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Independent motion control of a tower crane through wireless sensor and actuator networks

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ABSTRACT

The problem of independent control of the performance variables of a tower crane through a wireless sensor and actuator network is investigated. The complete nonlinear mathematical model of the tower crane is developed. Based on appropriate data driven norms an accurate linear approximant of the system, including an upper bound of the communication delays, is derived. Using this linear approximant, a dynamic measurable output multi delay controller for independent control of the performance outputs of the system is proposed. The controller performs satisfactory despite the nonlinearities of the model and the communication delays of the wireless network.

1. Introduction

Cranes are used in several applications having significant economic impact. Classical uses are in construction (bridges, dams, buildings), transportation (loading and unloading cargo), industry (oil platforms, refineries), in nuclear power plants and in bio/ecological applications (see [1–3] and the references therein). Efficient crane maneuverability needs appropriate control, requiring accurate mathematical model of the crane (see f.e. [4–14]).

For the case of tower cranes significant results have been presented in [1–4]. In [4] a simplified nonlinear model of a tower crane is being developed in the form of a spherical pendulum in a non-inertial frame. The model is then used to analyze the cases of linearly accelerating support and the support describing a circular path at constant speed. In [5], a simplified mathematical model of a tower crane is being developed. The model is then used to demonstrate the performance of event trigger controllers for wireless control of multiple 3d tower cranes. The influence of the network uncertainties such as time delays and packet dropouts are not taken into account in the controller design stage but they are used in the computational experiments of the closed loop system. Similar issues are investigated in [6]. In [7], the mathematical model of a laboratory tower crane is being developed and a local nonlinear model predictive control is proposed for the performance output to follow a desired path. The dynamics of the trolley, the length and the angular displacement of the jib are neglected and the respective accelerations are considered as actuatable input to the system.

For other categories of cranes (such as bridge cranes, overhead cranes, rotary cranes and boom cranes), several results have been published. In particular in [8] the Bluetooth protocol is used for short range wireless control of a bridge crane system. The controller is of the rule based type not using information from the system dynamics. The influence of network parameters is not investigated. In [9], a local fuzzy logic control scheme and a local LQG controller are being used to regulate the performance output of an 2d overhead crane made up of a platform carrying a cable holding the load. The results are validated using physical experiments. In [10] the mathematical model of the 2d overhead crane system is used to develop a local controller which combines a feedback linearization approach and a time delay control scheme. In [11] a simplified mathematical model of a rotary crane system is being used to develop a local neuro-controller for vibration control of the load involving the rotation about the vertical axis only. In [12], based upon a simplified mathematical model of a boom

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crane, the I/O linearization approach is being used to locally control slewing and luffing motion. The efficiency of the proposed approach is demonstrated through physical experiments on an industrial harbor mobile crane. In [13] a simplified mathematical model of a rotary crane is being developed and an optimal local open loop control approach is being used for sway free, point to point motion of the load mass. The performance of the proposed approach is demonstrated through physical and computational experiments. In [14] the mathematical model of a crane system which is equipped with a flexible cable is being developed in the form of hybrid system represented by partial-ordinary differential equations. Based upon the mathematical model of the system, a local integral-barrier Lyapunov function based control scheme is proposed to suppress the undesirable vibrations.

From the communication point of view, the controllers in [5,6,8] use wireless connections. The controllers proposed in [7,9,10–14] use wired connections.

From the control point of view, in [5,6] event triggered schemes have been proposed. In [8,9] pure rule based and fuzzy approaches have been used. In [9,13] optimal approaches have been applied. In [11] an intelligent neural approach has being used. In [7] model predictive controllers are used. In [10,12] feedback linearization approaches are used. In [10] a delay is also included to improve the control performance. In [14] a nonlinear Lyapunov based controller is proposed.

Here, we propose Input Output (I/O) Decoupling of the motion variables of a tower crane through a wireless sensor and actuator network. The complete nonlinear dynamic mathematical model of a tower crane is developed. The crane is considered to be equipped with three preinstalled approximate PID controllers. Using the nonlinear model, the linear approximant of the system is derived. Its accuracy is investigated via series of computational experiments. For the remote signal transmission among the sensors, the actuators and the controller, the ZigBee protocol is used. A synchronization algorithm, guaranteeing constant transmission delay, is proposed. Additionally, an algorithm towards signal reconstruction of the analogue continuous time signals from the digital transmitted signals is proposed.

The contribution of the present paper is summarized to the following points:

1. A dynamic model of the system is developed. The model is more general, as compared to those in [4–7], in the sense that it includes variable cable length and all coupling terms in the system kinetics.
2. As compared to [5,6,8] the delays of the wireless communication are taken in to account in the controller design. The issue is treaded as follows:

   a) Due to the presence of the delays, an inverse dynamics controller compensating the nonlinearities of the system is not adequate. This is why a linear approximant, as well as a linear controller, performing satisfactory despite the nonlinearities of the crane is proposed.
   b) A synchronization algorithm is proposed. Using this algorithm, the uncertain communication delay becomes constant and known to the designer. The values of the delay are used to develop an appropriate realizable multi-delay dynamic controller providing I/O Decoupling for the performance outputs preserving the accuracy of the closed loop linear approximant.

2. Dynamics of a tower crane

Cranes are worksite mechanisms used to lift and lower loads as well as to place them in the site. A tower crane (see Fig. 1) is a modern form of balance crane consisting of three mechanical parts: an arm rotating around a vertical mast, a trolley moving along the arm and a cable drum with a load at its end. The arm rotates around the mast by an arm motor (actuator 1), the trolley moves along the arm by another motor (actuator 2) and the payload is lifted or lowered by a third motor (actuator 3) rotating the cable drum to gather or release the cable. The tower crane is a highly oscillatory system with linear and nonlinear dynamics. The nonlinear dynamics come mainly from the rotational motion inducing centripetal and Coriolis accelerations producing instability.

In what follows, the mathematical model of the tower crane will be developed using the Euler–Lagrange approach. The tower crane is inherently unstable with respect to all motion variables. In such mechanical systems it is a common practice (see [15]) to use pre-installed three term controllers to regulate local performance variables. Such pre-installed local PID controllers are necessary for the safe ground operation. Here, 3 pre-installed approximate PID controllers are considered. The 1st PID stabilizes the velocity of the arm, the 2nd the position of the trolley along the arm and the 3rd the cable length.

2.1. 2.1 State space model of the crane

Define $x = \begin{bmatrix} x_1 & \cdots & x_{16} \end{bmatrix}^T = \begin{bmatrix} q_1 & q_2 & q_3 & q_4 & q_5 & \dot{q}_1 & \dot{q}_2 & \dot{q}_3 & \dot{q}_4 & \dot{q}_5 & \chi_{1,1} & \chi_{1,2} & \chi_{2,1} & \chi_{2,2} & \chi_{3,1} & \chi_{3,2} \end{bmatrix}^T$

$w = \begin{bmatrix} w_1 & w_2 & w_3 \end{bmatrix}^T$, $y = \begin{bmatrix} y_1 & y_2 & y_3 \end{bmatrix}^T$ and $\psi = \begin{bmatrix} \psi_1 & \cdots & \psi_5 \end{bmatrix}^T$, where x is the state vector, y is the performance output vector, ψ is the measurable output vector, w is the vector of external commands of the pre-installed PID controllers (w_1,w_2 and w_3 are the external commands for the rotational velocity of the crane, the position of the trolley and the cable length, respectively), q_1 is the arm rotation angle with respect to an inertial frame, q_2 is the distance of the trolley from the crane's revolution axis, q_3 and q_4 are the cable's angles and q_5 is the cable length, $\chi_{i,j}$ ($i = 1,2,3$ and $j = 1,2$) are internal variables of the approximate PID controllers. The mathematical model of the tower crane is developed to be

$$\frac{dx}{dt} = [E(x)]^{-1} f(x,w), y = r(x), \psi = Lx; E(x) \in \mathbb{R}^{16\times 16}, f(x,w) \in \mathbb{R}^{16\times 1}, r(x) \in \mathbb{R}^{3\times 1}, L \in \mathbb{R}^{5\times 16} \quad (1)$$

The nonzero elements of $E(x)$ and $F(x,w)$ are:

$e_{1,1}(x) = 1$, $e_{2,2}(x) = 1$, $e_{3,3}(x) = 1$, $e_{4,4}(x) = 1$, $e_{5,5}(x) = 1$,
$e_{6,6}(x) = J_1 + J_2 + J_5 + l_c^2 m_1 + (m_2 + m_5)x_2^2 - 2s_{x_4} m_5 x_2 x_5 - 0.25\left(c_{2x_3} + 2c_{x_3}^2 c_{2x_4} - 3\right) m_5 x_5^2$, $e_{6,7}(x) = -c_{x_4} s_{x_3} m_5 x_5$, $e_{7,10}(x) = -s_{x_4} m_5$,
$e_{6,8}(x) = c_{x_3} c_{x_4} m_5 x_5 \left(x_2 - s_{x_4} x_5\right)$, $e_{6,9}(x) = s_{x_3} J_5 + m_5 s_{x_3} x_5 \left(x_5 - s_{x_4} x_2\right)$,
$e_{6,10}(x) = c_{x_4} s_{x_3} m_5 x_2$, $e_{7,6}(x) = -c_{x_4} s_{x_3} m_5 x_5$, $e_{7,7}(x) = m_2 + m_5$,
$e_{7,9}(x) = -c_{x_4} m_5 x_5$, $e_{8,6}(x) = c_{x_3} c_{x_4} m_5 x_5 \left(x_2 - s_{x_4} x_5\right)$,
$e_{8,8}(x) = c_{x_4}^2 m_5 x_5^2 + J_5$, $e_{9,6}(x) = s_{x_3} J_5 + m_5 s_{x_3} x_5 \left(x_5 - s_{x_4} x_2\right)$,
$e_{9,7}(x) = -c_{x_4} m_5 x_5$, $e_{9,9}(x) = m_5 x_5^2 + J_5$, $e_{10,6}(x) = c_{x_4} s_{x_3} m_5 x_2$,
$e_{10,7}(x) = -s_{x_4} m_5$, $e_{10,10}(x) = m_5$, $e_{11,11}(x) = 1$, $e_{12,12}(x) = 1$,
$e_{13,13}(x) = 1$, $e_{14,14}(x) = 1$, $e_{15,15}(x) = 1$, $e_{16,16}(x) = 1$,
$f_1(x,w) = x_6$, $f_2(x,w) = x_7$, $f_3(x,w) = x_8$, $f_4(x,w) = x_9$,
$f_5(x,w) = x_{10}$, $f_6(x,w) = -2m_2 x_2 x_6 x_7 + 0.5 m_5 x_5 \Big\{ x_6 \Big[4s_{x_4} x_7 - 2x_5 \left(c_{x_4}^2 s_{2x_3} x_8 + c_{x_3}^2 s_{2x_4} x_9\right)\Big] - x_5 x_8 \left(s_{x_3} s_{2x_4} x_8 + 4c_{x_3} s_{x_4}^2 x_9\right) + \Big[\left(c_{2x_3} + 2c_{x_3}^2 c_{2x_4} - 3\right) x_6 + 2c_{x_3} s_{2x_4} x_8 - 4s_{x_3} x_9\Big] x_{10} \Big\} + m_5 x_2 (-2x_6 x_7 + c_{x_4} \left\{ x_5 \left[2x_6 x_9 + s_{x_3}\left(x_8^2 + x_9^2\right)\right] - 2c_{x_3} x_8 x_{10} \right\} + 2s_{x_4} \left[c_{x_3} x_5 x_8 x_9 + \left(x_6 + s_{x_3} x_9\right) x_{10}\right]) + w_1 \left(\gamma_1 f_{D,1} + f_{P,1}\right) - J_5 c_{x_3} x_8 x_9 - \gamma_1^2 x_{12} f_{D,1} + \left(\gamma_1 x_{11} + x_{12}\right) f_{I,1} - x_6 \left(\gamma_1 f_{D,1} + f_{P,1}\right)$, $f_7(x,w) = m_2 x_2 x_6^2 + m_5 x_2 x_6^2 + 2m_5 x_5 c_{x_3} c_{x_4} x_6 x_8 - m_5 x_5 s_{x_4} \left(x_6^2 + 2s_{x_3} x_6 x_9 + x_9^2\right) + 2m_5 c_{x_4} \left(s_{x_3} x_6 + x_9\right) x_{10} + \gamma_2 f_{D,2}(w_2 - x_2) - \gamma_2^2 x_{14} f_{D,2} + (\gamma_2 x_{13} + x_{14}) f_{I,2} + (w_2 - x_2) f_{P,2}$, $f_8(x,w) = J_5 c_{x_3} x_6 x_9 - g m_5 c_{x_4} x_5 s_{x_3} - 2m_5 c_{x_4}^2 x_5 x_8 x_{10} + m_5 c_{x_4} x_5^2 \left[2s_{x_4} x_8 x_9 + c_{x_3} c_{x_4} x_6 \left(s_{x_3} x_6 + 2x_9\right)\right]$