Tracking Control of Mobile Harbor Crane to Moving Container Ship

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Abstract

In this paper, the tracking control of mobile harbor (MH) crane is proposed for dynamic positioning of containers to moving container ship. During operation of MH exposed to external disturbances, the MH and container ship have 6 degree of freedom motions. In such cases, a container position becomes difficult to control accurately due to the unwanted swing motion of payload and variation of target position. It is the most significant technology in the MH system. The MH crane model in 3D space with roll, pitch and heave motion caused by disturbances is derived. Then, this model is linearized and the parameters of the linear model is identified by experiments of 1/20 scale model. In the proposed tracking control, a preview control method is applied including feed-back and feed-forward control with predicted reference information in near future. Through numerical simulations and experiments of small scaled model, the performances of the proposed position control method are verified when roll and pitch motion is generated as disturbances.

Keywords: Mobile harbor, Offshore crane, Tracking control, Moving target, Preview control

1. Introduction

The Mobile Harbor (MH) is a novel maritime cargo transfer system proposed by Korea Advanced Institute of Science and Technology (KAIST) instead of the construction of deep draft ports for easier access to overcome the capacity of the existing conventional harbor system. The MH is designed to carry containers from large container ship to the small ship: the MH equipped with a crane in deep water. Figure 1. shows the typical concept of the MH system. Due to external disturbances such as sea wave and wind, the MH and container ship have the wave-induced 6-DOF motions: surge, sway and heave in translational motions, and roll, pitch and yaw in rotational motions. These motions make not only a swing motions of the containers hanging on the ropes of the crane and persistently time-varying target position to load/unload. Therefore, during a work of the MH, it is difficult to guarantee safe and efficient transportation even by skilful operators. The design of the accurate positioning control system is the most important technology in the MH system.

Fig. 1 The concept of the Mobile Harbor in open sea

Many crane control methods have been already studied for various applications in the industry. The existing crane systems were generally designed to suppress the swing motions of payload when the trolley is moving or stopped at the
goal position due to the crane dynamics and disturbances. However, these crane control methods are not applicable to an offshore crane directly. A few researches recently have tried to reduce the oscillation of the payload for an offshore crane. H. Schaub (2007) developed a new ship motion sensing system to compensate the transport payload swing. Z. Masoud et al. (2004) developed a control strategy using delayed feedback of the angles of the cargo-hoisting cable and showed performance through simulation and experiment with a 1/24 scale model of crane mounted on moving platform. K. Terashima et al. (2010) established the integrated computer simulator of rotary ship-board crane with ship behavior in consideration of ship sway and load sway including transfer control system. Q. H. Ngo et al. (2012) proposed a sliding mode control for an offshore container crane. And D. Kim et al. (2011) proposed the anti-swing control using optimal control scheme based on dynamic crane model. B. Kimiaghalam et al. (2001) designed model predictive control based on nonlinear model for swinging suppression for a ship-board crane. However, these researchers have not considered the moving target in the open sea, because the container ship motion is assumed to be stationary due to its huge size. In this paper, the position control of MH crane system is proposed for payload tracking by considering the moving target position. This tracking control method is designed by a preview control scheme using a preview information which is the container ship motions in near future.

2. Mobile harbor crane model

2.1 Dynamic model of the MH

Figure 2. shows the dynamic model of MH crane. Let \( OX_0Y_0Z_0 \) denote the reference coordinate frame. \( OX_0Y_0Z_0 \) and \( OX_2Y_2Z_2 \) is the mobile harbor and container ship coordinate frame with respect to the center of gravity of the mobile harbor and container ship. \( OX_1Y_1Z_1 \) is the trolley coordinate, in which two sub-trolleys can move independently in the x and y directions that is the dual-stage trolley system (D. Kim et al. 2011). Thus, using additional sub-trolley in the x
direction comparing with the other trolley systems, it is possible to control the payload position in the x-y plane. The trolley and the payload position are defined as Eq. (1) and (2) in the global coordinate. In the equations of motion, s and c denotes sin and cos for simplicity.

$$X_t = \begin{bmatrix} x \alpha + y \alpha s \phi + h \alpha c \phi \\ y c - h s \phi \\ z - x s \alpha + y e a s \phi + h c c \phi \end{bmatrix}$$

(1)

$$X_p = \begin{bmatrix} x \alpha + y \alpha s \phi + h \alpha c \phi - l c \phi \\ y c - h s \phi + l \phi \\ z - x s \alpha + y e a s \phi + h c c \phi - l c \phi \end{bmatrix}$$

(2)

Based on the positions of the trolley and payload, the velocities of the trolley and payload by time derivative are also given as $v_{x_t}, v_{y_t}, v_{z_t}$, $v_{x_p}, v_{y_p}$ and $v_{z_p}$. The kinetic and the potential energy of the trolley and payload are given as:

$$T = \frac{1}{2} m_t (v_{x_t}^2 + v_{y_t}^2 + v_{z_t}^2) + \frac{1}{2} m_p (v_{x_p}^2 + v_{y_p}^2 + v_{z_p}^2)$$

(3)

$$U = m_t g (z - x s \alpha + c e a s \phi + h c c \phi) + m_p g (z - x s \alpha + c e a s \phi + h c c \phi) - m_p g l c \phi$$

(4)

Applying the Lagrange equation with respect to generalized coordinates $x, y, \theta, \phi$ and $l$, the equations of motion of the trolley and payload are derived.

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<tr>
<th>Table 1 Nomenclature</th>
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2.2 Linearization

For small motions of $\alpha, \beta, \theta$ and $\phi$ about the equilibrium point, $\alpha=0, \beta=0, \theta=0$ and $\phi=0$, because not only swing motions of payload excepting for a case of resonance excitation but also the roll and pitch motions of ships is very small enough to be ignored, it can be $s i n \alpha=\alpha, s i n \beta=\beta, s i n \theta=\theta, s i n \phi=\phi, c o s \alpha=1, c o s \beta=1, c o s \theta=1$ and $c o s \phi=1$. Additionally, the higher order terms in the equations of motion are able to be ignored. As a result, the linearized equations are decoupled in the x and y directions as follows:
\[ m\ddot{x}_i + D\dot{x}_i + m_y g/l (x_i - x_t) + (m_x + m_y)g\beta = f_s \]  
(3)

\[ \ddot{y}_i + g(x_i - x_t) = 0 \]  
(4)

\[ m\ddot{y}_i + D\dot{y}_i + m_y g/l (y_i - y_t) - (m_x + m_y)g\beta = f_s \]  
(5)

\[ \ddot{y}_i + g(y_i - y_t) = 0 \]  
(6)

where
\[
\begin{bmatrix}
  x_i \\
  y_i \\
  x_t \\
  y_t
\end{bmatrix} = \begin{bmatrix}
  x + h\alpha \\
  y - h\beta \\
  x + h\alpha - \lambda \phi \\
  y - h\beta + \lambda \theta
\end{bmatrix}
\]

3. System Identification

In this research, system identification is performed based on the small scale MH model. The detail of the MH model will be explained in Chapter 6. The equations of motion in Eq. (3), (5) and Eq. (4), (6) are symmetric each other, the parameters are found in the only one direction without subscripts x and y. It is assumed that the payload acceleration and the roll disturbance have small effects on the trolley dynamics in Eq. (3) and (5). Then, transfer functions of the trolley and payload system are obtained through Laplace transformation.

\[
\frac{V_i(s)}{F(s)} = \frac{1}{m_s + D} \]  
(7)

\[
\frac{X_i(s)}{X_i(s)} = \frac{g}{ls^2 + g} \]  
(8)

A dual-stage trolley is driven by AC velocity servo motor. Motor dynamics is much faster than the trolley dynamics, so that it can be ignored. \( K_s \) is a scaling factor composed of various constants and \( U(s) \) is control input of AC velocity servo motor.

\[ F(s) = K_s U(s) \]  
(9)

As a result, trolley dynamic model is expressed as:

\[
G_t(s) = \frac{V_i(s)}{U(s)} = \frac{K_s}{m_s + D} \]

(10)

\( G_t(s) \) is the transfer function between control input \( U(s) \) and the trolley velocity \( V_i(s) \). Finally, the velocity servo trolley system is derived as the second order system as Eq. (11):

\[
G_t(s) = \frac{V_i(s)}{V_i(s)} = \frac{G_t(s)K_t(s)}{1 + G_t(s)K_t(s)} = \frac{c_i}{s^2 + a_s + b_i} \]  
(11)

\( V_i(s) \) is the velocity command and \( K_t(s) \) is the velocity servo controller using PI control. \( a_s, b_s, \) and \( c_i \) are parameters representing the trolley system that should be estimated through experiments. The payload system model in Eq. (8) is also obtained as the second order system with parameters \( a_s, b_i \) and \( c_i \) including damping.

\[
G_t(s) = \frac{X_i(s)}{X_i(s)} = \frac{c_i}{s^2 + a_s + b_i} \]  
(12)
Generally, for the system identification, an external force with broadband signals or white noise are used as the input to excite the system. On the other hand, in this trolley control system, it is impossible to impose these input signals. Instead of white noise, a sinusoidal signal with specific frequency band: 0.05Hz to 0.5Hz with interval of 0.05Hz that is target dynamic range for the MH crane system, is applied for the system identification. Parameters are extracted by the approximated transfer function using the response of the trolley velocity via the reference signal. The transfer function between reference signal and output signal in the frequency domain are written as Eq. (13) and Eq. (14) and shown as Fig. 4. The approximated transfer functions are well identified enough to represent the derived second order trolley system. The experiments are carried out for both the x and y axis.

\[ G_{x,s}(s) = \frac{0.29}{s^2 + 11.58s + 74.9} \]  
\[ G_{y,s}(s) = \frac{0.24}{s^2 + 9.56s + 62.98} \]  

The approximated transfer functions of payload dynamic model are given in Eq. (15) and (16), and the transfer function of the payload system in the frequency domain is also depicted in Fig. 5.
The resonant frequency is equal in the x and y axis as Eq. (8). However, it is different as Eq. (15) and Eq. (16) represented as parameter $c_i$ due to the additional mechanical device for suppressing large swing motion of the payload that is only equipped in the y direction. In addition, if the rope length is changing, this parameter in Eq. (15) should be adapted according to the current rope length.

Finally, the state space model is established based on identified parameters as follows:

$$
\dot{x} = Ax + Bu
$$

$$
y = Cx
$$

where

$$
x = \begin{bmatrix}
x_0 & x_i & \dot{x}_0 & \dot{x}_i \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
c_i & -b_i & 0 & -a_i \\
0 & 0 & -b_i & 0 & -a_i \\
\end{bmatrix}
$$

$$
A = \begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
c_i & -b_i & 0 & -a_i \\
0 & 0 & -b_i & 0 & -a_i \\
\end{bmatrix},
$$

$$
B = \begin{bmatrix}
0 \\
0 \\
0 \\
C = \begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1 \\
\end{bmatrix}
$$

\section{4. Tracking Controller Design}

In this paper, a preview control scheme is applied for tracking control of the MH crane. A preview control is kind of model predictive control (MPC), but the input and output constraints are not taken into account differently. In this method, the optimal control input is calculated by iteration on a finite horizon and combined with feedback control and feed-forward control. The container ship motions in the x and y directions as a preview information is adaptively used in a feed-forward control that is assumed be given by the developed ship motion predictor (T. Perez et al. 2008).

The discrete system model with specific sampling time $T_s$ is given by a continuous time model, Eq. (17):

$$
x(k+1) = Gx(k) + Hw(k)
$$

$$
y(k) = Lx(k)
$$

The discrete system in referenced predictive forms is as follows:

$$
x(k+j) = Gx(k+j|k) + Hw(k+j|k)
$$

$$
y(k+j|k) = Lx(k+j|k)
$$

A cost function of preview control is defined as:

$$
J = \sum_{j=0}^{N_s-1} \left[ (x(k+j|k) - x^*(k+j|k))^T \bar{Q}(x(k+j|k) - x^*(k+j|k)) + u^T(k+j|k)R_u(k+j|k) \right] \\
+ (x(k+N_s|k) - x^*(k+N_s|k))^T \bar{Q}_f(x(k+N_s|k) - x^*(k+N_s|k))
$$

where

$$
\bar{Q} = C^TQC \\
\bar{Q}_f = C^TQ_fC \\
Q = diag([\rho_1, \rho_1, \rho_1, \rho_1]) \\
R = \rho_u
$$
where $x'$ is reference signal which is the surge and sway container ship motions, $Q \geq 0$ is the state weighting matrix, $R>0$ is the input weighting matrix, $Q_2 \geq 0$ is the terminal weighting matrix and $\rho_1$, $\rho_2$, $\rho_3$, $\rho_4$, $\rho_5$ and $\rho_6$ are weighting factors. The control input of each step is obtained by iteration process (W. Kwon and S. Han 2005).

5. Simulation

The environment of simulation based on MATLAB$^\text{TM}$ Simulink including the velocity servo trolley system. The target model is the 1/20 scale MH crane which is implemented by KAIST MH center. In these numerical simulations, we performed an operation of unloading containers on the moving container ship with a sinusoidal motion. Since the real sea wave consists of a summation of sinusoidal functions with some specific frequencies (T. Perez et al. 2008), the movement of container ship is assumed to have a sinusoidal function with single frequency in the region of target frequency. A frequency bandwidth is up to 0.5Hz which is decided by considering a scale of MH crane model when the sea state is 2.

The frequencies of reference signal as the container ship motions are between 0.1Hz and 0.5Hz with 0.1Hz of interval and the magnitude of the reference signal is 0.05m: 1m in real scale model, but it is different as a kind of ships. The prediction time is 1 second, sampling time is 0.05 second, and the rope length is 1m. And the pitch and roll motions by sea waves are also considered as a sinusoidal wave which has 0.5 degree of the magnitude and same frequency range of reference signal. However, the heave motion is ignored in this numerical simulation while it is not interested motion in the x-y plane position control. Under these conditions, the performance of the designed tracking controller is discussed.

Figure 6. presents errors of the position and the velocity according to various frequencies of the reference and disturbance. As the frequency of the reference signal and disturbance increase, the position errors also increase that is caused by the uncertainties that the MH crane model which is linearized from nonlinear dynamic equations is growing more different from the real model. In the process of system identification, it is hard to make the linear model matched with the experiment data. However, the position error is less than 10mm of target boundary.

![Fig. 6 position errors of simulations(a) x axis (b) y axis](image_url)

6. Experiment

6.1. 1/20 scale model

In order to evaluate the performance of the designed tracking controller, experiments of the 1/20 MH crane are carried out. An experimental model is implemented as possible as representing the real MH crane model comparing the other simple crane model (Z. N. Masoud et al. 2004). A number of sensors and actuators are used to measure defined state variables in Eq. (17). First, the dual-stage trolley system is driven by a belt mechanism and AC velocity servo motors. Two servo motors have encoders for measurement of the trolley positions in the surge and sway axis and manipulate the sub-trolleys independently in each axis. Under the trolley system, a smart vision is equipped and an infrared rays (IR)
marker is also installed on the spreader. The IR pass filter in the smart vision captures the IR marker on a spreader selectively which provides data on in-plane motions. And to describe as if the ships are in sea environment, the MH crane is installed on Stewart Platform which is able to generate wanted 6-DOFs motions. The rotational movements such as roll and pitch of the MH is given by inertia measurement unit (IMU). The measurement data is transferred to PC by wire, the PC-based controller commands actuators. Figure 7. shows the entire view of MH crane.

![MH Crane Image](image)

Fig. 7 1/20 scale mobile harbor crane

6.2. Experiment results

For comparison of the experiments and simulations, the conditions of the disturbances and reference signals are almost same as the simulations. The magnitude of reference signal is 0.03m, differently. The designed position controller is applied in only sway axis for checking the feasibility. Therefore, there are roll motions of the MH as the disturbance and translational motion of the container ship in the x direction. As shown as Fig. 8, the trend of position error is similar with simulation results. However, the magnitude of the position errors in the experiments is larger than simulation results. And a little phase error between the reference signal and the payload position makes the position error larger as the frequency of reference signal and roll motions increase. Because it is found that a system uncertainty, a measurement delay and control input delay affect the tracking performance. In addition, the beating phenomenon such as Fig. 9 is demonstrated due to a composite of different frequencies of the reference signal and the disturbances that also can become another reason of the magnitude error of the position. Since we didn’t design for the disturbance rejection in a preview control, it is clearly that the proposed method could not reject a disturbance effectively. And on the contrary of the simulations, the control input with tuning the large weighting factors is not available in the experiments due to the saturation of the actuators. Therefore, the proposed tracking controller has a continuous position errors unless the methods for a compensation of phase error and a disturbance rejection is developed in advance.

7. Conclusion

The MH system is new maritime cargo transfer system overcoming the limitation of the existing harbor. However, it is hard to control the payload position to moving container ship accurately in both the sway and surge axis due to external disturbances. In order to design the accurate payload positioning system, the dynamic equations of the MH crane are derived and the parameters of the linearized trolley model and payload model are obtained by a system identification. It is impossible to apply the conventional crane control methods, so that a preview control scheme using the dual-stage trolley is used in this study. In numerical simulations and experiments of 1/20 scale model, the overall performance of tracking controller is verified when the MH motion exerts as the disturbance and the container ship motions are used as the reference signal. In experiments, when the disturbances are assumed to be a sinusoidal wave with specific frequency bandwidth determined by the sea state, the tracking errors become larger as frequency of the
reference signal and disturbance increases. On the other hand, the position errors of simulations is about a half of the position error of experiments even though the magnitude of the reference signal is 0.02m smaller in simulation. It is obvious that the actuator power is more important factors than other things in real application. Therefore, the proposed position control should be modified to get the more accurate tracking performance considering a maximum power of actuators and so on. But we expect to find a potential of the MH crane control system to guarantee safe and efficient transfer operations in open-sea condition.

Fig. 8  position errors of experiments (a) x axis (b) y axis

Fig. 9  Performance of tracking control, reference frequency : 0.3Hz, disturbance frequency : 0.5Hz

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References


W. Kwon and S. Han, Receding horizon control: model predictive control for state models (2005), Springer.