley and spreader can be approximately expressed as :

$$\begin{aligned}
P_{s1} &= Rot(\alpha)\cdot[-\frac{b_a}{2} \quad \frac{a_a}{2} \quad -l]^T + T_r && (10)\\
P_{s2} &= Rot(\alpha)\cdot[\frac{b_a}{2} \quad \frac{a_a}{2} \quad -l]^T + T_r && (11)\\
P_{s3} &= Rot(\alpha)\cdot[\frac{b_a}{2} \quad -\frac{a_a}{2} \quad -l]^T + T_r && (12)\\
P_{s4} &= Rot(\alpha)\cdot[-\frac{b_a}{2} \quad -\frac{a_a}{2} \quad -l]^T + T_r && (13)\\
P_{t1} &= [-\frac{B_a}{2} \quad \frac{A_a}{2} \quad 0]^T && (14)\\
P_{t2} &= [\frac{B_a}{2} \quad \frac{A_a}{2} \quad 0]^T && (15)\\
P_{t3} &= [\frac{B_a}{2} \quad -\frac{A_a}{2} \quad 0]^T && (16)\\
P_{t4} &= [-\frac{B_a}{2} \quad -\frac{A_a}{2} \quad 0]^T && (17)\\
P_{sti} &\equiv [P_{stix} \quad P_{stiy} \quad P_{stiz}]^T && (18)\\
&\equiv P_{ti} - P_{si} \qquad (i = 1,2,3,4) && (19)\\
u_{sti} &= \frac{P_{sti}}{||P_{sti}||} \qquad (i = 1,2,3,4) && (20)
\end{aligned}$$

where $||\cdot||$ denotes magnitude of a vector, l the length of main cables and P_{si} and $P_{ti}(i = 1,2,3,4)$ the cabling points on spreader and trolley, respectively, as shown in Fig. 3. And a_a and b_a are width and depth between cabling point of auxiliary cables on spreader as shown in Fig. 3. A_a and B_a are those on the trolley. In fact, u_{sti} is a unit vector in direction P_{sti}. Let $T_i(i = 1,2,3,4)$ denote tension of auxiliary cables that connects P_{si} and $P_{ti}(i = 1,2,3,4)$, then control torque($f_{\alpha c}$) applied on spreader by tension of auxiliary cables is :

$$f_{\alpha c} = \sum_{i=1}^{4} T_i(\overrightarrow{OP_{si}} \times u_{sti})_z \tag{21}$$

where '$\times$' denotes vector product and $\overrightarrow{OP_{si}}$ denotes vector from center of spreader to point P_{si}.
And from force equilibrium, control force(f_{xc} and f_{yc} in x and y direction, respectively) by auxiliary cables can be expressed as :

$$\begin{aligned}
f_{xc} &= \sum_{i=1}^{4} T_i u_{sti}\cdot[1 \quad 0 \quad 0]^T && (22)\\
f_{yc} &= \sum_{i=1}^{4} T_i u_{sti}\cdot[0 \quad 1 \quad 0]^T && (23)
\end{aligned}$$

where $\cdot$ denotes scalar product of vectors.
In the following, we derive relation of $F_c \equiv [f_{xc} \quad f_{yc} \quad f_{\alpha c}]^T$ and $T \equiv [T_1 \ T_2 \ T_3 \ T_4]^T$ in a compact matrix form, which is convenient in control system design. Then moment applied on spreader(m_i) by unit tension of auxiliary cable i can be written as :

$$\begin{aligned}
m_i &\equiv [m_{ix} \ m_{ix} \ m_{ix}]^T && (24)\\
&= (\overrightarrow{OP_{si}} \times u_{sti}) && (25)
\end{aligned}$$

Then we can arrange results in matrix form as :

$$F_c \equiv [f_{xc} \quad f_{yc} \quad f_{\alpha c}]^T \tag{26}$$

$$
\begin{aligned}
&= JT_p \quad \text{and} && (27)\\
T_p &= NT \quad \text{where} && (28)\\
J &= \begin{bmatrix} \cos\theta_1 & \cos\theta_2 & \cos\theta_3 & \cos\theta_4 \\ \sin\theta_1 & \sin\theta_2 & \sin\theta_3 & \sin\theta_4 \\ j_1 & j_2 & j_3 & j_4 \end{bmatrix} && (29)\\
& && (30)
\end{aligned}
$$

where

$$
j_1 = \frac{m_{1z}}{\sqrt{u_{st1x}^2 + u_{st1y}^2}} \qquad j_2 = \frac{m_{2z}}{\sqrt{u_{st2x}^2 + u_{st2y}^2}}
$$

$$
j_3 = \frac{m_{3z}}{\sqrt{u_{st3x}^2 + u_{st3y}^2}} \qquad j_4 = \frac{m_{4z}}{\sqrt{u_{st4x}^2 + u_{st4y}^2}}
$$

$$
N = diag\begin{bmatrix} \sqrt{u_{st1x}^2 + u_{st1y}^2} \\ \sqrt{u_{st2x}^2 + u_{st2y}^2} \\ \sqrt{u_{st3x}^2 + u_{st3y}^2} \\ \sqrt{u_{st4x}^2 + u_{st4y}^2} \end{bmatrix} \qquad (31)
$$

where T_p denotes auxiliary cable tension projected on trolley plane. And θ_i denotes the angle :

$$
\theta_i = \text{Atan2}(P_{stiy}, P_{stix}) \qquad (i = 1, 2, 3, 4) \qquad (32)
$$

where 'Atan2' represents two argument arc tangent function [17]. Consequently, control force vector can be expressed as :

$$
F_c = CT \quad \text{where } C = JN \qquad (33)
$$

In Eq. 33, C is 3×4 matrix. And our purpose is to generate three control variables($f_{xc},\ f_{yc},\ f_{\alpha c}$) by using four control inputs($T_1,\ T_2,\ T_3$ and T_4). Therefore the problem of generating control forces by controlling tension of auxiliary cables are inherently redundant.

The redundancy can be relaxed as follows. The tensions of auxiliary cables can be calculated using equations 26 and 28,

$$
T = C^+F_c + (I - C^+C)\kappa \qquad (34)
$$

In this equation, C^+ denotes generalized Moore Penrose pseudo inverse [18], and κ denotes a free parameter.

$$
C^+ = (C^TC)^{-1}C^T \qquad (35)
$$

As one can easily see, the determination of tensions of four auxiliary cables is intrinsically a redundant problem. And it is desirable to distribute cables tensions evenly. This can be expressed as:

$$
P_t = \sum_{i=1}^{i=4} T_i^2 \qquad (36)
$$

One more constraint should be imposed on cable tension. Because we use flexible cables for auxiliary cables, the cable tension can not become negative.

$$
0 < T_{min} < T_i \quad \text{where } i = 1, 2, 3, 4 \qquad (37)
$$

Positive value of T_{min} is imposed to keep auxiliary cables taut always. Constraints on tensions of four auxiliary cables described in equations 36 and 37 can be resolved by controlling free parameter in eq. 34. Of course, the redundancy can be used for other purposes, and this topic requires further research.

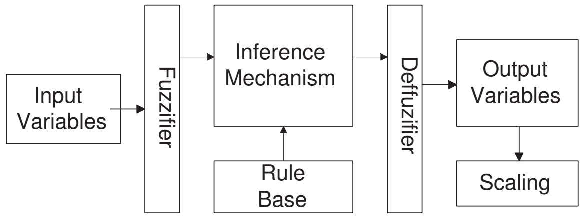

Fig. 4. Fuzzy inference machine.

4. Design of a Fuzzy Controller

As analyzed in previous section, the control problem is nonlinear and redundant. And the relaxation of redundancy is proven to be a constrained nonlinear optimization problem. Due to these reasons, the effective control algorithm is hard to develop. But as is well known in control society, the fuzzy controller is proven to be well suited for this kind of problems [19, 20].

To completely define the state of a spreader, the following variables should be measured and they should be an input set to fuzzy inference mechanism [21].

- Position of spreader x_s,y_s,θ_s
- Velocity of spreader $\dot{x}_s$,$\dot{y}_s$,$\dot{\theta}_s$
- Control force F_{xc},F_{xc},$F_{\theta c}$
- Length and speed of main cables

In designing fuzzy controller, theoretically, the input variables to the fuzzy controller should be the measured position of a spreader(3 inputs), measured velocity of a spreader(3 inputs), control force required, speed of a trolley and length of a main cable. The output variables of a fuzzy controller are the tension of four auxiliary cables. If the complete input and output variables of a fuzzy controller are used, the fuzzy inference engine becomes so large that the implementation of the controller becomes unrealistic. To design a practical controller, the reduced set of input variables is composed and the structure of fuzzy controller is reduced to a reasonable size. The reduced input set is composed of spreader position as an input(x_s,y_s,θ_s). And tension of the four auxiliary cables as outputs(T_i,i=1,2,3,4). As a result, some information regarding the speed of spreader and the length of main cable are lost in this process. And the influence of the lost information on the controller performance is analyzed not so small when the relative planar offset of spreader is not small, but, to avoid the complexity of computation, this is turned out to be inevitable to realize real time control.

Even though the inference machine is used, the cable tension generated may be greater than the practical limit of cable winding motors. For this reason, the scaling factor is used when the greatest tension exceeds maximum tension.

$$
\begin{aligned}
S &= \frac{T_{max}}{max(T_i)} && (38)\\
T_i|_{control} &= S \times T_i \ , i = 1, 2, 3, 4 && (39)
\end{aligned}
$$

, where S denotes cable tension scale factor.

5. Numerical Experiments

In this section, a typical example of industrial mobile gantry crane is used for computer simulations. As mentioned in

Table 1. Rule table used in fuzzy controller. (PB:Positive big, PM:Positive medium, NZ:near zero, NM:Negaive medium, NB:Negative big)

		T_1	T_2	T_3	T_4	Note
	NB	0	2	2	0	
	NM	0	1	1	0	
x_s	NZ	0	0	0	0	
	PM	1	0	0	1	
	PB	2	0	0	2	
	NN	0	0	2	2	
	NM	0	0	1	1	Big=2
y_s	NZ	0	0	0	0	Medium=2
	PM	1	1	0	0	Zero=0
	PB	2	2	0	0	
	NB	0	2	0	2	
θ_s	NM	0	1	0	1	
	NZ	0	0	0	0	
	PM	1	0	1	0	
	PB	2	0	2	0	

sections 2.and 3. the spreader is connected to the trolley by four auxiliary cables to reduce positional offset during trolley motion. The cabling position of auxiliary cables are shown in Fig. 3, and the dimensions are :

$$a_a = 0.38, \quad b_a = 5.0, \quad A_a = 3.0, \quad B_a = 3.3 \tag{40}$$

In Table 2, some physical constants used in computer simulations are summarized. Length of main cables are set to 5m,

Table 2. Constants used in computer simulations

width of spreader a	5m
depth of spreader b	1.5m
modulus of elasticity E_i	83.4GN/m^2
cable diameter	25mm
spreader weight M	20000kg
spreader inertia moment	$I_s = \frac{m(a^2+b^2)}{12}$
damping coefficients	$C_\alpha = .09I_s$ $C_{x,y} = .03m_s$

which is the normal height of spreader when trolley moves. And we assume that tension of auxiliary cables are controlled by torque of cable winding motors and auxiliary cables can apply only planar control force(f_x, f_y, f_α) on the trolley. In Fig. 5, the control result of fuzzy controller is shown. In the figure, the trolley velocity is shown on lower right corner. And in Fig. 6, the control force generated by the fuzzy controller is shown. The control force is not so large because it is the scaled according to Eq. 39. And as can be seen in Fig. 7, the tension of cables remains within practical region. In Fig. 6, the force applied on rotational direction is shown on the lower side. The control force shows the some undesirable fashion during 10sec-20sec and 30-40sec. This is due to the fact that the cables tension generated from fuzzy controller is not so accurate that the rotational force is generated.

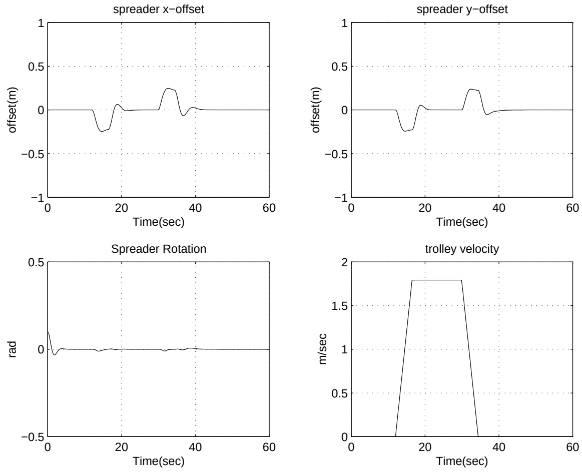

Fig. 5. Result of fuzzy control.

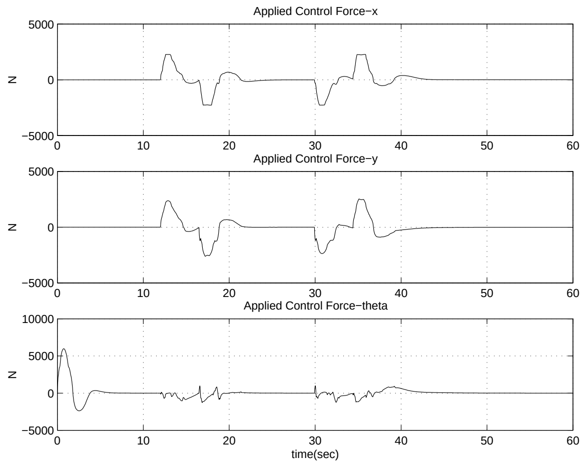

Fig. 6. Applied control force during trolley motion.

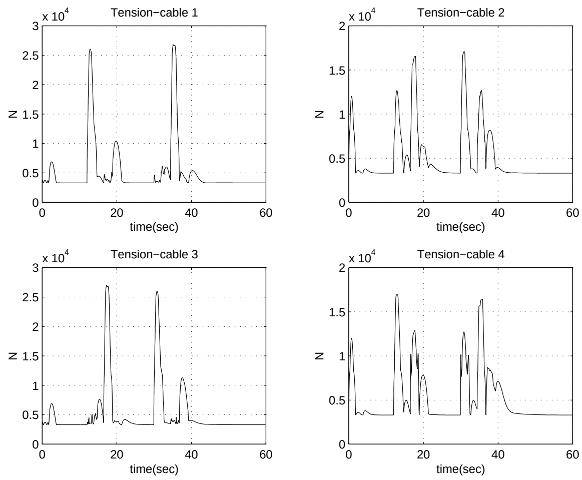

Fig. 7. Cables tension applied during trolley motion.

6. Results and Discussions

In this paper, fuzzy control of sway and skew of spreader is presented based on the three dimensional dynamic equations of the motion of spreader and trolley. Because spreader motion is controlled by four auxiliary cables, the problem of controlling spreader motion in planar and rotational motion becomes redundant. And due to the flexibility of cables, the control problem is turned out to be a problem of constrained optimization. Based on the two constraints(positive tension and minimization of sum of squared tensions), the control algorithm is reformed to effectively resolve the redundancy. In principle, the controller should be implemented through the optimization of nonlinear constraint problem, which requires some computation time. To implement real time controller, fuzzy controller with reduced set of input variables is proposed. The control algorithm shows good performance. The limit of cables tension is resolved in a natural way, and the computation time to generate the cables tension is reduced greatly. But, regrettably, the generated control force shows some undesirable rotational force, which is caused by the cable tension scaling. This problem is remained for further study.

References

[1] Rodger Bostlemann and Ken Goodwin, "Survey of cargo handling research relative to the mobile offshore base needs", Technical report, National Institute of Standards and Technology, Gaitherberg, Maryland, USA, July 1998.

[2] L Morrish, M. P. Cartmell, and A. J. Taylor, "Geometry and kinematics of multicable spreader lifting gear", *Proc. Instn. Mech. Engrs.*, vol. 211, no. C, pp. 185–194, 1997.

[3] L. Morrish, M. P. Cartmell, and A. J. Taylor, "Cable stretch assymetries in multi-cable spreader suspension systems undergoing combined translations and rotations", *Proc. Instn. Mech. Engrs.*, vol. 210, no. C, pp. 225–237, 1996.

[4] Doo-Hyung Kim, Jeong-Woo Lee, Kyoung-Taik Park, and Jun-Ho Oh, "Closed form kinematic solution of a non-parallel reeving crane system", *Proc. Instn. Mech. Engrs. part D*, vol. 217, pp. 257–269, 2003.

[5] Jeong-Woo Lee, Doo-Hyung Kim, and Jun-Ho Oh, "A unified approach of the kinematics of spreader suspended by multiple cables", *Proc. Instn. Mech. Engrs.-Part D*, vol. 217, pp. 289–312, 2003.

[6] Doo-Hyung Kim and Jeong-Woo Lee, "Dynamics of the spreader suspended by four flexible cables", *Proc. Instn. Mech. Engrs. part D*, vol. 218, pp. 1125–1138, 2004.

[7] Yoshiyuki Sakawa and Hideki Sano, "Nonlinear model and linear robust control of overhead traveling cranes", *Nonlinear Analysis, Theory, and Applications*, vol. 30, no. 4, pp. 2197–2207, 1997.

[8] Y. Sakawa and Y. Shindo, "Optimal control of container cranes", *Automatica*, vol. 18, no. 3, pp. 257–266, 1982.

[9] Yoshiyuki Sakawa, "Modelling and control of overhead travelling cranes", *J. Japan Society of Measurement and Control*, vol. 34, no. 8, pp. 962–967, 1998.

[10] A. M. Ebeid, Kamal A. F. Moustafa, and Hosam E. Emara-Shabaik, "Electromechanical modelling of overhead cranes", *Int. J. System Sci.*, vol. 23, no. 12, pp. 2155–2169, 1992.

[11] Sandeep Joshi and Christopher D. Rahn, "Position control of a flexible cable gantry crane: Theory and experiment", in *American Control Conference*, Seattle, 6 1995, pp. 2820–2824.

[12] Arto Marttinen, Jouko Virkkunrn, and Riku T. Salminen, "Control study with a pilot crane", *IEEE Trans. on Education*, vol. 33, no. 3, pp. 298–305, 8 1990.

[13] Giorgio Corriga, Alessandro Guia, and Giampaolo Usai, "An implicit gain-scheduling controller for cranes", *IEEE Trans. Control Systems Technology*, vol. 6, no. 1, pp. 15–20, 1 1998.

[14] Shinishi Sagara and Fujio Ohkawa, "Adaptive control for crane", *J. Japan Society of Mechanical Engineers(C)*, vol. 56, no. 526, pp. 1494–1498, 6 1996, in Japanese.

[15] Ho-Hoon Lee and Sung-Keun Cho, "Position and swing angle control for loads of overhead cranes", *J.of Korean Society of Mechanical Engineers(A)*, vol. 21, no. 2, pp. 297–304, 1997, in Korean.

[16] M. P. Cartmell, L. Morrish, and A. J. Taylor, "Dynamics of spreader motion in a gantry crane", *Proc. Instn. Mech. Engrs.*, vol. 212, no. C, pp. 85–105, 1998.

[17] John J Craig, *Introduction to Robotics-Mechanics and Controls*, Addison Wesley, Reading, Massachusetts, 2nd edition, 1989.

[18] Peter Lancaster and Miton Tismenetsky, *The Theory of Matrices with Applications*, Academic Press, Orlando, 2nd edition, 1985.

[19] Witold Pedrycz, *Fuzzy control and fuzzs ystems*, Research Studies Press, Sommerset, U.K., 2nd edition, 1993.

[20] Mi-Xin Wang, *A course in Fuzzy Systems and Control*, Prentice Hall, N.J., USA, 1997.

[21] Jeong-Woo Lee, Doo-Hyung Kim, and Kyoung-Taik Park, "Practical pd control of a multiple cable suspended spreader with four auxiliary cables", *International Journal of Control, Automation and Systems*, 2004,Dec, Submitted for possible publication.