An Implicit Gain-Scheduling Controller for Cranes

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***Abstract*— To improve the efficiency of cargo handling with cranes it is necessary to control the crane trolley position so that the swing of the hanging load is minimized. In this paper we consider a linear parameter-varying model of the crane, where the time-varying parameter is the length of the suspending rope. We consider the set of models given by frozen values of the rope length and show how all these models can be reduced to a single time-invariant model using a suitable time scaling. The time scaling relation can be used to derive a control law for the time-varying system that implements an implicit gain scheduling. Using a Lyapunov-like theorem, it is also possible to find relative upper bounds for the rate of change of the varying parameter that ensure the stability of the time-varying system.**

***Index Terms*— Adaptive control, asymptotic stability, gain scheduling, linear-quadratic control, mechanical cranes, time-varying systems, vibration control.**

I. Introduction

THE NEED for faster cargo handling, in particular in loading and unloading container ships whose service time is to be minimized, requires the control of the crane motion so that its dynamic performance is optimized.

A planar operation cycle can be divided into three fundamental motions: the hoisting of the load from a given point, its transfer with a usually constant trolley speed, the lowering at the end of the transfer. The problem is that of reducing the swing of the load while moving it to the desired position as fast as possible.

Several authors have considered control optimization techniques to be applied either to the complete cycle or to one of the motions that compose it. Auernig and Troger [2] and Hippe [3] have used minimal time control techniques; Sakawa and Shindo [6] have used optimal control to minimize load swing. Since the swing of the load depends on the acceleration of the trolley, minimizing the cycle time and minimizing the load swing are partially conflicting requirements.

In this paper we consider an approach that is based on the minimization of the load swing and uses a linear parameter-varying model of the crane to implement a gain-scheduling controller. The varying parameter is the length of the rope that sustains the load. We consider a cycle in which the load can be hoisted or lowered while being transferred.

We consider the set of frozen models given by different constant values of the rope length. Using a suitable time scaling as in [4], all these models can be reduced to a single time-invariant model that does not depend on the value of the rope length.

The time scaling relation can be used to derive a control law for the time-varying system that implements an implicit gain scheduling [1].

We have also studied the stability of the closed-loop system with gain scheduling. Recent works [7]–[9] present several methodologies that can be used to find upper bounds on the rate of change of the varying parameter to ensure stability of a given parameter-varying system. These methodologies give sufficient conditions that are usually very conservative, in the sense that they often require rates of change of the varying parameter so small as to be practically meaningless. These upper bounds, in fact, depend heavily on the procedure used to determine them and are usually far from the real bounds of the system.

However, one classic methodology—reported in [8] and based on a Lyapunov-like theorem—could be applied in the application case we consider to ensure the stability of the time-varying system for the nominal rate of change of the rope length.

An important issue that warrant comments regards the practical implementation of the methodology we describe. Our approach requires that the mass of the load be known to reconstruct the position of the center of gravity. This is a realistic assumption in many applications, such as the handling of ship containers, in which the information on the physical (initial and final) position and on the weight of each container is known before the loading/unloading operation is started. The trolley position, the load position, the rope angle and the rope length can be easily measured by appropriate sensors as discussed in [5], [10], and [11], while the rate of change of the trolley position and of the load angle can be reconstructed by an observer that can also be designed using a gain-scheduling technique as we will discuss in a future work. Thus the position of the center of gravity and its derivative (that we have assumed as state variables) can also be easily computed.

There exist many industrial applications in which the value of the load mass is not known before hand. However, in several of these applications the mass of the load is much smaller than the mass of the trolley. In this case, we may simply neglect the mass of the load and make the position of the center of gravity coincide with the trolley position. This is a particular case of our approach in which we take $m_L = 0$, and the simulations we have performed (not reported here) showed that the control methodology described in this paper gives still good performances.

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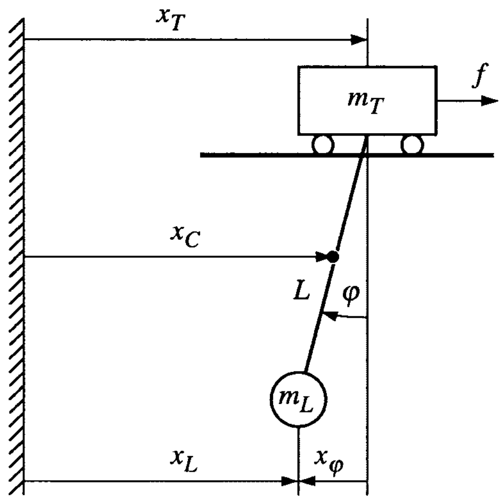

Fig. 1. Model of the crane.

Furthermore, if necessary, a strain gauge may well be used during each crane operation to measure the load weight on-line [10], [11].

This paper is structured as follows. Section II presents the time-varying model of the crane and discusses the time scaling that can be used to reduce the set of frozen models to a single time-invariant model. Section III shows how a simple gain-scheduling control scheme can be derived to improve the dynamic performance of the crane and how it is possible to study the stability of the closed-loop system. Section IV presents an application example for a container crane. The results of numerical simulations show that the proposed approach gives acceptable performance while ensuring the stability of the system. The derivation of the simplified equations for the crane is reported in the Appendix.

II. Time-Varying Model and Time Scaling

We will consider a planar crane, whose model is shown in Fig. 1. The following notation is used:

m_T, m_L	Mass of the trolley and the load, respectively.
L	Length of the suspending rope.
x_T, x_L	Displacement of the trolley and that of the load with respect to (wrt) a fixed coordinate system, respectively.
$x_C = (m_T x_T + m_L x_L)/(m_L + m_T)$	Displacement of the center of gravity of the overall system wrt a fixed coordinate system.
φ	Angle between the suspending rope and the vertical taken as positive in the clockwise direction (see figure).
$x_\varphi = x_T - x_L = L \sin\varphi$	Load displacement wrt the vertical;
f	Control force applied to the trolley;
g	Gravitation constant.

If the load is heavy enough, it is possible to consider the suspending rope as a rigid rod. Under the assumptions reported in the Appendix (namely, small angles and force applied by the rope equal to the weight of the load) choosing the following state variables:

$$x_1(t) = x_\varphi(t), \quad x_2(t) = x_C(t)$$
$$x_3(t) = \dot{x}_\varphi(t), \quad x_4(t) = \dot{x}_C(t) \tag{1}$$

and denoting

$$\omega_t \equiv \omega_t(L(t)) = \left(\frac{g(m_T + m_L)}{m_T L}\right)^{0.5} \tag{2}$$

we get the following state variable equation (see the Appendix for a derivation):

$$\dot{x}_t = A_t x_t + B_t f \tag{3}$$

with

$$x_t = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \end{bmatrix}; \quad A_t = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\omega_t^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix};$$

$$B_t = \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{m_T} \\ \dfrac{1}{m_T + m_L} \end{bmatrix}.$$

The subscript t has been introduced to recall that the variables are functions of time. The model given by (3) is time-varying because ω_t is a function of $L(t)$.

If we consider a given constant value of ω_t, i.e., if we consider the system (3) for a frozen value of L, we can consider the following transformation:

$$\tau = \omega_t t. \tag{4}$$

This transformation defines a time scaling that enables us to rewrite (1) as

$$\begin{aligned} x_1(t) &= x_\varphi(t) = x_\varphi(\tau) = x_1(\tau) \\ x_2(t) &= x_C(t) = x_C(\tau) = x_2(\tau) \\ x_3(t) &= \frac{dx_\varphi(t)}{dt} = \frac{dx_\varphi(\tau(t))}{dt} = \omega_t \frac{dx_\varphi(\tau)}{d\tau} = \omega_t x_3(\tau) \\ x_4(t) &= \frac{dx_C(t)}{dt} = \frac{dx_C(\tau(t))}{dt} 0 = \omega_t \frac{dx_C(\tau)}{d\tau} = \omega_t x_4(\tau). \end{aligned} \tag{5}$$

According to (5), variables x_C and x_φ can be taken as functions of t or τ, while their derivatives are changed by the time scaling. We can write (5) as

$$x_t = N x_\tau \tag{6}$$

where

$$N = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \omega_t & 0 \\ 0 & 0 & 0 & \omega_t \end{bmatrix}; \quad x_\tau = \begin{bmatrix} x_1(\tau) \\ x_2(\tau) \\ x_3(\tau) \\ x_4(\tau) \end{bmatrix}. \tag{7}$$

According to (5) we may also write

$$\dot{x}_t = \omega_t N \dot{x}_\tau \tag{8}$$

where $\dot{x}_\tau$ is the derivative of x_τ wrt τ.

Using (6) and (8), it is possible to rewrite the system (3) as

$$\dot{x}_\tau = A_\tau x_\tau + B_\tau u_\tau \tag{9}$$

with

$$A_\tau = \omega_t^{-1} N^{-1} A_t N = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{10}$$

$$B_\tau = \omega_t N^{-1} B_t m_T = \begin{bmatrix} 0 \\ 0 \\ 1 \\ \dfrac{1}{1+\mu} \end{bmatrix}; \quad \left(\mu = \frac{m_L}{m_T}\right) \tag{11}$$

$$u_\tau = \frac{f}{\omega_t^2 m_T}. \tag{12}$$

The representation given by (9) is time invariant and does not depend on the frozen value of L in (3). It is also possible to express the relationships between the eigenvalues and eigenvectors of the matrices A_t and A_τ. Let Λ_t (Λ_τ) be the diagonal matrix of the eigenvalues of $A_t(A_\tau)$; then from (10) we obtain

$$\Lambda_t = \omega_t \Lambda_\tau \tag{13}$$

while between the eigenvector matrices V_t and V_τ

$$V_t = N V_\tau \tag{14}$$

holds, i.e., given a matrix of eigenctors V_τ for A_τ it is possible to compute one of the possible matrices of eigenctors V_t for A_t.

Note that $\Lambda_\tau = \mathrm{diag}(0, 0, j1, -j1)$, and from (13) $\Lambda_t = \mathrm{diag}(0, 0, j\omega_t, -j\omega_t)$, i.e., the frozen system (3) has an undamped oscillation of angular frequency ω_t. Thus we can also say that the variable τ defined by (4) is the time measured using as units $1/\omega_t = T_t/2\pi$, where T_t is the period of the undamped oscillation of system (3).

An optimal regulator can be used to control system (9) minimizing the linear quadratic cost functional

$$J = \int_0^\infty (x_\tau^T Q_\tau x_\tau + u_\tau^T R_\tau u_\tau)\, d\tau \tag{15}$$

where $Q_\tau = Q_\tau^T \geq 0$ and $R_\tau = R_\tau^T > 0$ are suitable weight matrices. The resulting control law has the form

$$u_\tau = -K_\tau x_\tau \tag{16}$$

where K_τ is a constant matrix and does not depend on the value of L.

The above equation can be transformed, using (6) and (12), into a corresponding law for the frozen system (3) that gives

$$f(t) = -K_t x_t \tag{17}$$

where

$$K_t = m_T \omega_t^2 K_\tau N^{-1}. \tag{18}$$

The feedback laws (16) and (17) lead to closed-loop systems whose characteristic matrices are

$$\overline{A}_\tau = A_\tau - B_\tau K_\tau \quad \overline{A}_t = A_t - B_t K_t. \tag{19}$$

Equations (10), (13), and (14), written for the open-loop systems, still hold for the corresponding closed-loop systems. The poles of the closed-loop system in t depend on the value of L, and thus on ω_t, but they have the same damping factor for all values of L.

Using (4), (6), and (12), the cost functional (15) can also be rewritten for the frozen system in t as

$$J = \int_0^\infty \left(x_t^T N^{-1} Q_\tau N^{-1} x_t + \frac{R_\tau}{\omega_t^4 m_T^2} f^2 \right) \omega_t \, dt. \tag{20}$$

Thus we can say that the feedback law (17) is optimal for the frozen system (3) if the following weight matrices are chosen:

$$Q_t = N^{-1} Q_\tau N^{-1} \omega_t; \quad R_t = \frac{R_\tau}{\omega_t^3 m_T^2}. \tag{21}$$

III. Gain Scheduling and Stability

Let now $L(t)$ be a time-varying parameter (we always assume $\dot{L}(t) \neq 0; \ddot{L}(t) = 0$). Then (17) and (18) can be used to implement a time-varying control feedback law that can be seen as an "implicit" gain scheduling. In fact, in (18) both ω_t and N^{-1} are functions of $L(t)$. Since the frozen system (3) with frozen control law (17) is optimal wrt the weights given by (21), then all eigenvalues of $\overline{A}_t$ have negative real part for all frozen values of $L(t)$. This, however, is not sufficient to ensure the stability of the time-varying system.

New theoretical results recently discussed in the literature [7], [9] consider the case of gain scheduling control systems and give some upper bounds for the rate of change of a time-varying parameter in order to ensure stability. In our case these methods could be applied to find an upper bound for $|\dot{L}(t)|$ such that for nominal values of $\dot{L}(t)$ the time-varying closed-loop system is certainly stable. These methods can only give sufficient conditions and in the case at hand have been shown to be too conservative, in the sense that they give upper bounds too small to be of practical interest as discussed in the next section.

Enhanced stability bounds have been achieved using a classic procedure based on the following Lyapunov-like theorem reported by Shamma in [8].

Theorem 3.1: Given the time-varying system

$$\dot{x}(t) = A(t) x(t) \tag{22}$$

where $A(t)$ is bounded and globally Lipschitz continuous, let there exist matrices $P(t)$ and $Q(t)$, symmetric and positive definite, such that

1) $P(t)$ is continuously differentiable for all $t > 0$;
2) there exist constants $\alpha_1, \alpha_2,$ and $\alpha_3 > 0$ such that for all $t \geq 0$

$$\begin{gathered} \alpha_1 \leq \sigma_{\min}\{P(t)\} \leq \sigma_{\max}\{P(t)\} \leq \alpha_2 \\ \lambda_{\min}\{Q(t) - \dot{P}(t)\} \geq \alpha_3; \end{gathered} \tag{23}$$

3) $P(t)A(t) + A^T(t)P(t) = -Q(t) \quad (\forall t \geq 0)$;

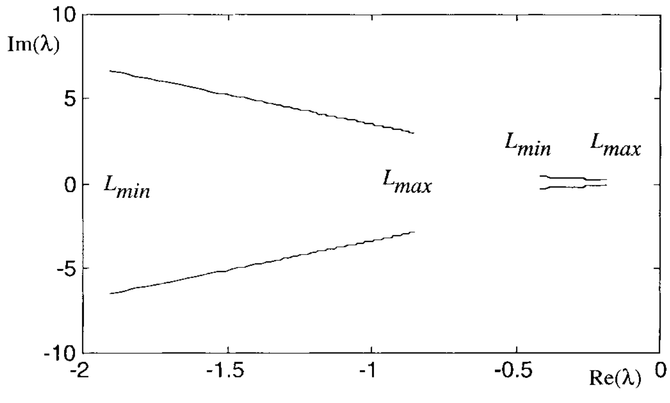

Fig. 2. Eigenvalues of the matrix $\overline{A}_t$ for different values of L.

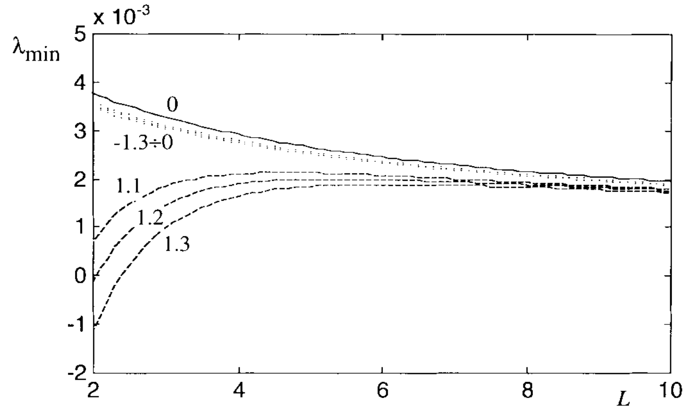

Fig. 3. Plot of $\lambda_{\min}\{Q(L) - (dP/dL)\dot{L}\}$ for different values of the parameter $\dot{L}$.

where $\sigma_{\min}$ (respectively, $\sigma_{\max}$) denotes the smaller (respectively, larger) singular value and $\lambda_{\min}$ denotes the smaller eigenvalue.

Under these conditions, the linear system of (22) is exponentially stable.

IV. Simulation Results

The above described approach was applied to a container crane whose model is shown in Fig. 1. The values of the parameters are: $m_T = 6 \cdot 10^3$ kg, $m_L = 42.5 \cdot 10^3$ kg. These values are taken from [3] and are those of a container crane at the port of Kobe, Japan.

We assume the length of the suspending rope to be: $L(t) \in [L_{\min}, L_{\max}]$, where $L_{\min} = 2$ m and $L_{\max} = 10$ m. In nominal operating conditions $|\dot{L}| \le 1$ m/s.

The weights of the performance index (15) are

$$Q_\tau = \begin{bmatrix} 16 & -0.5 & 0 & 0 \\ -0.5 & 0.2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}; \quad R_\tau = 40.$$

These values were obtained by a trial-and-error procedure. The corresponding control feedback matrix is

$$K_\tau = [0.2611 \quad 0.0707 \quad 0.5760 \quad 1.2821].$$

Fig. 2 shows the locus of the eigenvalues of the matrix $\overline{A}_t$ as L changes between $L_{\min}$ and $L_{\max}$.

To study the stability of the time-varying system with system matrix $\overline{A}_t$, we have tried several approaches.

First of all we tried to apply the results of [7, Lemmas 3.5 and 3.6], and the *matrix exponential method* as described by Shamma [8, p. 53]. However, these methods gave upper bounds on $\dot{L}$ too restrictive and practically meaningless: stability was ensured for $|\dot{L}| \le 2 \cdot 10^{-5}$ m/s.

Then we tried to apply Theorem 3.1. In particular, let $\overline{\Lambda}_\tau$ and $\overline{V}_\tau$ be the eigenvalue and eigenvector matrices for $\overline{A}_\tau^T$. Then, using the transpose of (10), it is possible to show that $\overline{\Lambda}_t = \omega_t \overline{\Lambda}_\tau$ and $\overline{V}_t = N^{-1}\overline{V}_\tau$ are eigenvalue and eigenvector matrices for $\overline{A}_t^T$. We then choose the matrix $P(t)$ in Theorem 3.1 as

$$P(t) = \overline{V}_t \overline{V}_t^H = N^{-1}\overline{V}_\tau \overline{V}_\tau^H N^{-1}$$

where ^{H} denotes the complex conjugate transpose. Thus, the corresponding matrix $Q(t)$ satisfying the equation in Theorem 3.1 part 3) will be

$$Q(t) \equiv Q(L(t)) = -\overline{V}_t(\overline{\Lambda}_t + \overline{\Lambda}_t^H)\overline{V}_t^H.$$

It is also possible to compute analytically the matrix $\dot{P}(t)$. Let

$$\dot{N}^{-1} = \mathrm{diag}\left(0, 0, \frac{1}{2(g(1+\mu)L)^{0.5}}, \frac{1}{2(g(1+\mu)L)^{0.5}}\right)\dot{L}.$$

Then it follows that:

$$\dot{P}(t) = \dot{N}^{-1}\overline{V}_\tau \overline{V}_\tau^H N^{-1} + N^{-1}\overline{V}_\tau \overline{V}_\tau^H \dot{N}^{-1} = \left(\frac{dP}{dL}\right)\dot{L}.$$

Fig. 3 shows the plot of $\lambda_{\min}\{Q(L) - (dP/dL)\dot{L}\}$ versus L for different values of $\dot{L}$. According to the Theorem 3.1, the upper bound on $|\dot{L}|$ is the value corresponding to the first curve that, as $|\dot{L}|$ is increased, goes to negative values. As can be seen from the figure, this happens for $\dot{L} = 1.2$ m/s, hence it can be concluded that the time-varying system with system matrix $\overline{A}_t$ is stable if $|\dot{L}| < 1.2$ m/s. Since in normal operating conditions $|\dot{L}| \le 1$ m/s, this result ensures the stability of the time-varying system.

Figs. 2 and 3 warrant comment. Fig. 2 shows that as L is increased the frozen systems with system matrix $\overline{A}_t$ always have eigenvalues with negative real part and closer to the imaginary axis. This suggests that increasing L may lead the time-varying system toward instability.

On the contrary, from Fig. 3 it can be seen that stability is difficult to prove for small values of L. In fact it is well known that when gain scheduling is used the stability of frozen systems ensures the stability of time-varying system for very slow relative changes of the varying parameter. In the case at hand, for a given $|\dot{L}|$, the relative rate of change of L will be higher for small values of L. This also shows that although we have considered $L \le L_{\max} = 10$ m, these stability results also hold for higher values of $L_{\max}$.

The results of two simulations computed with SIMULINK are shown in Figs. 4 and 5.

In Fig. 4, the variables $x_\varphi(t), x_C(t), x_L(t), x_T(t)$, and $f(t)$ are plotted for rope length changing from $L_{\max}$ to $L_{\min}$ with

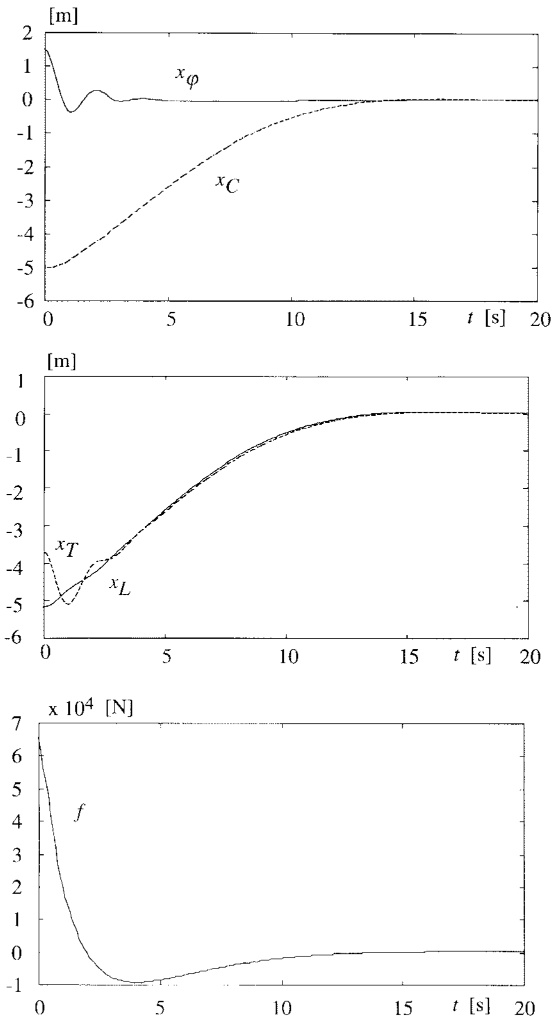

Fig. 4. Simulation results for a lifting movement with $x_\varphi(0) = 1.5$ m, $x_C(0) = -5$ m.

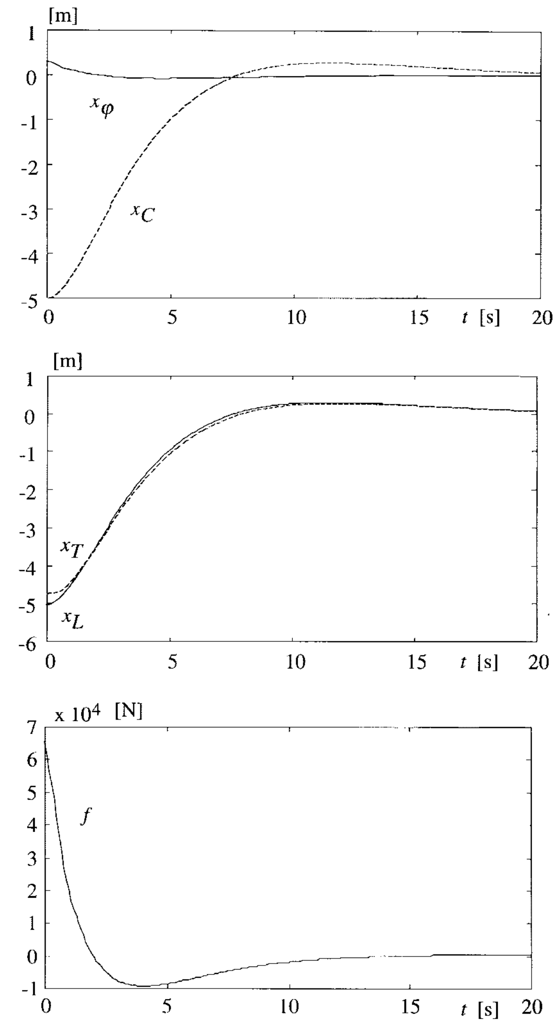

Fig. 5. Simulation results for a lowering movement with $x_\varphi(0) = 0.3$ m, $x_C(0) = -5$ m.

a constant speed $\dot{L} = -0.5$ m/s and initial state $x_\varphi(0) = 1.5$ m, and $x_C(0) = -5$ m.

In Fig. 5, the variables $x_\varphi(t), x_C(t), x_L(t), x_T(t)$, and $f(t)$ are plotted for rope length changing from $L_{\min}$ to $L_{\max}$ with a constant speed $\dot{L} = 0.5$ m/s and initial state $x_\varphi(0) = 0.3$ m, and $x_C(0) = -5$ m.

V. Conclusions

Several control methodologies for improving the efficiency and reducing the time of cargo handling with cranes have been presented in literature. In this paper, we developed an approach that aims to reduce the load swing while the load is simultaneously hoisted (or lowered) and transfered.

Using a time scaling, the control problem for the original linear time-varying system has been reduced to the optimal control of a linear time-invariant system. The time scaling relation has been used to derive a control law for the original system that takes the form of an implicit gain scheduling.

We also studied the stability of the time-varying system with gain scheduling. Using a Lyapunov-like theorem it was possible to find upper bounds for the rate of change of the varying parameter (the length of the suspending rope) that ensure the stability of the crane studied in the application example during nominal operating conditions.

Appendix

The dynamics of the system in Fig. 1 are described by the following equations (obtained by the translational equilibrium of the two masses):

$$\begin{aligned} m_T \ddot{x}_T &= f - F \sin\varphi \\ m_L \ddot{x}_L &= F \sin\varphi \\ m_L \ddot{y}_L &= m_L g - F \cos\varphi \end{aligned} \tag{24}$$

where F is the force in the direction of the rope

$$x_L = x_T - L \sin\varphi \tag{25}$$

is the displacement of the load in the horizontal direction wrt to a fixed coordinate system

$$y_L = L \cos\varphi \tag{26}$$

is the displacement of the load in the vertical direction wrt to a fixed coodinate system.

With the coordinate trasformations $x_C = (m_T x_T + m_L x_L)/(m_L + m_T)$ and $x_\varphi = L \sin\varphi = x_T - x_L$, the first two equations of (24) can be rewritten as

$$\ddot{x}_\varphi + \frac{F(\vec{\varphi}, \vec{L})}{L}\left(\frac{1}{m_T} + \frac{1}{m_T}\right)x_\varphi = \frac{f}{m_T}$$
$$\ddot{x}_C = \frac{f}{m_T + m_L} \quad (27)$$

where the rope force $F(\vec{\varphi}, \vec{L})$ is a function of $\vec{\varphi} : (\varphi, \dot{\varphi}, \ddot{\varphi})$ and $\vec{L}$: $(L, \dot{L}, \ddot{L})$ as can be determined by twice differentiating (26) and substituting into the third equation of (24):

$$m_L(\ddot{L}\cos\varphi - 2\dot{L}\dot{\varphi}\sin\varphi - L\dot{\varphi}^2\cos\varphi - L\ddot{\varphi}\sin\varphi) = m_L g - F\cos\varphi. \quad (28)$$

Linearizing around the equilibrium point $\vec{\varphi}^*$: $(\varphi = 0, \dot{\varphi} = 0, \ddot{\varphi} = 0)$ is equivalent to setting

$$\sin\varphi = \varphi, \quad \cos\varphi = 1, \quad \dot{\varphi}\sin\varphi = 0$$
$$\dot{\varphi}^2 = 0, \quad \ddot{\varphi}\sin\varphi = 0$$

and assuming $\ddot{L}(t) = 0$ (28) yields $F(\vec{\varphi}^*, \ddot{L}(t) = 0) = m_L g$, i.e., the force along the rope is equal to the weight of the load. Substituting this value of F into (27) we obtain the linearized model

$$\ddot{x}_\varphi + \frac{g(m_T + m_L)}{m_T L}x_\varphi = \frac{f}{m_T}$$
$$\ddot{x}_C = \frac{f}{m_T + m_L}. \quad (29)$$

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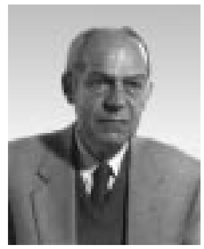

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He joined the Istituto di Elettrotecnica of the University of Cagliari in 1961 as Assistant Professor of Electrotechnics. He became Assistant Professor of Automatic Control in 1971, Associate Professor in 1982, and Full Professor in 1987. He teaches the course of Automatic Control in the industrial engineering curriculum. He is currently Professor and Director of the Automatic Control Group in the Department of Electrical and Electronic Engineering of the University of Cagliari, Italy. His current research interests include modeling and control of open-channel networks, modeling and control of forestal systems, and vibration control of mechanical systems such as suspension systems for road vehicles, train pantographs, and cranes.

Prof. Corriga has been chairman of several sessions in international conferences on control and industrial electronics. He has been a reviewer for international journals on water management systems.

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Giampaolo Usai was born in Cagliari, Sardinia, Italy, in 1939. He received the Laurea degree in civil engineering in 1965 from the University of Cagliari, Italy.

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