Load Swing Damping in Overhead Cranes by Sliding Mode Technique

Giorgio BARTOLINI, Nicola ORANI, Alessandro PISANO and Elio USAI

Department of Electrical and Electronic Engineering (DIEE)

University of Cagliari, P.zza d'Armi, 09123 Cagliari, Italy.

Fax +39 070675.5900

E-mails: {giob,norani,pisano,eusai}@diee.unica.it

Abstract : Moving a suspended load is not an easy task when strict specifications on the swing angle and on the transfer time need to be satisfied. Nevertheless, these type of requirements are always present in industry because they are related to operation safety and cost. Intuitively, minimizing the cycle time and the load swing are conflicting requirements, and their satisfaction requires proper control actions, especially if some uncertainties in the system dynamics are present.

In this paper we propose a simple control scheme based on second order sliding modes which is proved to be effective also in the case of poor knowledge of the system dynamics and/or parameters.

Such controller has been tested on a laboratory-size model of an overhead crane by means of commercial devices, and some experimental results are reported within the paper.

Keywords: Overhead Cranes, Second Order Sliding Modes, Underactuated Systems, Uncertain Systems.

1 Introduction

Cranes are widely used to transfer heavy loads over long distances. Safe operation and economical saving require that both the load swing and the operation time are minimized.

Often the control consists of a two-stage procedure: off-line path planning, in accordance with some optimal criterion, and on-line path tracking by traditional controllers. Optimal control strategies have been widely used to solve the associated control problem [1,2,12,17,18]. In particular, the optimal control approach has been applied to design trajectories minimizing some specific indexes, linked to the swing angle and its derivative [18] or to the energy consumption, which is claimed to be meaningful with respect to system stresses such as oscillations and non-smooth motions [12]. Nevertheless, the high sensitivity of the resulting open-loop strategies to parameter mismatching and external disturbances has been evidenced in the literature [26], making this approach not much effective in practice.

A linear parameter-varying crane model can be obtained by means of a suitable time normalization [23,25], which allows to use adaptive pole-placement control techniques [24], or Lyapunov-equivalence-based observer-controller design [11].

From a theoretical point of view, the control problem is challenging mainly due to the fact that the overall system is under-actuated, since there are three output variables to be controlled (the load coordinates and the swing angle) and two control actions (the trolley and hoisting forces).

We consider a planar motion of the load, as the motion in the orthogonal direction is practically de-coupled from the other, and the technique we propose can be applied in a modular way to each of the two subsystems.

We assume that the actual load mass and the physical system parameters are uncertain but belonging to a known interval, therefore the use of robust control techniques is motivated.

Variable structure systems are well known to be robust and easy to implement [10,22]. Their robustness is due to the intrinsic capability to deal with uncertain objects.

A suitable manifold is defined such that the system's zero dynamics locally exhibits the desired behavior, and the plant is constrained to evolve on such a manifold. As a result, the plant behavior becomes insensitive to any disturbance that does not steer the plant outside from the manifold. Being the uncertainties in some known compact set D, a control action is defined by worst-case analysis to reject any disturbance in the set D.

The considered case does not belong to the standard class of problems dealt with by this methodology. When the number of output variables. is the same of the independent controls, a sliding manifold is chosen so that, in any constrained motion, the dynamics of the d.o.f. is de-coupled.

If we try to apply this logic to the problem under investigation, at least one d.o.f. dynamics would result in

being uncontrollable.
In this paper, even if no systematic procedure is available for dealing with more general classes of under-actuated systems, we succeed in proving that it is possible to identify a suitable sliding quantity such that the associated zero-dynamics is asymptotically stable
In the next Section the crane model is given, while in the following Section 3 the control problem is addressed. In Section 4 the problem is discussed and solved by second order SMC technique. The subsequent Section 5 is devoted to discuss some practical implementation issues and to show the experimental results.

2 The crane model

In this work we consider the control problem for a planar overhead crane. The laboratory-sized crane used for the experiments is shown in Fig. 1.

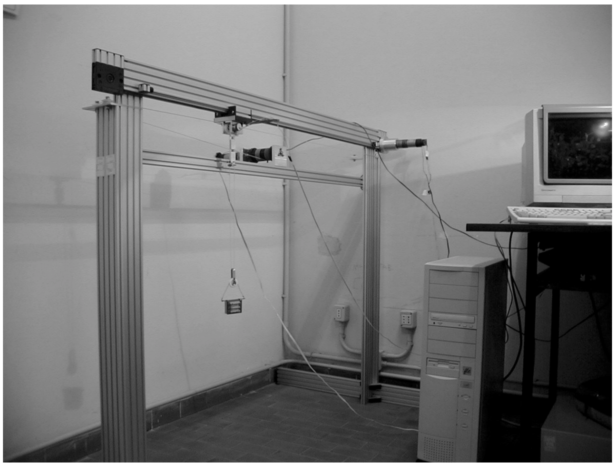

Fig. 1: The crane prototype

The system's model can be defined by Lagrangian approach, assuming that the load can be regarded as a material point and that the rope is always stretched, so that the swing angle can be uniquely defined. A 6th order model can be derived, in which the state variables x_1, x_2 and x_3 are the trolley displacement, the rope length and the vertical rope angle, while the remaining ones x_4 , x_5 and x_6 are their time derivatives, respectively. The crane model can be reduced in regular form, and it can be expressed as

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{G}(\mathbf{x})\mathbf{T} \tag{1}$$

where

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} x_2 \\ \frac{A_2}{\alpha}K_1 - \frac{m_l b \sin x_5}{\alpha}K_2 - \frac{A_2 m_l b \cos x_5}{\alpha}K_3 \\ x_4 \\ -\frac{m_l b \sin x_5}{\alpha}K_1 + \frac{\left(A_1 - m_l b \cos^2 x_5\right)}{\alpha}K_2 + \frac{m_l^2 b^2 \sin x_5 \cos x_5}{\alpha}K_3 \\ x_4 \\ -\frac{A_2 b \cos x_5}{\alpha x_3}K_1 + \frac{m_l b \sin x_5 \cos x_5}{\alpha x_3}K_2 + \frac{A_1 A_2 - m_l^2 b^2 \sin^2 x_5}{\alpha x_3}K_3 \end{bmatrix} \tag{2}$$

$$\mathbf{G}(\mathbf{x}) = \begin{bmatrix} 0 & 0 \\ \frac{A_2}{\alpha} & -\frac{m_l b \sin x_5}{\alpha} \\ 0 & 0 \\ -\frac{m_l b \sin x_5}{\alpha} & \frac{A_1 - m_l b \cos^2 x_5}{\alpha} \\ 0 & 0 \\ -\frac{\mathrm{A}_2 \sin x_5}{\alpha} & \frac{m_l b \sin x_5 \cos x_5}{\alpha} \end{bmatrix} \tag{3}$$

x= [x_1, x_2, …, x_6] is the state vector and **T**= [T_1 , T_2] is the vector of the applied torques. The mechanical parameters are the trolley mass *m*, the load mass *M*, the trolley and hoist sheave inertias J_{ts}, and J_{hs} and the trolley and hoist motors' sheave radius b_{ts}, and b_{hs}, while the parameters $A_1$and A_2, and the state functions α, K_1, K_2, K_3, are defined as follows

$$A_1 = \frac{J_{tm} + J_{ts}}{b} + (m + m_l)b \tag{4}$$

$$A_2 = \frac{J_{hm} + J_{hs}}{b} + m_l b \tag{5}$$

$$\alpha = A_1 A_2 - m_l\left(J_{hm} + J_{hs}\right)\cos^2 x_5 - (m_l b)^2 \tag{6}$$

$$K_1 = m_l b x_3 x_6^2 \sin x_5 - 2 m_l b x_4 x_6 \cos x_5 \tag{7}$$

$$K_2 = m_l b x_3 x_6^2 + m_l b g \cos x_5 \tag{8}$$

$$K_3 = -2 x_4 x_6 - g \sin x_5 \tag{9}$$

where *g* is the gravitation constant and J_{tm}, J_{hm} are the trolley and hoist torque actuator inertia. The non-null entries of the control matrix **G**(**x**) are the first two columns of the inverse of the 3x3 inertia matrix of the system, which is structurally under-actuated.
The control torques are generated by means of two DC motor drives (trolley motor and lift motor).
The electrical dynamics of the actuators can be represented by

$$\mathbf{V} - k_v \boldsymbol{\omega} = \frac{R}{k_i}\mathbf{T} + \frac{L}{k_i}\dot{\mathbf{T}} \tag{10}$$

where V_1 and V_2 are the trolley and lift motor voltages respectively, **V**= $[V_1 \quad V_2]^T$,**ω**=(*N*/*b*)· [x_2 , x_4]^T, *R* is the winding resistance, *L* is the winding leakage inductance, K_i is the torque constant, K_v is the back EMF constant, and *N* is the gear ratio.

3 The Control Problem

The goal is to move the load from the initial position (x_i,y_i) to the final position (x_f , y_f), while keeping the load swing angle as small as possible both during transfer and after the desired location is reached.
As the rope is assumed always stretched, the load displacement can be related to the state as follows

$x = x_1 - x_3 sin(x_5)$ load horizontal displacement
$y = x_3 \; cos(x_5)$ load vertical displacement

Usually the overall loading and unloading motion of the suspended mass is divided in three different phases which are separately dealt with, the vertical motion (pure load hoisting and lowering), the transversal motion and the horizontal one. Apart from the pure vertical motion, any generic motion task can be characterized by load oscillation. It is the main purpose of this work to define a control objective (reference trajectories to be tracked) and suitable control techniques such that, during the motion between any two points of the working space, the load swing is counteracted. The way in which this objective is pursued relies in the intrinsic property of the sliding mode approach, the so-called equivalent control principle, which will be detailed in the next section.
The control objective should be expressed in terms of a suitable reference trajectory for the load coordinates, but the high de-coupling between the trolley position x_1 and the rope length x_3 suggests to express the control task in terms of x_1 and x_3. Indeed, $x_5 \approx 0$ implies both $x \approx x_1$ and $y \approx x_3$.
Let the desired trajectory be expressed as

$$x_3^* = f(x_1) \tag{11}$$

being

$$y_i = f(x_i) \tag{12}$$

$$y_f = f(x_f) \tag{13}$$

The relationship between the desired velocities of the rope and of the trolley is derived by (11) as

$$\dot{x}_3^* = x_4^* = \frac{df}{dx_1}\dot{x}_1^* = \frac{df}{dx_1}x_2^* \tag{14}$$

The reference trolley speed is generally defined in accordance with some proper optimality criterion, and then the system is forced to track the desired path with no feed-back on the swing angle.
We consider a sufficiently smooth reference speed. The swing suppression in not explicitly dealt with in the path design, but it is obtained on-line by the choice of a suitable sliding manifold which involves both the desired path and the swing angle.

4 2-SMC for trajectory tracking and oscillation damping

It has been early noticed that the control problem is complicated by the fact that the crane is under-actuated. This is because two independent controls have to guarantee the three-fold objective of the tracking of the desired trajectory (11)-(14) and the suppression of the load swing during the operation.
However, the system motion can be constrained to occur on a two-dimensional sliding manifold, whose choice is the most critical point of the controller design.
When constrained onto the manifold, the system dynamics (i.e. zero-dynamics [13]) must exhibit the desired path tracking performances, and, at least, its local asymptotic stability must be ensured.

To this end we consider the following two-dimensional sliding manifold

$$\begin{aligned} \sigma_x &= \dot{x}_1 - \dot{x}_1^* + c_x\left(x_1 - x_1^*\right) + kx_5 = 0 \\ \sigma_y &= \dot{x}_3 - \dot{x}_3^* + c_y\left(x_3 - x_3^*\right) = 0 \end{aligned} \tag{15}$$

where the superscript * defines the desired behavior and k, c_x, c_y are positive constants.
The requirements regarding the trolley position and the swing angle should be satisfied by keeping the equality $\sigma_x=0$. Note that σ_x contains a term proportional to the swing angle. This implies that, on $\sigma_x=0$, x_1 does not tend to the desired profile due to the “disturbance” kx_5. This apparently noxious choice reveals to be effective for our purpose. Indeed, due to the presence of this term, a viscous damping is artificially added to the swing dynamics. This fact, at least locally, is sufficient to make feasible the stabilization of the swing dynamics. As a consequence the “disturbance” kx_5 vanishes, and x_1 turns out to track the reference profile.
The manifold $\sigma_y=0$ is designed in order to ensure the desired law of variation of the rope length.
In the following it will be shown that:

- on the set $\sigma_x = \sigma_y = 0$ the system exhibits the desired performance, i.e. the reference path is tracked and the load swing is damped (Subsect. 4.1).
- under sensible assumptions on system's parameters and dynamics, a control vector input **V** can be defined such that σ_x and σ_y are reduced in finite time to zero (Subsect. 4.2 and 4.3).

4.1 The local asymptotic stability of the zero dynamics

It is known that the dynamics of a system performing a sliding mode is of reduced-order with respect to the original plant. The dimension of the sliding manifold determines the reduction order. In the considered case, when constrained onto the two-dimensional manifold $\sigma_x = \sigma_y = 0$, the original 6th order system is embedded in a 4th order plant, which must be proved to exhibit the desired properties of tracking and stability. A rigorous analysis of this problem is out from the scope of this paper, and will be the object of future researches.
The reduced order dynamics is expressed as

$$\begin{cases} \dot{x}_1 = \dot{x}_1^* - c_x\left(x_1 - x_f\right) - kx_5 \\ \dot{x}_3 = \dot{x}_3^* - c_y\left(x_3 - x_3^*\right) \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = \varphi(\mathbf{x}) + \gamma(\mathbf{x})\mathbf{T}_{eq} \end{cases} \tag{16}$$

where $\varphi(\mathbf{x})$ and $\gamma(\mathbf{x})$ are derived by (1)-(10) and $\mathbf{T}_{eq}$ is the equivalent control vector [22], solution of the equation $\dot{\boldsymbol{\sigma}}(\mathbf{x},\mathbf{T}) = 0$ (see eq. (18)).
In particular, the term T_{1eq} introduces an arbitrarily large viscous damping proportional to kx_6.
In accordance with [18], we assume that the load swing angle is so small that all terms containing $x_5^\alpha x_6^\beta$ ($\alpha,\beta \geq 0$, $\alpha+\beta \geq 2$) can be neglected and the approximations $sin(x_5) \approx x_5$ and $cos(x_5) \approx 1$ hold.

We study the stability of the zero dynamics in a neighborhood of the destination point after the sliding regime has been established, so that the product by x_6 and x_4 and the exponentially decaying term x_3-x_3^* can be neglected in the swing dynamics. The relevant zero dynamics is given by

$$\begin{cases} \dot{x}_1 = -c_x\left(x_1 - x_1^*\right) - kx_5 \\ \dot{x}_3 = -c_y\left(x_3 - x_3^*\right) \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = \dfrac{c_x}{x_3^*}x_2 + g\dfrac{A_2Mb - A_1A_2}{\bar{\alpha}x_3^*}x_5 + \dfrac{k}{x_3^*}x_6 \end{cases} \quad (17)$$

The k parameter can be chosen to assign stable eigenvalues to the fourth order linearized dynamics (17).

4.2 The sliding variable dynamics

Let $\mathbf{x}^* = \left[x_1^*(t), x_2^*(t)\right]$ define the reference path, and $\boldsymbol{\sigma}=[\sigma_x,\sigma_y]^T$ be the auxiliary output to be stabilized. Successive differentiation of $\boldsymbol{\sigma}$ yield

$$\dot{\boldsymbol{\sigma}} = \mathbf{f}_1\left(\mathbf{x},\mathbf{x}^*,\dot{\mathbf{x}}^*,\ddot{\mathbf{x}}^*\right) + \mathbf{M}(\mathbf{x})\mathbf{T} \quad (18)$$

$$\ddot{\boldsymbol{\sigma}} = \mathbf{f}_2\left(\mathbf{x},\mathbf{x}^*,\dot{\mathbf{x}}^*,\ddot{\mathbf{x}}^*,\dddot{\mathbf{x}}^*,\mathbf{T}\right) + \frac{k_i}{L}\mathbf{M}(\mathbf{x})\mathbf{V} \quad (19)$$

where $\mathbf{f}_i$, i=1,2, is an uncertain vector field, norm-bounded in any bounded domain, and

$$\mathbf{M}(\mathbf{x}) = \begin{bmatrix} \dfrac{A_2}{\alpha} & -\dfrac{m_l b \sin x_5}{\alpha} \\ -\dfrac{m_l b \sin x_5}{\alpha} & \dfrac{A_1 - m_l b \cos^2 x_5}{\alpha} \end{bmatrix} \quad (20)$$

is uncertain but it can be proved to be dominant diagonal. Note that it contains selected entries of the previously introduced matrix $\mathbf{G}(\mathbf{x})$.
The relative degree between the sliding variable and the actuator control is two, and, as the sliding variable derivative is not measurable, a second order sliding mode controller is well suited. As typical of 2-SMC, the unavailable sliding variable derivative is reduced to zero as well.
If the actuator dynamics is so fast that it can be neglected (assuming ideal torque-controlled DC motors), then the sliding variable dynamics can be expressed as

$$\ddot{\boldsymbol{\sigma}} = \mathbf{f}_3\left(\mathbf{x},\mathbf{x}^*,\dot{\mathbf{x}}^*,\ddot{\mathbf{x}}^*,\dddot{\mathbf{x}}^*,\mathbf{T}\right) + \frac{k_i}{R}\mathbf{G}(\mathbf{x})\dot{\mathbf{V}} \quad (21)$$

having set to zero the inductance L, where

$$\mathbf{f}_3\left(\mathbf{x},\mathbf{x}^*,\dot{\mathbf{x}}^*,\ddot{\mathbf{x}}^*,\dddot{\mathbf{x}}^*,\mathbf{T}\right) = \mathbf{f}_2\left(\mathbf{x},\mathbf{x}^*,\dot{\mathbf{x}}^*,\ddot{\mathbf{x}}^*,\dddot{\mathbf{x}}^*,\mathbf{T}\right) - \frac{k_i k_v}{R}\mathbf{G}(\mathbf{x})\boldsymbol{\omega} \quad (22)$$

Under sensible assumptions on system dynamics and reference trajectory, a continuous reference voltage can be applied to the DC motor drives, which is obtained by integrating the relevant discontinuous second order sliding mode control law.

4.3 The multi-input sub-optimal controller

2-SMC of systems of any order can be reduced, after a suitable initialization phase, to the stabilization problem of a second order system with uncertain bounded dynamics in which the state variables are defined as the sliding variable and its total derivative [4].
In this paper we refer to the multi-input version of the "sub-optimal" 2-SMC algorithm previously presented by the authors [3,4], which is briefly resumed for the reader's convenience, where $\mathbf{y}_1(t)= \boldsymbol{\sigma}(\mathbf{x}(t))$ is the sliding variable [7].
Consider system

$$\begin{cases} \dot{\mathbf{y}}_1(t) = \mathbf{y}_2(t) \\ \dot{\mathbf{y}}_2(t) = \boldsymbol{\Phi}(\cdot) + \boldsymbol{\Gamma}(\cdot)\mathbf{u}(t) \end{cases} \quad (23)$$

where $\mathbf{y}_1(t)=[y_{11}(t), y_{12}(t), \ldots, y_{1m}(t)]\in R^m$ is the sliding variable, which vanishes on the sliding manifold, $\mathbf{u}(t) \in R^m$ is the control vector, $\boldsymbol{\Phi}(\cdot)\in R^{m,m}$ and $\boldsymbol{\Gamma}(\cdot)\in R^{m,m}$ are uncertain vector fields, and $\mathbf{y}_2(t)$ *is* not available for measurements. Assume that the following inequalities are satisfied

$$\left\|\boldsymbol{\Phi}(\cdot)\right\| \le \Phi_M \quad (24)$$

$$\Gamma_1 \le \left\|\boldsymbol{\Gamma}(\cdot)\right\| \le \Gamma_2 \quad (25)$$

where Φ_M, Γ_1, Γ_2 are known positive constants, and that the matrix $\boldsymbol{\Gamma}(\cdot)$ is definite positive and sufficiently dominant diagonal, with the entries of the main diagonal, Γ_{ii}, i=1,2,…,m satisfying the bounds

$$0 < \Gamma_{ii1} \le |\Gamma_{ii}| \le \Gamma_{ii2} \qquad i=1,2,\ldots,m$$

Then, the feedback control law

$$u_i(t) = -\alpha_i(t)U_M \operatorname{sign}\left(y_{1i}(t) - \frac{1}{2}y_{1iM}\right) \quad i=1,2,\ldots,m \quad (26)$$

$$\alpha_i(t) = \begin{cases} 1 & if\ y_{1iM}\left(y_{1i}(t) - \frac{1}{2}y_{1iM}\right) \le 0 \\ \alpha^* & otherwise \end{cases} \quad (27)$$

where y_{1iM} is the last singular value of y_{1i} (local minima or maxima, horizontal flex point), α^* V_M , i=1,2,…,m, are proper positive constants such that

$$\alpha^* \in \left(0, \frac{3\Gamma_1}{\Gamma_2}\right) \cap (0,1] \quad (28)$$

$$U_M = \eta \max_{i=1,2,\cdots,m}\left\{\frac{1}{\alpha^*\Gamma_1}; \frac{4}{3\Gamma_{ii1} - \left(\Gamma_{ii2} + 4(m-1)\Gamma_2\right)}\right\}\Phi_M \qquad \eta > 1 \quad (29)$$

causes the finite-time convergence of the $\mathbf{y}_1$, $\mathbf{y}_2$ variables to zero [6].

5 Implementation issues and experimental results

The sub-optimal SOSMC algorithm has been shown to be robust against the sample-and-hold effect [5], so that the feasibility of the digital implementation of the control law does not require further investigations.
The proposed control scheme has been tested on a laboratory-sized prototype built for experimental

investigations (see Figs. 1 and 2).

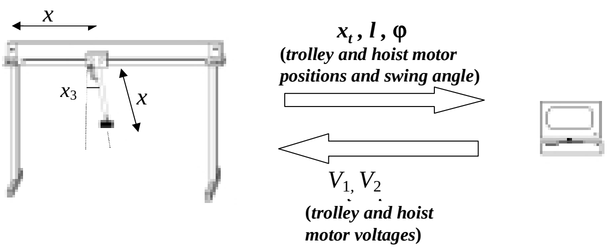

Fig. 2: The signal flux of the experimental setup

Crane parameters and motor ratings	
M	0.275Kg
m_1	1 Kg
R	5.5 Ω
L	.00085 H
K_i	.0415 Nm/A
K_v	.041 V s/rad
J	49.03 g cm^2
N	43

Table I: Experimental setup parameters

The digital control system is implemented by means of a Pentium III™ 133Mhz-based PC unit equipped with a commercial digital 12-bit input-output board (CIO-DAS1602-12), programmed using C code.
The trolley and the rope are actuated by two DC motors, whose ratings are reported in Table I.
The digital 360-ppr quadrature encoder signals are acquired by means of a dedicated commercial encoder interface board (CIO-QUAD04) mounted on the PC.
In order to simplify the hardware complexity, to improve reliability and reduce cost, the trolley position and the rope length are the only measured quantities. The relevant input-output relative degree is three, and the 2-SMC scheme here proposed couldn't be applied. We exploits the results in [8], in which the stability of a control systems in which the output derivatives are estimated by means of 2-sliding differentiators has been demonstrated, to justify the use of robust differentiators based on second order sliding modes to estimate the trolley velocity and the rope length derivative [7,15]. Therefore, the encoder signal is real-time processed by means of a sliding differentiator to estimate corresponding derivative.
The coefficient c_x in the definition of the sliding manifold is updated depending on x_1 in accordance with the following requirements: it is null far from the final desired position, to improve the path tracking in the convergence phase, and it is increased while approaching the final location, to make it attractive despite of disturbances.
The small inductance L motivates the design choice of neglecting the actuator dynamics, in order to justify the control of the DC motor drive with a continuous voltage reference signal (see (21)).
Two tests have been performed, the load transfer test and the fast damping test. As for the first one, the control goal is to move the load from the initial position (x_1,x_3)=(0, 50cm) toward the final location (80cm, 50cm) following a parabolic reference trajectory. The load coordinates and the swing angle versus time are depicted in Figg. 3 and 4 respectively.
In the second experiment, the fast damping of a strong load oscillation has been performed. The only objective is to stabilize the load position as faster as possible, and the fast decay exhibited by the swing angle is displayed in Fig. 5.

The sampling period is T_s=.002*s*. The acquired data have been on-line stored in the memory of the PC and then off-line processed to produce the relevant graphics.

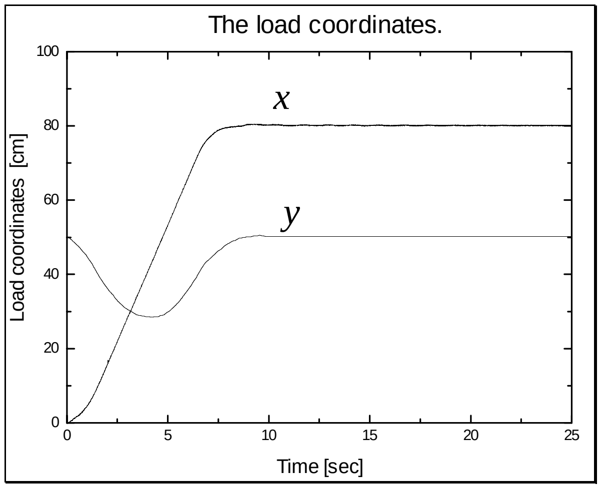

Fig. 3: Load transfer test. The actual load coordinates.

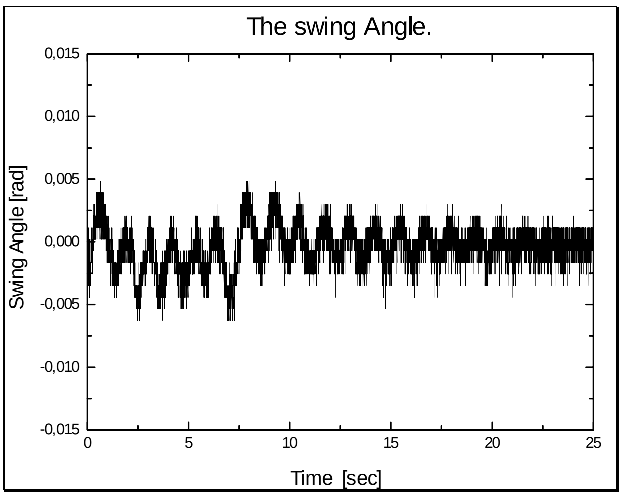

Fig. 4: Load transfer test. The swing angle.

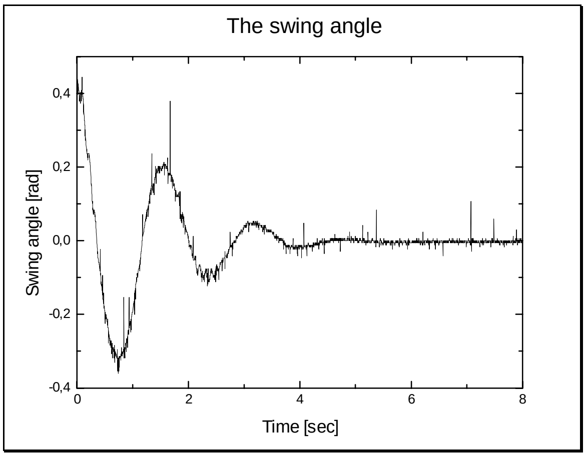

Fig. 5: Fast damping test. The swing angle.

7 Conclusions

The control problem of an underactuated electromechanical system with not complete state availability has been addressed and solved by means of a combined observer/controller scheme based on second order sliding controllers. The system outputs have been suitably defined so that the corresponding system's zero dynamics is locally asymptotically stable. Experimental results of a digital realization of the control scheme on a laboratory-sized overhead crane confirm the practical effectiveness of the proposed approach.

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