INPUT SHAPING-BASED CONTROL SCHEMES FOR A THREE DIMENSIONAL GANTRY CRANE

MOHAMMAD JAVAD MAGHSOUDI

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Universiti Teknologi Malaysia

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DEDICATION

To my dearly beloved wife, Fatemeh for her support and encouragement.
   To my lovely daughter Saba for making my life beautiful.
   To my dearest parents, for their love and blessing.
ACKNOWLEDGEMENT

First and foremost, praise and thank be to Almighty Allah, the most Gracious and the most Merciful.

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ABSTRACT

The motion induced sway of oscillatory systems such as gantry cranes may decrease the efficiency of production lines. In this thesis, modelling and development of input shaping-based control schemes for a three dimensional (3D) lab-scaled gantry crane are proposed. Several input shaping schemes are investigated in open and closed-loop systems. The controller performances are investigated in terms of trolley position and sway responses of the 3D crane. Firstly, a new distributed Delay Zero Vibration (DZV) shaper is implemented and compared with Zero Vibration (ZV) shaper and Zero Vibration Derivative (ZVD) shaper. Simulation and experimental results show that all the shapers are able to reduce payload sway significantly while maintaining desired position response specifications. Robustness tests with ±20% error in natural frequency show that DZV shaper exhibits asymmetric robustness behaviour as compared to ZV and ZVD shapers. Secondly, as analytical technique could only provide good performance for linear systems, meta-heuristic based input shaper is proposed to reduce sway of a gantry crane which is a nonlinear system. The results show that designing meta-heuristic-based input shapers provides 30% to 50% improvement as compared to the analytical-based shapers. Subsequently, a particle swarm optimization based optimal performance control scheme is developed in closed-loop system. Simulation and experimental results demonstrate that the controller gives zero overshoot with 60% and 20% improvements in settling time and integrated absolute error value of position response respectively, as compared to a specific designed PID-PID anti swing controller for the lab-scaled gantry crane. It is found that crane control with changing cable length is still a problem to be solved. An adaptive input shaping control scheme that can adapt to variation of cable’s length is developed. Simulation with real crane dimensions and experimental results verify that the controller provides 50% reduction in payload sway for different operational commands with hoisting as compared to the average travel length approach.
ABSTRAK

Ayunan hasil pergerakan sistem berayun seperti kren gantri akan mengurangkan keberkesanan proses pembuatan. Tesis ini membentangkan pemodelan dan pembangunan skema kawalan berasaskan pembentuk masukan untuk kren gantri tiga dimensi (3D) berskala makmal. Beberapa skema pembentuk masukan telah dikaji dalam sistem gelung buka dan gelung tutup. Prestasi pengawal dikaji berdasarkan sambutan kedudukan troli dan ayunan kren 3D. Pertama, pembentuk Getaran Sifar dengan Lengah teragih (DZV) digunakan dan dibandingkan dengan pembentuk Getaran Sifar (ZV) dan pembentuk Pembezaan Getaran Sifar (ZVD). Keputusan simulasi dan eksperimen menunjukkan semua pembentuk berupaya mengurangkan ayunan beban secara berkesan disamping mencapai spesifikasi sambutan masa yang diperlukan. Ujikaji ketegapan dengan ±20% ralat dalam frekuensi tabii menunjukkan pembentuk DZV mempunyai ciri-ciri ketegapan yang tidak simetri berbanding pembentuk ZV dan DZV. Disebabkan kaedah analitik hanya dapat memberikan keputusan yang baik untuk sistem lelurus, pembentuk masukan berasaskan meta-heuristik dicadangkan untuk mengurangkan ayunan kren gantri. Keputusan menunjukkan pembentuk masukan berasaskan meta-heuristik menghasilkan ayunan yang lebih baik dalam jutaan 30% hingga 50% berbanding pembentuk masukan berasaskan analitik. Kemudian, skema kawalan prestasi optima berasaskan pengoptimuman kerumunan zarah dibangunkan dalam sistem gelung tutup. Keputusan simulasi dan eksperimen menunjukkan bahawa pengawal tersebut menghasilkan sambutan kedudukan dengan lajak sifar dan perbaikan sebanyak 60% dan 20% dalam masa menetap dan nilai ralat purata kamiran berbanding pangawal anti-ayunan PID-PID. Disebabkan kawalan kren dengan perubahan panjang kabel masih merupakan masalah yang perlu diselesaikan, skema kawalan pembentuk masukan penyesuaian yang berupaya untuk menyesuaikan kepada perubahan panjang kabel dibangunkan. Keputusan simulasi dalam dimensi kren sebenar dan eksperimen menunjukkan bahawa pengawal ini berupaya menghasilkan pengurangan ayunan beban sebanyak 50% berbanding kaedah panjang perjalanan purata untuk berbagai jenis operasi kren.
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LIST OF SYMBOLS

\[ A_j \] - amplitude of the \( j \)th impulse
\[ D \] - initial amplitude of DZV delay
\[ F_x \] - force driving the moving rail
\[ F_y \] - force driving the trolley
\[ F_z \] - force lifting the payload
\[ G_i \] - position of the best particle thus far in the entire swarm
\[ K_d \] - derivative gain
\[ K_i \] - integral gain
\[ K_p \] - proportional gain
\[ P \] - local best position of the particle
\[ T \] - reaction force in the payload rope acting on the trolley
\[ T_x \] - components of the force \( T \)
\[ T_y \] - components of the force \( T \)
\[ T_z \] - components of the force \( T \)
\[ V_i \] - the present velocity of the particle
\[ X_{des} \] - desired position
\[ X_i \] - the present position of the particle
\[ a_{c1} \] - acceleration constant
\[ a_{c2} \] - acceleration constant
\[ e(t) \] - system error
\[ f_x, f_y, f_z \] - corresponding friction forces
\[ g \] - gravitational constant
\[ i_w \] - inertia weight
\[ l \] - length of the lift-line
\[ m_p \] - payload mass
\[ m_r \] - moving rail
\begin{itemize}
  \item $m_t$ - trolley mass (including gear box, encoders and DC motor)
  \item $r_1$ - positive random number produced by a uniform distribution
  \item $r_2$ - positive random number produced by a uniform distribution
  \item $t_0$ - time of the impulse
  \item $t_j$ - time of the $j^{th}$ impulse
  \item $t_m$ - time of the last impulse
  \item $x$ - delay input
  \item $y$ - delay output
  \item $\alpha$ - angle of lift-line with Y axis
  \item $\beta$ - angle between negative part of Z axis and projection of the payload rope onto the XZ plane
  \item $\delta(t)$ - dirac delta function
  \item $\zeta$ - damping ratio of the system
  \item $\psi$ - maximum range of delay
  \item $\omega(\epsilon)$ - delay distribution over the interval $[0,\psi]$
  \item $\omega_n$ - natural frequency
\end{itemize}
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<td>Three-dimensional</td>
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<td>ATL</td>
<td>Average travel length</td>
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<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DZV</td>
<td>Distributed delay Zero Vibration</td>
</tr>
<tr>
<td>IAE</td>
<td>Integrated Absolute Error</td>
</tr>
<tr>
<td>MAX</td>
<td>Maximum</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multi-Input Multi-Output</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PD</td>
<td>Proportional Derivative</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional-Integral-Derivative</td>
</tr>
<tr>
<td>PSO</td>
<td>Particle Swarm Optimization</td>
</tr>
<tr>
<td>UM</td>
<td>Unity Magnitude</td>
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<tr>
<td>ZV</td>
<td>Zero Vibration</td>
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<tr>
<td>ZVD</td>
<td>Zero Vibration Derivative</td>
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CHAPTER 1

INTRODUCTION

1.1 Background

Generally, role of crane in human life is very important. Cranes are mostly utilized in construction of structures like bridges, dams, buildings, and high-rise towers. They are used for transportation of heavy loads and hazardous materials in shipyard, factories and warehouses. Cranes are also used in energy-based industries such as nuclear power plants and oil platforms in refineries. The task of a crane is to lift a load from a source place and transfer it to a target place. For this purpose, the mechanism of a crane should consist of a hoisting system including hoisting line and a hook for vertical movements of the load. Moreover, it needs a support mechanism which is cart-girder, cart-jib or a boom that moves the load around the crane workspace in horizontal space. It should be mentioned that there are different type of cranes such as gantry, overhead, jib, tower and boom cranes (Abdel-Rahman et al., 2003). For this study a gantry crane is considered as this is one of the widely used cranes in factories and warehouses (Butler et al., 1991).

One of the significant factors affecting productivity and efficiency of the industrial systems is speed. However, it is obvious that for a flexible system such as a gantry crane increasing the speed of manoeuvres cause the flexible system to oscillate more. This oscillation can result in considerable residual sway that negatively affects performance of the systems (Gholabi et al., 2013). At low speeds, the payload’s sways are not considerable and can be neglected. However, at higher speed, these sway angles prevent the payload to settle down during movement and
unloading. This problem will be crucial particularly for industrial applications where operators should manipulate the cranes (Peng et al., 2012). To address the mentioned issues, an efficient controller should be designed to improve the system performance.

1.2 Statement of the Problem

To increase the production speed the commands to the crane should be fast but this type of commands causes undesirable residual oscillation of payload in three dimensional (3D) gantry cranes. This low damped sway definitely decreases the efficiency of production line and may cause some serious damages to the production area.

1.3 Objectives of the Study

The work focuses mainly on the control of a 3D gantry crane. The main objectives of the study are as follows:

(a) To implement and investigate a new input shaping technique on a 3D gantry crane
(b) To design and implement meta-heuristic based input shapers for a non-simplified model of a 3D gantry crane
(c) To design and implement a PSO-based PID controller to cater two control objectives including fast and accurate positioning and low payload sway
(d) To design and implement an open-loop adaptive input shaping controller for the 3D crane with varying cable lengths

1.4 Scope of Works

This work has been conducted within the following scope:
1) Matlab and Simulink are used to simulate and investigate the behaviour of the system
2) Experiments are conducted based on a lab-scaled 3D gantry crane
3) The cable is considered to be inextensible
4) Horizontal movements are restricted to 55 cm and hoisting range is between 0-75 cm
5) ZV, ZVD, UM-ZV, UM-ZVD and DZV shapers are considered as input shapers
6) PSO is considered in the development of a meta-heuristic based input shaping scheme
7) PID controller is utilized for closed-loop control design
8) Input is limited based on movement’s restrictions of the lab-scaled gantry crane
9) Maximum input for all three directions is considered as 1 N.
10) Cable length is the only variable characteristic of the crane

1.5 Thesis Contributions

This study may have several contributions in modelling and control of the system as follows:
(a) Development of a DZV based control scheme for payload sway control of a 3D gantry crane
(b) Development of a meta-heuristic based input shapers for a non-simplified model of a 3D gantry crane
(c) Development of a PSO-based PID controller including an input shaper for input tracking and payload sway reduction of the system.
(d) Development of an adaptive input shaping controller for handling varying cable lengths
1.6 Thesis Organisation

This thesis is organised as follows. Chapter 2 provides a review of the existing modelling and control for a 3D gantry crane. Chapter 3 describes research methodology of the current study. Chapter 4 describes the 3D gantry crane system considered in this study and incorporating payload’s damping, and dead zone of actuator into the dynamic model. Experimental results are presented for verification and assessment of the developed model. Also, implementation of DZV shaper for control of the 3D gantry crane is described. Development of a PSO-based input shaping scheme for payload sway control of the 3D gantry crane is described in chapter 5. Moreover, an optimal performance controller including PID control algorithm and input shaping techniques is also proposed in chapter 5. Adaptive input shaping scheme is proposed in Chapter 6. Finally, the conclusions of the thesis as well as the research direction of the work are presented in Chapter 7.


Mediterranean Conference on Control and Automation. Limassol, Cyprus, 485-490.


