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Point-to-Point Control of a Gantry Crane: A Combined Flatness And IDA-PBC Strategy

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***Abstract*— A prevalent approach to control in the gantry crane industry is to track a trajectory using an open-loop strategy based on notions of differential flatness. Point-to-point control is achieved by selecting a suitable trajectory to be followed. To cope with disturbances and uncertainties, a nominal feedback controller is added to the loop. We have approached the objective of point-to-point transfer with swing suppression along the trajectory by combining notions of flatness and the IDA-PBC technique. The applications like handling liquid filled container demand such kind of quasi-static trajectories. Initially, a flatness based control law is used to follow a desired trajectory that transfers the system to a neighbourhood of the final state. Then the IDA-PBC control law is switched on for robust stabilization of the system.**

***Keywords*— Flatness, IDA-PBC, holonomic constraints, cable-operated robot**

I. Introduction

A schematic representative of one such mechanism operating in two dimensions is shown in Figure 1. The objective here is to move the payload from any given initial configuration to the desired configuration following a specified trajectory. There are two actuators - a linear actuator which actuates the cart and a rotary one which actuates the winch. For the purpose of the study here, we make the following assumptions:

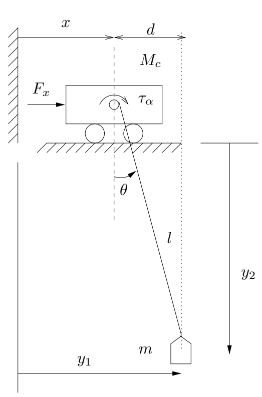

Fig. 1. Overhead gantry crane

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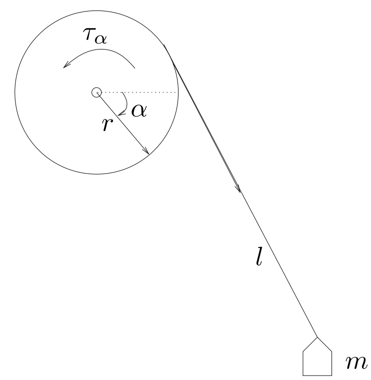

Fig. 2. Pulley and cable schematic

1) The cable is massless and inelastic
2) Dissipative forces on the cart and at the winch are negligible
3) No slipping occurs at the point of contact between the winch and the cable.

Assumption 1 simplifies the dynamic model and is a reasonable assumption given the comparatively large inertias of the payload and the cart. Assumption 2 is used to simplify the modeling. Assumption 3 is a natural idealization of pulley mechanisms. One final comment: A more general mechanism would involve two translational motions of the cart and a spherical pendulum-like motion of the payload.

Several researchers have examined the control problem for the overhead crane system to achieve precise payload positioning with minimum swing. Fang *et al* [1] utilize a simple proportional-derivative (PD) controller to asymptotically regulate the overhead crane system, the coupling between the planar gantry position and the payload angle is increased by the nonlinear controllers. In [2], an overhead crane that exhibits double-pendulum dynamics is investigated by Weiping *et al*. Still other researchers have proposed controllers synthesized from the differential flatness property of these systems to follow for a specified trajectory [3], [4]. Flat systems are equivalent to linear ones via a special type of feedback called endogenous. For such systems, control inputs as well as all internal variables can be expressed in terms of the measured outputs.

Control of mechanical systems in a nonlinear setting has received much attention in the past decade. Amongst the techniques developed, a general and promising one has been the IDA-PBC methodology. The idea here is to synthesize a controller that stabilizes the closed loop system about a desired equilibrium and imparts certain

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characteristics to the closed loop response by modifying the energy function and adding damping based on passivity. However, for a general trajectory tracking problem, we need to modify the energy function into a time-varying one and this time-varying nature, in general, destroys passivity. Hence the trajectory tracking control problem using a passivity based approach is difficult and has not been investigated so far. Only some preliminary results are available in the literature [5], [6].

In [7] and [8], passivity based interconnection and damping assignment control techniques are used to stabilize underactuated mechanical systems. The asymptotic stabilization of classical ball and beam system and a novel inertia wheel pendulum is achieved through a new parametrization of the closed loop inertia matrix. The matching conditions of controlled Lagrangian and IDA-PBC are discussed in [9]. The IDA-PBC methodology is extended to the class of underactuated mechanical systems with kinematic constraints in [10]. It also introduces the simplified matching equations on constrained manifold and is closely related to the controlled Lagrangian strategy for generalized matching equations for underactuated mechanical systems proposed in [11] and [12]. The stabilization of a gantry crane system modeled with pulley dynamics leading to holonomic constraint using IDA-PBC is described in [13]. In [14], Kenji Fujimoto *et al* presented an asymptotic stabilization procedure of nonholonomic systems which are described in Hamiltonian framework. These systems are then transformed into canonical forms with specified structure matrices using generalized canonical transformations. In [15] Sorensen *et al* proposed augmentation of kinematic inputs with standard Hamiltonian formulation. These inputs change the internal structure of the mechanical system but do not change the stored total energy of the system.

In this paper our objective is two-fold. We wish to achieve point-to-point transfer as also minimizing cable swing along the way. We solve the problem using a combination of flatness and the IDA-PBC techniques. The paper is organized as follows: Section II presents the dynamic model of the crane. In Section III the system is shown to be flat. This leads to system inversion which is then used to derive the feedforward control law. Section IV provides a brief introduction to the IDA-PBC theory applied to such systems. In this section we also discuss the IDA-PBC controller design for the robust stabilization of the gantry crane in the neighbourhood of an equilibrium. The simulations and the results are discussed in Section V. We wrap up this paper with some concluding remarks in Section VI.

II. Dynamic Model

In this section we develop the dynamic model for the overhead gantry crane system. The system under consideration is as shown in Figure 1. The configuration variables are

$$q = [\theta \quad x \quad \alpha \quad l]^T$$

where $\theta \in S^1$ denotes the payload angle about the vertical axis, $x \in I\!R$ denotes the gantry position along the X coordinate axis, $l \in I\!R$ denotes the cable length and α denotes the angle through which the pulley rotates, measured with respect to a fixed radius vector on the winch. The control $u \in I\!R^2$ is defined as

$$u = [F_x \quad \tau_\alpha]^T \tag{1}$$

where F_x indicates the control-force input acting on the cart and τ_α denotes the torque acting on the winch. Note that the rotary actuation of the winch translates to the winding/unwinding action of the cable. The no-slip constraint at the pulley implies

$$r\dot{\alpha} = \dot{l} \tag{2}$$

where r is the radius of the pulley, see Figure 2.

We make two additional assumptions

- The radius of the pulley is small as compared to the cart length
- The minimum length of the cable is l_0.

The control objective is to move the payload from any position $q_i = [\theta_i \quad x_i \quad \alpha_i \quad l_i]^T$ to the desired position specified as $q_D = [0 \quad x_D \quad \alpha_D \quad l_D]^T$, while the load coordinates

$$y = [y_1 \quad y_2]^T \tag{3}$$

track a desired trajectory $\hat{y}(t)$ in the vertical plane. Note that the desired pulley angle α_D can be expressed in terms of the desired cable length l_D and initial cable length l_0 by virtue of no slip constraint.

A. Reducing the configuration dimension

We begin with the Euler-Lagrange formulation of the system. The Lagrangian of the system is

$$\mathcal{L}(q, \dot{q}) = \frac{1}{2}\dot{q}^T M(q)\dot{q} - V(q) \tag{4}$$

where

$$\begin{aligned} M(q) &= \begin{bmatrix} ml^2 & ml\cos\theta & 0 & 0 \\ ml\cos\theta & (M_c+m) & 0 & m\sin\theta \\ 0 & 0 & I_p & 0 \\ 0 & m\sin\theta & 0 & m \end{bmatrix}, \\ V(q) &= -mgl\cos\theta, \end{aligned}$$

where M_c is the mass of the cart, m is the mass of the payload and I_p is the moment of inertia of the pulley about its axis of rotation. The constraint at the velocity level can be further written as

$$(0 \quad 0 \quad -r \quad 1)\dot{q} = 0.$$

We see that the codistribution $(0 \quad 0 \quad -r \quad 1)$ is expressed as $\nabla h(q)$ where $h(q) = l - r\alpha$. This one dimensional velocity constraint is clearly integrable in nature and reduces the dimension of the configuration manifold to 3. From the physics of the problem $l(t) - r\alpha(t) = l_0$.

To write the system Lagrangian on the reduced manifold, we first perform a linear transformation of coordinates as $\tilde{q} = Aq$ where $q = \begin{pmatrix} \theta & x & \alpha & l \end{pmatrix}^T$ and $\tilde{q} = \begin{pmatrix} \theta & x & \alpha & l - r\alpha \end{pmatrix}^T$ and

$$A = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -r & 1 \end{pmatrix}, \quad A^{-1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & r & 1 \end{pmatrix}.$$

In the new coordinates the Lagrangian is

$$\mathcal{L}(\tilde{q}, \dot{\tilde{q}}) = \frac{1}{2}(A^{-1}\dot{\tilde{q}})^T M(A^{-1}\tilde{q})(A^{-1}\dot{\tilde{q}}) - V(A^{-1}\tilde{q}) \quad (5)$$

and the inertia matrix becomes

$$\begin{aligned} & \tilde{M}(\tilde{q}) \\ = \; & A^{-T} M(\tilde{q}) A^{-1} \\ = \; & \begin{pmatrix} ml_0^2 & ml_0\cos\theta & 0 & 0 \\ ml_0\cos\theta & m + M_c & m\sin\theta & mr\sin\theta \\ 0 & m\sin\theta r & mr^2 + I_p & rm \\ 0 & m\sin\theta & rm & m \end{pmatrix}. \end{aligned}$$

On the lower dimensional manifold ($l - r\alpha = l_0$), using the configuration variables as

$$\dot{\tilde{q}}_r = \begin{pmatrix} \dot{\theta} \\ \dot{x} \\ \dot{\alpha} \end{pmatrix}$$

we get the inertia matrix

$$\tilde{M}_r(\tilde{q}) = \begin{pmatrix} ml_0^2 & ml_0\cos\theta & 0 \\ ml_0\cos\theta & m + M_c & mr\sin\theta \\ 0 & m\sin\theta r & mr^2 + I_p \end{pmatrix}.$$

The potential energy $V(\tilde{q}) = -mgl_0\cos\theta$ represents the potential energy of the system in the new coordinates. Where the Hamiltonian $\tilde{H}$ is expressed as

$$\tilde{H}(\tilde{q}, \tilde{p}) = \frac{1}{2}\tilde{p}^T \tilde{M}_r^{-1}(\tilde{q}_r)\tilde{p} + V(\tilde{q}_r). \quad (6)$$

We now express the crane dynamics on the reduced manifold as follows

$$\begin{bmatrix} 0 \\ F_x \\ \tau_\alpha \end{bmatrix} = \begin{bmatrix} ml_0^2 & ml_0\cos\theta & 0 \\ ml_0\cos\theta & m + M_c & mr\sin\theta \\ 0 & m\sin\theta r & mr^2 + I_p \end{bmatrix} \begin{bmatrix} \ddot{\theta} \\ \ddot{x} \\ \ddot{\alpha} \end{bmatrix} + \begin{bmatrix} 0 & 0 & -mr\cos\theta\dot{x} \\ ml_0\sin\theta\dot{\theta} & 0 & mr\cos\theta\dot{\theta} \\ mr\cos\theta\dot{x} & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ \dot{x} \\ \dot{\alpha} \end{bmatrix} + \begin{bmatrix} mgl_0 \\ 0 \\ 0 \end{bmatrix}. \quad (7)$$

These Euler-Lagrange equations on reduced manifold can be cast in the following form for notational simplicity as:

$$G(q)u = M(q)\ddot{q} + C(q, \dot{q})\dot{q} + \nabla V(q) \quad (8)$$

where $C(q, \dot{q})\dot{q}$ represents the centrifugal and Coriolis forces. Notice that, $\dot{M}(q) - 2C(q, \dot{q})$ is skew-symmetric which is closely related to the fact that the forces $C(q, \dot{q})\dot{q}$ do not perform work on the system.

III. Trajectory Tracking using Flatness

A control system is said to be (differentially) *flat* if the following conditions are satisfied: [3]

1) there exists a finite set $y = (y_1, \cdots, y_m)$ of variables which are differentially independent, that is, which are not related by any differential equations
2) the y_i's are differential functions of the system variables, that is, are functions of the system variables (state and input) and of a finite number of their derivatives
3) any system variable is a differential function of the y_i's

Here, $y = (y_1, \cdots, y_m)$ is called as a *flat* or linearizing output. Its number of components equals the number of input channels.

Proposition 3.1: The reduced system in the new coordinates $\tilde{q_r} = [\theta \quad x \quad \alpha]^T$ with the dynamics given by (7) and the constraint $(y_1 - x)^2 + {y_2}^2 - l^2 = 0$ is flat with $y = [y_1 \quad y_2]^T$ as the flat output.

Proof: To show the flatness of the system we have to prove that the control inputs $u = [F_x \quad \tau_\alpha]^T$ as well as all the states can be expressed in terms of control output y and its finite numbers of time derivatives. This can be done in two steps:

First the crane dynamics are expressed as

$$m\ddot{y}_1 = -T\sin\theta \quad (9)$$
$$m\ddot{y}_2 = -T\cos\theta + mg \quad (10)$$

where T denotes the cable tension. The cable tension T can be extracted from (10) as

$$T = ml\frac{(g - \ddot{y}_2)}{y_2}. \quad (11)$$

Note that for positive cable tension we need $\ddot{y}_2$ to be less than g. We can now show the system variable d as a differential function of y by solving (10) using (11) as follows:

$$\begin{aligned} m\ddot{y}_1 &= -ml\frac{(g - \ddot{y}_2)}{y_2}\sin\theta \\ &= -ml\frac{(g - \ddot{y}_2)}{y_2}\frac{d}{l} \quad (12) \\ d &= -\frac{y_1\ddot{y}_2}{(g - \ddot{y}_2)}. \quad (13) \end{aligned}$$

We can now write,

$$\theta = \arctan\frac{d}{y_2} = \arctan\frac{\ddot{y}_1}{(\ddot{y}_2 - g)} \quad (14)$$
$$x = y_1 - d = y_1 + \frac{y_1\ddot{y}_2}{(g - \ddot{y}_2)} \quad (15)$$
$$l = \sqrt{\left(\frac{\ddot{y}_1 y_2}{g - \ddot{y}_2}\right)^2 + {y_2}^2} \quad (16)$$
$$\alpha = \frac{l - l_0}{r}. \quad (17)$$

In the second step, the control input u is obtained from the crane dynamics (7) with no slip constraint, $\dot{l} - r\dot{\alpha} = 0$, and differentiation of (13)-(17) as,

$$u = \psi(y, \dot{y}, \ddot{y}, y^{(3)}, y^{(4)}). \quad (18)$$

Thus, we have shown that the system under consideration is flat.

A. Feedforward Control Based On Flatness

The flatness property of the system under consideration can be exploited to solve the system inversion problem for trajectory tracking control. The schematic is shown in Figure 3. The differential parameterization (13)-(17) and

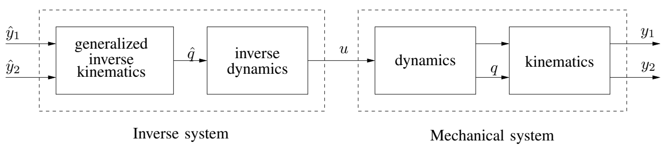

Fig. 3. Feedforward control based on flatness

(18) allows explicit off-line computation of suitable reference trajectories. The feedforward control law is then used to calculate control forces $u(t)$ for given output function $\hat{y}(t)$ up to the fourth-order time derivatives. According to Figure 3, the feedforward control consists of two steps:

- The *generalized inverse kinematics* calculates reference values of the crane coordinates $\hat{q}$ and their time derivatives $\dot{\hat{q}}$ and $\ddot{\hat{q}}$ using (13)-(17)
- The *inverse dynamics* yields the control forces $u(t)$ by means of (18).

We use the flatness based control to take us close to the desired final position and then switch to a stabilizing feedback control law designed on the IDA-PBC principles.

IV. Stabilization of the Gantry Crane using IDA-PBC Methodology

The basic philosophy of the IDA-PBC methodology is to assign the closed loop dynamics of a Hamiltonian system characterized by the Hamiltonian $H(q,p) = \frac{1}{2}p^T M^{-1}(q)p + V(q)$ and the dynamics

$$\begin{bmatrix} \dot{q} \\ \dot{p} \end{bmatrix} = \begin{bmatrix} 0 & I_n \\ -I_n & 0 \end{bmatrix} \begin{bmatrix} \nabla_q H \\ \nabla_p H \end{bmatrix} + \begin{bmatrix} 0 \\ G(q) \end{bmatrix} u. \quad (19)$$

to a desired Hamiltonian system characterized by the triple (M_d, J_2, V_d) standing for the desired inertia matrix, a skew-symmetric matrix and a desired potential energy respectively and the desired dynamics

$$\begin{bmatrix} \dot{q} \\ \dot{p} \end{bmatrix} = \begin{bmatrix} 0 & M^{-1}M_d \\ -M_d M^{-1} & J_2(q,p) \end{bmatrix} \begin{bmatrix} \nabla_q H_d \\ \nabla_p H_d \end{bmatrix}.$$

The resulting equality

$$\begin{aligned} & \begin{bmatrix} 0 & I_n \\ -I_n & 0 \end{bmatrix} \begin{bmatrix} \nabla_q H \\ \nabla_p H \end{bmatrix} + \begin{bmatrix} 0 \\ G(q) \end{bmatrix} u_{es} \\ = & \begin{bmatrix} 0 & M^{-1}M_d \\ -M_d M^{-1} & J_2(q,p) \end{bmatrix} \begin{bmatrix} \nabla_q H_d \\ \nabla_p H_d \end{bmatrix}. \end{aligned}$$

gives rise to two PDEs

$$\begin{aligned} G^{\perp}\{\nabla_q (p^T M^{-1} p) & \\ -M_d M^{-1} \nabla_q (p^T {M_d}^{-1} p) + J_2 {M_d}^{-1} p\} &= 0 \quad (20) \\ G^{\perp}\{\nabla_q V - M_d M^{-1} \nabla_q V_d\} &= 0 \quad (21) \end{aligned}$$

whose solution yields the control law. For further details, the interested reader is referred to [8]. The control input is naturally decomposed into two terms

$$u = u_{es}(q,p) + u_{di}(q,p) \quad (22)$$

where the first term is designed to achieve the energy shaping and the second one injects the damping. The PDEs yield the energy shaping term given as

$$\begin{aligned} u_{es} = & (G^T G)^{-1} G^T (\nabla_q H - M_d M^{-1} \nabla_q H_d \\ & + J_2 {M_d}^{-1} p). \quad (23) \end{aligned}$$

and the damping-injection term is given by

$$u_{di} = -K_v G^T \nabla_p H_d \quad (24)$$

where $K_v = {K_v}^T > 0$. We will require that V_d have an isolated minimum at q_*, that is,

$$q_* = \arg\min V_d(q). \quad (25)$$

A result on asymptotic stability of the desired closed-loop dynamics and en estimate of domain of attraction can be found in [8].

A. Solving the Potential Energy PDE

The aim of potential energy shaping is to freely assign equilibrium points in the closed loop potential function V_d, which is a solution of (21). The potential energy function of the open loop system is $V = mg(l-r)\cos\theta$ with m is a positive constant and $(l-r) = l_0$ being a constant with suitable coordinate transformations. If we do not modify the interconnection matrix then we recover the well-known potential energy shaping procedure of PBC. If $M_d = M$ and $J_2 = 0$ then the controller equation (23) reduces to

$$u_{es} = (G^T G)^{-1} G^T (\nabla_q V - \nabla_q V_d) \quad (26)$$

which is a familiar potential energy shaping control. With $G^{\perp} = (1 \;\; 0 \;\; 0)$ the potential energy PDE (21) takes the form

$$\nabla_{q_1} V - \nabla_{q_1} V_d = 0 \quad (27)$$

which is solved to give

$$V_d = -mg(l-r)\cos\theta + \Phi(q_2, q_3).$$

Note that the selection of Φ is governed by the condition (25). For this, the necessary condition $\nabla_q V_d(q_*) = 0$ is satisfied if and only if $\nabla\Phi(q_*) = 0$, while the sufficient condition $\nabla_q^2 V_d(q_*) > 0$ will hold if the Hessian of Φ at

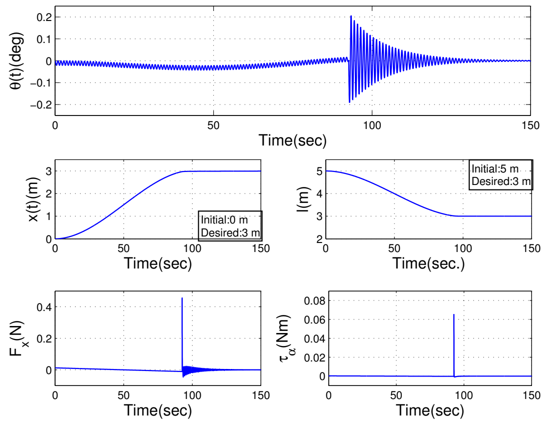

Fig. 4. Simulation results for combined Flatness and IDA-PBC strategy: Switching at 90 % of desired cart position

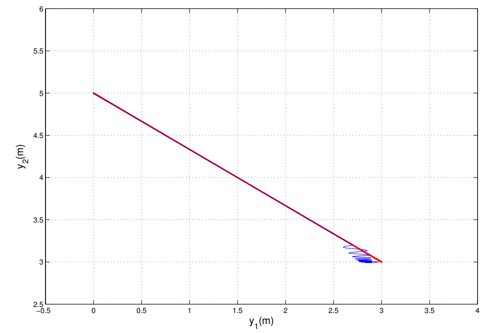

Fig. 5. Trajectory tracking using combined Flatness and IDA-PBC strategy

the q_* is positive [8]. In our case we choose Φ to be a quadratic function which yields

$$\begin{aligned} V_d(q) &= -mg(l-r)\cos\theta + \frac{K_{p_1}}{2}(q_2 - q_{2*})^2 + \\ &\quad \frac{K_{p_1}}{2}(q_3 - q_{3*})^2 \end{aligned} \tag{28}$$

where $(0, q_{2*}, q_{3*})$ denotes the equilibrium configuration and $K_{p_i} > 0$, $i = 1, 2$ are used as tuning parameters. To compute the final control law we first determine the energy-shaping term u_{es} from (26), which, in this case, takes the form

$$u_{es} = \begin{bmatrix} K_{p_1}(q_{2*} - q_2) \\ K_{p_2}(q_{3*} - q_3) \end{bmatrix}$$

The controller design is completed with the damping injection term (24), which yields

$$\begin{aligned} u_{di} &= -K_v G^T \dot{q} \\ &= -\begin{bmatrix} K_a \dot{q}_2 + K_b \dot{q}_3 \\ K_b \dot{q}_2 + K_c \dot{q}_3 \end{bmatrix} \end{aligned} \tag{29}$$

The role of the tuning parameters has a clear interpretation, namely, K_p is a proportional gain in position as it multiplies terms that grow linearly in q, and K_v injects damping along a specified direction of velocities with $K_p, k_v > 0$.

V. Simulations and Results

Simulations are carried out to validate the results presented in the previous sections. The system parameters are taken as $M_c = 6$ kg, $m = 1$ kg, radius of pulley $r = 0.03$ m, initial cable length $l_0 = 0.35$ m, whereas the mass of pulley is taken as 4 kg for calculation of moment of inertia about its axis of rotation.

The off-line desired trajectory computation was done employing cubic polynomial of the form $y_d(t) = at^3 + bt^2 + ct + d$ where a, b, c, d are constants which are appropriately selected. Here velocity at both end of the trajectory is assumed to be zero. The initial and final positions are selected to be $y(t_i) = [0 \quad 5]^T m$ and $y(t_f) = [3 \quad 3]^T m$. The time for trajectory acts like one more tuning parameter which can be used to optimize the performance. Flatness based control law is then used to decide control forces acting on cart and winch. The controller switching from flatness based to IDA-PBC takes place after reaching in the neighbourhood of the desired equilibrium. We select $0.9x_D$ as the switching condition, where x_D is the desired cart position. The main task of the IDA-PBC based controller is to robustly stabilize the crane system to its desired position. The damping injection matrix was taken to be of the following form $K_v = \begin{bmatrix} K_a & K_b \\ K_b & K_c \end{bmatrix}$. For the simulations the tuning parameters were selected as $K_a = 50, K_b = 4, K_c = 0.6, K_{p_x} = 15, K_{p_\alpha} = 0.1$. Fig. 4 illustrates the performance of the combined flatness and IDA-PBC methodology employed for trajectory tracking problem. Abrupt changes in F_x and τ_α were observed at the switching instant. This is a point of concern and we are addressing this issue currently. Such spikes would also prove harmful to the actuator. Fig. 5 shows trajectory tracking wherein IDA-PBC controller takes over for robust stabilization.

VI. Conclusions

The point-to-point control problem of a gantry crane while minimizing swing is solved by combining two nonlinear control techniques - flatness and IDA-PBC based control. We exploit the property of flatness of the system to compute control inputs based on an off-line computed trajectory. Since the flatness based feedforward control strategy inherently lacks robustness due to its open-loop nature, we complemented this with IDA-PBC for solving the trajectory tracking and stabilization problem. The current strategy lacks smoothness during the transition and this aspect is being investigated. We also propose to compare a (1) flatness with PI control law to (2) flatness with an IDA-PBC control law, to see which technique is superior in terms of robustness and performance.

On the modeling side, many earlier attempts on this problem have considered the system using a fixed cable length like a simple pendulum on a cart. Here we have considered cable length as a variable, which closely replicates real-life crane systems. We have also introduced a no-slip constraint in the pulley/cable model as a holonomic constraint and proposed a coordinate transformation to reduce the manifold to a lower dimension. This obviates the need for the cable guidance system for the measurement of the cable length and allows one to directly compute torque acting on winch since it is not possible to directly affect the cable tension. Future efforts are directed towards smooth transition from flatness based controller to IDA-PBC.

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