Anti-swinging Input Shaping Control of an Automatic Construction Crane

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Abstract—**This paper describes the control of an automatic overhead crane for assembly of modular building elements. The automatic system was developed using a commercial crane, which was modified by adding the adequate sensors, servomotors and control strategy[1] [2]. The crane, transformed to robotic system, is controlled via computer-based multi-axes control board. The implemented algorithms solve two main problems of modules assembly: 1) precision positioning of the modules, and 2) anti-swinging transportation of modules.**

The automatic control was designed by using a new form of Input Shaping strategy that was developed for use on the crane. The control was implemented in a 8 x 5 x 4m range 3D crane (Fig. 1). The control algorithm is divided into two parts: 1) Basic Input Shaping anti-swing control that guarantees a smooth and accurate movements (in the order of +/- 5 cm), and 2) elimination of external perturbation due to wind disturbance, or other exogenous factors. The implementation of the anti-swinging control is done by using the on-line 2D inclinometer measurements and on-line calculation of input impulse train.

Experimental results of the developed algorithms are presented which demonstrate the effectiveness of the new process.

Index Terms—**Input shaping, Crane Control, Automatic Crane, Automation in Construction.**

I. INTRODUCTION

Methods that have been investigated for controlling flexible structures in general and cranes in particular, can be roughly divided into feedback and feedforward approaches. Feedback control methods use measurements and estimates of the system states to reduce vibration, while feedforward techniques alter the actuator commands so that the system oscillation are reduced. The performance of feedback methods can often be improved by additionally using a feedforward controller, and properly designed feedforward compensators can dramatically reduce the complexity of the required feedback controller for a given level of performance. Thus, the development of effective feedforward algorithms can lead to more practical and accurate control of flexible systems.

One particular feedforward approach, input shaping [3] [4] has proven to be an especially practical and effective method of reducing vibrations in flexible systems. Several other methods have been developed to deal with the issue of minimizing the residual vibration. Smith [5] proposed the Posicast Control of Damped Oscillatory Systems, that is a technique to generate a non-oscillatory response from a damped system to a step input. This technique breaks a step of a certain magnitude into two smaller steps, one of which is delayed in time. Swigert [6] proposed Shaped Torques Techniques, which consider the sensitivity of terminal states to variations in the model parameters. He demonstrated that velocity and torque can be implemented on systems that modally decompose into second order harmonic oscillators. He showed that inputs in the form of the solutions for the decoupled modes can be added so as not to excite vibration in any of the modes.

More recently, in the control of overhead cranes, Mita and Kanai [7] solved a minimum time control problem for swing free velocity profiles, which resulted in an open loop control.

Fig. 1. Robotized crane

Ohnishi adopted a feedback control scheme based on load swing dynamics, whereas Ridout [8] designed a linear feedback
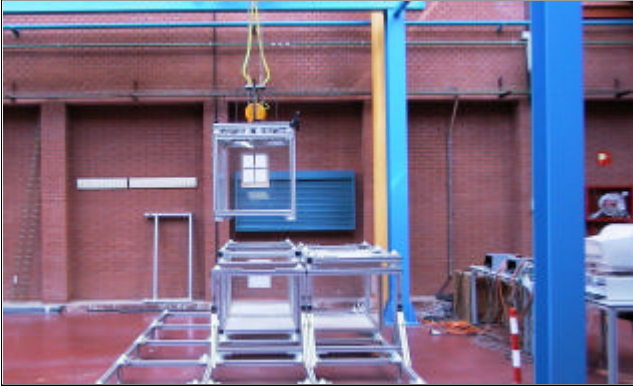
Fig. 2. Modules assembly process

control using the root locus method. Yu et al. [9] proposed a nonlinear control based on the singular perturbation method. Lee et al. [10] designed a high performance control based on the loop shaping and root locus methods. Singhose et al.[11] applied the input shaping method to the control of gantry cranes with load hoisting. Moustafa and Ebeid [12], on the other hand, proposed an anti swing control for a three dimensional overhead crane. Their control addresses the supression of load swing.

This paper describes an adaptation of the input shaping technique and implementing it on the developed prototype 3D crane shown in Fig. 1 and Fig. 2.

In the basic anti-swing control the input is the desired reference position. The first part of the algorithm (the path generator) transforms the reference position in a smooth path by generating appropriate velocity profiles.

This data is commonly the input for the inverse kinematics module which generates the angular reference for the joint actuators. The second part of the developed algorithm (Input Shaping control itself) calculates the input impulse train (amplitude and time instant of applying) of the joint actuators according to: a) the semi-period of modules oscillation, and b) the length of the wire of the crane's hook. This way, the desired step input reference is transformed in a shaped signal which has an acceleration curve formed by a train of impulses that eliminates the swing of the load (modules).

Nevertheless, the above described control strategy works only in ideal environment. If some type of disturbances (wind, asymmetrical distribution of the load, friction, etc.) occurs, the transportation of the load will not be smooth and its assembly will be impossible due to residual swinging oscillations. To avoid this problems the system needs external information about the swinging of the load. For this purpose a 2D inclinometer is used. It provides the tilt and pan angles with sufficient sampling rate to identify the oscillation. The implemented algorithm detects this kind of oscillation and generates the input impulse train to joint actuators. This way
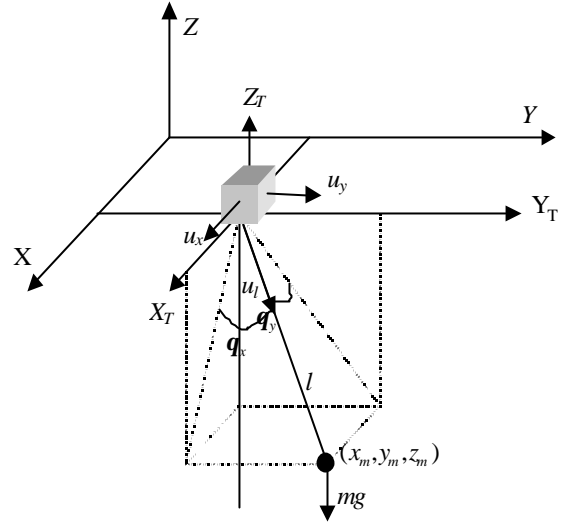

Fig. 3. Coordinate System of the robotized Overhead Crane .

the swinging of the load is eliminated and smooth transportation and assembly are possible.

II. MODEL OF THE CRANE

Figure 2 shows the model of the three-dimensional overhead crane and its load. XYZ is the inertial coordinate system. XTYTZT is the coordinate system attached to the trolley, whose origin is (x,y,0), $\boldsymbol{q}$ is the swing angle of the load, and $\boldsymbol{q}_x, \boldsymbol{q}_y$ its two components.

The position of the load (x_m, y_m, z_m) in the inertial coordinate system is

$$
\begin{aligned}
x_m &= x + l \sin \boldsymbol{q}_x \cos \boldsymbol{q}_y \\
y_m &= y + l \sin \boldsymbol{q}_y \\
z_m &= -l \cos \boldsymbol{q}_x \cos \boldsymbol{q}_y
\end{aligned}
\tag{1}
$$

The plant may be described by a system of nonlinear second order differential equations

$$
\begin{aligned}
(M_x + m)\ddot{x} + ml(\ddot{\boldsymbol{q}}_x \cos \boldsymbol{q}_x - \dot{\boldsymbol{q}}_x^2 \sin \boldsymbol{q}_x) &= u_x \\
m\ddot{x}\cos \boldsymbol{q}_x + ml\ddot{\boldsymbol{q}}_x &= -mg \sin \boldsymbol{q}_x \\
(M_y + m)\ddot{y} + ml(\ddot{\boldsymbol{q}}_y \cos \boldsymbol{q}_y - \dot{\boldsymbol{q}}_y^2 \sin \boldsymbol{q}_y) &= u_y \\
m\ddot{y}\cos \boldsymbol{q}_y + ml\ddot{\boldsymbol{q}}_y &= -mg \sin \boldsymbol{q}_y \\
m\ddot{l} + b_l \dot{l} - mg &= u_l
\end{aligned}
\tag{2}
$$

that can be linearized and result in the following model

$$(M_x + m)\ddot{x} + b_x\dot{x} + ml\ddot{\mathbf{q}}_x = u_x$$
$$l\ddot{\mathbf{q}}_x + \ddot{x} + g\mathbf{q}_x = 0$$
$$(M_y + m)\ddot{y} + b\dot{y} + ml\ddot{\mathbf{q}}_y = u_y \qquad (3)$$
$$l\ddot{\mathbf{q}}_y + \ddot{y} + g\mathbf{q}_y = 0$$
$$m\ddot{l} + b_l\dot{l} - mg = u_l$$

where m is the load mass; M_x and M_y are the components of the crane mass; b_x, b_y and b_l are the viscous damping coefficients; u_x, u_y and u_l are the force inputs to the crane and g denotes the gravitational acceleration.

The following assumptions are made for simplification of the model
- The crab moves along the track without slip.
- Dynamics and nonlinearity of the driving motor are neglected.
- The load can be modelled as a point mass whereas the stiffness of the rope can be neglected. The rope has no mass and no elasticity.
- The parameters are constant during each operation.

The linearized dynamic model consists of a travel dynamics (the two first equations), a traverse dynamics (the third and fourth) and the load hoisting dynamics. The travel and traverse dynamics are decoupled and symmetric.

Using
$$x = (x_1, x_2, \ldots, x_8)^T = (x, \dot{x}, \mathbf{q}_x, \dot{\mathbf{q}}_x, y, \dot{y}, \mathbf{q}_y, \dot{\mathbf{q}}_y, z, \dot{z})^T \quad \text{as}$$
state variables, the linearized system can be written as

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \qquad (4)$$

with

$$A = \begin{bmatrix} A_1 & 0 & 0 \\ 0 & A_2 & 0 \\ 0 & 0 & A_3 \end{bmatrix}, \ B = \begin{bmatrix} B_1 & 0 & 0 \\ 0 & B_2 & 0 \\ 0 & 0 & B_3 \end{bmatrix}, \ C = \begin{bmatrix} C_1 & 0 & 0 \\ 0 & C_2 & 0 \\ 0 & 0 & C_3 \end{bmatrix} \qquad (5)$$

and

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -b_{x_1} & mg/M_x & b_{x_2}/(M_x l) \\ 0 & 0 & 1 & 0 \\ 0 & b_{x_1} & -(M_x+m)\,g/(M_x+l) & -b_{x_2}(M_x+m)/(M_x ml^2) \end{bmatrix} \qquad (6)$$

$$A_2 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -b_{y_1} & mg/M_y & b_{y_2}/(M_y l) \\ 0 & 0 & 1 & 0 \\ 0 & b_{y_1} & -(M_y+m)g/(M_y+l) & -b_{y_2}(M_y+m)/(M_y ml^2) \end{bmatrix} \qquad (7)$$

$$A_3 = \begin{bmatrix} 0 & 1 \\ 0 & b_l/m \end{bmatrix} \qquad (8)$$

$$B_1 = \begin{bmatrix} 0 \\ -1/M_x \\ 0 \\ 1/(M_x l) \end{bmatrix}, \ B_2 = \begin{bmatrix} 0 \\ -1/M_y \\ 0 \\ 1/(M_y l) \end{bmatrix}, \ B_3 = \begin{bmatrix} 0 \\ 1/m \end{bmatrix} \qquad (9)$$

and

$$C_1 = C_2 = I_4, C_3 = I_2 \qquad (10)$$

III. PROPOSED ANTI-SWING CONTROL

As a first step to understand how to generate commands that move systems without vibration, it is helpful to start with the simplest of such command. It is known that giving the system an impulse will cause it to vibrate; however, if a second impulse is applied to the system in the right moment, the vibration induced by the first impulse is cancelled. This concept is shown in Fig. 4.

Input shaping is implemented by convolving the reference command with a sequence of impulses. This process is illustrated in Fig. 5. The impulse amplitudes and time locations of their sequence are calculated in order to obtain a stair-like command to reduces the detrimental effects of system oscillations.

If estimations of the system's natural frequency, $\mathbf{w}$, and of the damping ratio, V are known, then the residual vibration that results from the sequence of impulses can be described by

$$V(\mathbf{w}, V) = e^{-Vwt_n}\sqrt{C(\mathbf{w}, V)^2 + S(\mathbf{w}, V)^2} \qquad (11)$$

where,

$$C(\mathbf{w}, V) = \sum_{i=1}^{n} A_i e^{Vwt_i} \cos(\mathbf{w}_d t_i) \qquad (12)$$

$$S(\boldsymbol{w}, \boldsymbol{V}) = \sum_{i=1}^{n} A_i e^{\boldsymbol{V}\boldsymbol{w}t_i} \sin(\boldsymbol{w}_d t_i) \qquad (13)$$

where A_i and t_i are the amplitudes and time locations of the impulses, n is the number of impulses in the impulse sequence, and $\boldsymbol{w}_d = \boldsymbol{w}\sqrt{1-\boldsymbol{V}^2}$. To avoid the trivial solution of all zero-valued impulses and to obtain a normalized result, it is necessary to satisfy:

$$\sum A_i = 1 \qquad (14)$$

In the modelling of the crane, the damping of the load $\boldsymbol{V}$ can be neglected and the frequency for the linearized model is

$$\boldsymbol{w} = \sqrt{g / l} \qquad (15)$$

where l is the length of the cable.

In order to have a band of frequencies inhibited, it is possible to have N of these sequences of impulses $V(\boldsymbol{w}, \boldsymbol{V})$. In practice, N does not have to be large and a value between 3 and 10 is often enough.

The anti-swing control of the crane is composed by two parts. The first one consists in the transformation of a reference position in a smooth path in order to handle the load without any oscillation. The second one consists of reducing the load swinging caused by external excitations such as wind.

In the basic anti-swinging control, the controller intercepts the operator commands and modifies them in real time so that the crane is moved without residual sway in the load. Real systems cannot be moved around with impulses, therefore, a scheme is required to convert the properties of the sequence and put them into a usable command. This can be achieved in a simple and straightforward way. The impulse sequence is convolved with any desired command signal.

The control algorithm is usually implemented in a standalone controller or in a plug-in multi-axis control board. In the presented work, a PMAC (Programmable Multi-Axis Controller) is used . It belongs to a family of high-performance servo
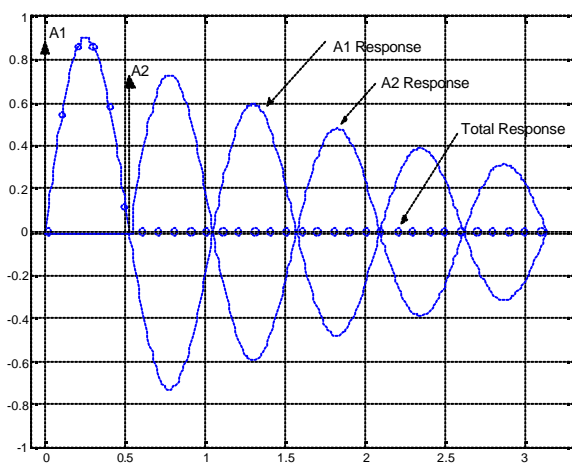

Fig. 4. Two Impulse Response

motion controllers capable of commanding up to eight axes of motion simultaneously with a high level of sophistication. The controller board come s with a complete and advanced tuneable PID algorithm. However, despite the sophistication of these controllers, the user is not always able to implement any control algorithm if it is not pre-designed in the PMAC by the manufacturer. Therefore the user is required to find a way to overcome this limitation and use other facilities of the controller to implement the desired control scheme. In this case it is possible to blend moves and send to the crane the stairs velocity profiles that correspond to the train impulses in the acceleration profile.
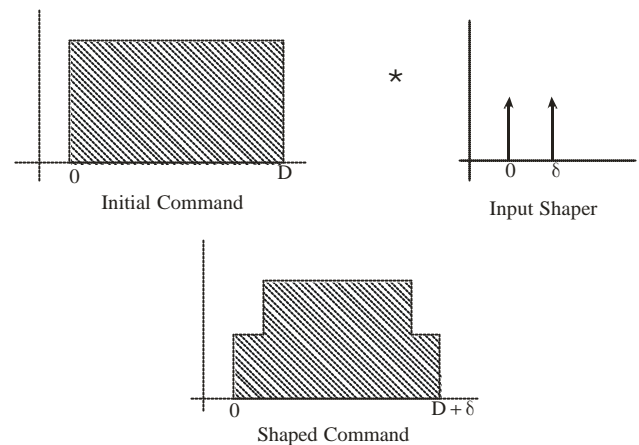

Fig. 5. "Shaped Input" Command Generation

In the PMAC, the move is set directly by TM (movement time) or indirectly based on the distances (e.g. X=10) and feedrate (F) which refers to the velocity . A linear movement consists of three parts: an acceleration, a constant velocity movement and a deceleration. The duration of the first and third parts is TA while TM is the time of the constant velocity part. If TA=0, the velocity profile represents a step.

This way, various moves can be concatenated to produce a stair-like velocity profile: Figure 4 illustrates this idea of concatenating/blending various moves. The corresponding acceleration profile represents the well known train of deltas used in Input Shaping. Instead of TM, it is possible to use the velocity command (F) and the required distance (X). For example, this part of the program can be:
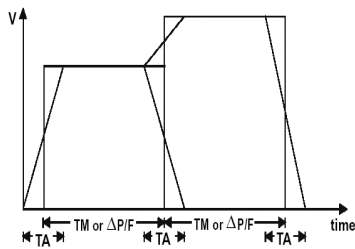
```
F(P3/2)
X(P2)
F(P3)
X80
F(P3/2)
X(P2)
```

where P3 represents the desired velocity and P2 represents a distance that corresponds to the elapsed time between two

deltas.
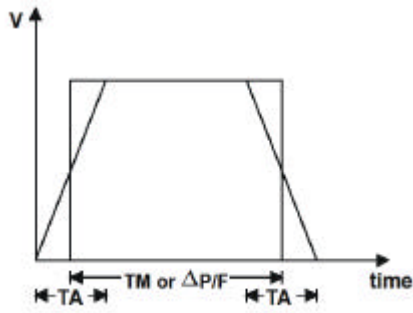
a)

b)

Fig. 6.   Parameters of a linear move, b) Blend of two moves in the velocity profile.
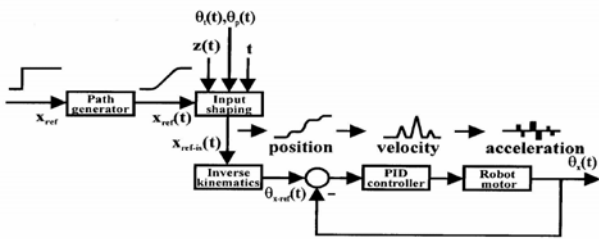

Fig. 7. Input shaping control scheme.

The second part of the control is the anti-swing control of an external oscillation. For this purpose a 2D inclinometer is used. It provides the pan and tilt angles with sufficient sampling rate to feedback the measured sway angles of the load. The implemented algorithm detects the oscillation and generates the corresponding train of impulses in order to reduce them to minimum. To do that, a table has been constructed with the angle and frequency that corresponds to the different impulse train amplitudes. This way the impulse train amplitude, as a function of the maximum oscillation angle, that is needed in order to stop the oscillations was calculated using a linear regression.

Figure 7 shows the overall control scheme that include the two above mentioned parts. The first part, the path generator, smoothes the target position profile which is the input to the input shaping block. The latter produces the stair-like profile by convolution of the previous signal with a train of impulses.

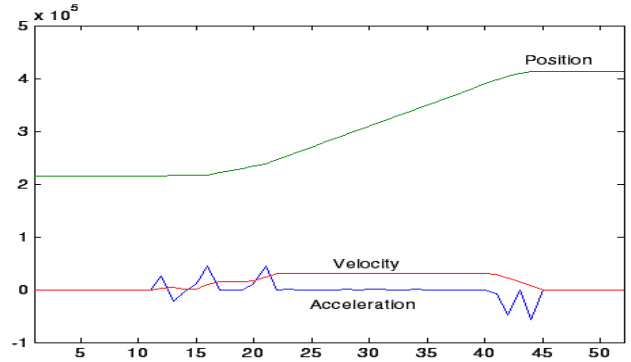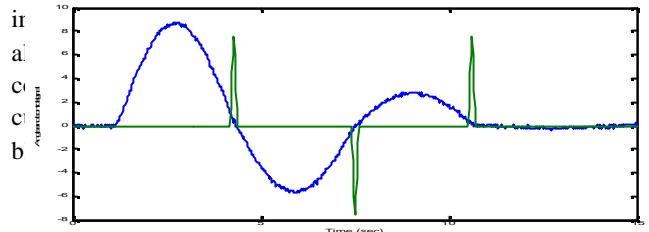All these represent feedforward filter to the PID controller.

Fig. 8. Input shaping control scheme.

Fig. 9. Swinging angle reduction by 3 impulse control signal

oscillation. Figure 10 shows a comparison of the load response when the control uses the input shaping   scheme with a response without any swinging attenuation.
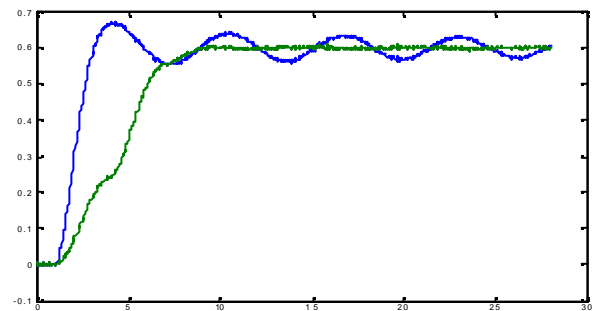

Fig. 10 . Load response with and without input shaping

V. Conclusion

A new procedure for designing an input-shaping control of a robotized crane. The procedure takes into account the unique properties of overhead cranes, such as the single-mode dynamics. The new shaping method was implemented on an overhead crane at the Robotics Laboratory of the University Carlos III of Madrid. Experimental results show that the method greatly reduces residual oscillations. The PID on board pre-programmed algorithms of the PMAC multiaxes control board were complemented with a shaped-command generation function block.

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