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COMPUTER SCIENCE AND AUTOMATION

COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems

Session 2 - Advances in Control Theory and Control Engineering

Session 3 - Optimisation and Management of Complex Systems and Networked Systems

Session 4 - Intelligent Vehicles and Mobile Systems

Session 5 - Robotics and Motion Systems

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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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52nd International Scientific Colloquium
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10 – 13 September 2007

E. Arnold / J. Neupert / O. Sawodny / K. Schneider

Trajectory Tracking for Boom Cranes Based on Nonlinear Control and Optimal Trajectory Generation

Abstract

The main objectives of crane automation are increasing the efficiency and safety of the transshipment processes. Therefore, advanced control strategies are applied for load sway reduction and trajectory tracking. The paper presents a nonlinear control strategy combined with a model-based optimal trajectory generation for the radial load movement of a boom crane. The results are validated by measurement results from a LIEBHERR harbor mobile crane.

1 Introduction

The paper addresses the problem of trajectory tracking and disturbance rejection for the transportation of crane loads. Advanced control systems are developed to meet the demands for fast, efficient, and safe transshipment of cargo in harbors, for example the CYCOPTRONIC system (Sawodny et al. [1], [2], Arnold et al. [3], Neupert et al. [4]) provided by the company 'Liebherr Werk Nenzing' as anti-sway control for harbor mobile cranes (see Fig. 1). These boom cranes are characterized by a load capacity of up to 140t, a maximum outreach of 48m and a rope length of up to 80m.

Because of the dominant nonlinearities of the dynamic system, the accurate tracking of the crane load on the desired reference trajectory during luffing motion is a challenge for the control system. The nonlinear model of the crane dynamics for the radial movement excluding the influence of the centrifugal forces is derived and discussed in Neupert et al. [5]. Further on, the design of the flatness based controller is presented in detail. Another challenge is the generation of these reference trajectories that have to take into account the system dynamics as well as input and state constraints.

Figure 1: LIEBHERR harbor mobile crane (LHM).

The theoretical foundation for the design of control structures for nonlinear systems and their analysis was introduced in numerous publications. Isidori et al. [6], [7] for example consider asymptotic output tracking of a certain class of nonlinear systems, where the reference or disturbance signals are generated by an exosystem. To calculate the feedforward trajectory partial differential equations are solved. Fliess et al. [8] discuss the differential flatness of nonlinear systems.

They formulate the major property of differential flatness and propose the defect of a nonlinear system as a non-negative integer, which measures the distance from flatness.

Fliess et al. [9] study a two-dimensional overhead crane as an application example of the nonlinear control. The system is characterized as a differential flat system by deriving a linearizing output. Other publications from Piazzi et al. [10] and Yanai et al. [11] are also focussed on the inversion based control of overhead cranes. This is why cranes are a typical example of an underactuated mechanical system with oscillatory behavior. Kiss et al. [12] show differential flatness for a class of cranes including overhead and rotary cranes.

Most of these contributions do not consider the actuator dynamics and kinematics. In case of a boom crane, which is driven by hydraulic actuators, the dynamics and kinematics of the hydraulic actuators are not negligible. Especially for the boom actuator (hydraulic cylinder) the kinematics have to be taken into account. The resulting nonlinear model for the luffing motion is derived in section 2. Based on the nonlinear model, the flatness based control approach is presented in section 3. It is shown, that a flat output can be found and a linearizing and stabilizing control law can be obtained.

The application of flatness based control methods requires sufficiently smooth reference trajectories that have to be feasible with respect to the input and state constraints of the system. For the tracking problem under consideration, the update of the reference trajectories requires the current state of the system thus forming an additional feedback loop.

An usual approach for on-line trajectory generation is the parameterization of the output and output derivatives profiles by stage-wise low-order polynomials. The coefficients of the polynomials are determined by the boundary values and bound constraints of the variables, see e. g. [13]. This can be interpreted as an approximate solution of a suitable optimal control problem. Because of the necessary increasing degree of the polynomials, this approach is limited to lower order derivatives of the output.

In this paper, a different approach is used. The flatness based controller linearizes and stabilizes the system. An optimal control problem is formulated and solved online to generate feasible reference trajectories for the linearized system including the state feedback. The reference trajectories take into account the current state of the system, therefore this outer feedback loop can be considered as a model predictive control (MPC) loop, see [14]. The formulation and the numerical solution of the optimal control problem is discussed in section 4.

The optimal trajectory generation and flatness based control for the luffing motion is applied to the LIEBHERR harbor mobile crane (LHM). The obtained measurement results are presented in section 5. In section 6 concluding remarks are given.

2 Nonlinear model of the crane

The performance of the crane's control is mainly measured by fast damping of load sway and exact tracking of the reference trajectory. To achieve these control objectives the dominant nonlinearities have to be considered in the dynamic model of the luffing motion.

The first part of this model is derived by the method of Newton-Euler considering the load as a point mass and neglecting the mass and elasticity of the rope as well as coriolis and centripetal terms. This results in the following differential equation which characterizes the radial load sway.

$$\ddot{\varphi}_{Sr} + \frac{g}{l_S}\sin\varphi_{Sr} = \frac{\cos\varphi_{Sr}}{l_S}\ddot{r}_A \qquad (1)$$

As shown in Fig. 2, φ_{Sr} is the radial rope angle, $\ddot{\varphi}_{Sr}$ the radial angular acceleration, l_S the rope length, r_A the distance from the vertical axis to the end of the boom, $\ddot{r}_A$ the radial acceleration of the end of the boom, m_L the mass of the load and g the gravitational constant.

The second part of the nonlinear model is obtained by taking the kinematics and dynamics of the actuator into account. This actuator is a hydraulic cylinder attached between tower and boom. Its dynamics can be approximated with a first order system

$$\ddot{z}_{zyl} = -\frac{1}{T_W}\dot{z}_{zyl} + \frac{K_{VW}}{T_W A_{zyl}}u_l \qquad (2)$$

where $\ddot{z}_{zyl}$ and $\dot{z}_{zyl}$ are the cylinder acceleration and velocity respectively, T_W the time constant, A_{zyl} the cross-sectional area of the cylinder, u_l the input voltage of the servo valve and K_{VW} the proportional constant of flow rate to u_l. In order to combine equation (1) and (2) they have to be in the same coordinates. Therefore a transformation of equation (2) from cylinder variables (z_{zyl}) to outreach variables (r_A) with the kinematical equation

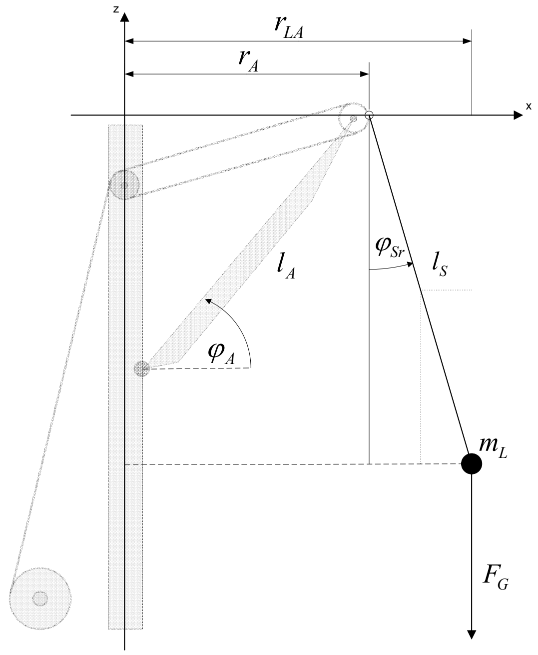

Figure 2: Radial movement of the load.

$$r_A(z_{zyl}) = l_A \cos\left(\alpha_{A0} - \arccos\frac{d_a^2 + d_b^2 - z_{zyl}^2}{2d_a d_b}\right) \qquad (3)$$

and its derivatives

$$\begin{aligned} \dot{r}_A &= -l_A \sin\varphi_a K_{Wz1}(\varphi_A)\dot{z}_{zyl} \\ \ddot{r}_A &= -l_A \sin\varphi_a K_{Wz1}(\varphi_A)\ddot{z}_{zyl} - K_{Wz3}\dot{z}_{zyl}^2 \end{aligned} \qquad (4)$$

is necessary. The dependency from the geometric constants d_a, d_b, α_1, α_2 and the luffing angle φ_A is substituted by K_{Wz1} and K_{Wz3}. The geometric constants, the luffing angle and l_A, which is the length of the boom, are shown in Fig. 3. As result of the transformation, equation (2) can be given in outreach coordinates.

$$\ddot{r}_A = -\underbrace{\frac{K_{Wz3}}{l_A^2 \sin^2\varphi_A K_{Wz1}^2}}_{a}\dot{r}_A^2 - \underbrace{\frac{1}{T_W}}_{b}\dot{r}_A - \underbrace{\frac{K_{VW} l_A \sin\varphi_A K_{Wz1}}{T_W A_{zyl}}}_{m}u_l \qquad (5)$$

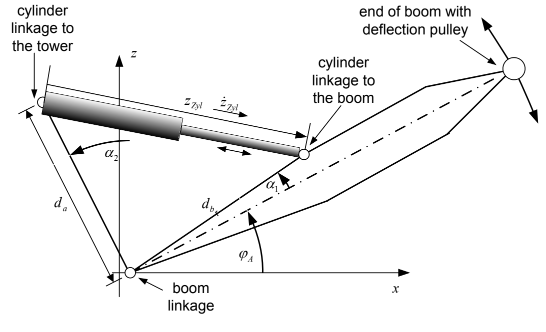

Figure 3: Mounting of the hydraulic cylinder.

In order to obtain a nonlinear model in the input affine form

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})u_l, \quad y = h(\mathbf{x}) \qquad (6)$$

equations (1) and (5) are used. With the states defined as $\mathbf{x} = \begin{bmatrix} r_A & \dot{r}_a & \varphi_{Sr} & \dot{\varphi}_{Sr} \end{bmatrix}^T$ and the output $y = r_{LA}$ follow the vector fields $\mathbf{f}$ and g and and the function h, respectively.

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} x_2 \\ -ax_2^2 - bx_2 \\ x_4 \\ -\frac{g}{l_S}\sin x_3 + \frac{\cos x_3}{l_S}\left(ax_2^2 + bx_2\right) \end{bmatrix}, \quad g(\mathbf{x}) = \begin{bmatrix} 0 \\ -m \\ 0 \\ \frac{\cos x_3 m}{l_S} \end{bmatrix}, \tag{7}$$

$$h(\mathbf{x}) = x_1 + l_S \sin x_3 \tag{8}$$

3 Nonlinear control approach

The following considerations are made assuming that the right side of the differential equation for the load sway (1) can be linearized.

$$\ddot{\varphi}_{Sr} + \frac{g}{l_S}\sin\varphi_{Sr} = \frac{1}{l_S}\ddot{r}_A \tag{9}$$

In order to find a linearizing output for the simplified nonlinear system the relative degree has to be ascertained.

The relative degree concerning the output of the system is defined by the following conditions

$$L_{\mathbf{g}}L_{\mathbf{f}}^i h(\mathbf{x}) = 0 \quad \forall i = 0,\ldots,r-2, \qquad L_{\mathbf{g}}L_{\mathbf{f}}^{r-1}h(\mathbf{x}) \neq 0 \quad \forall x \in \mathbb{R}^n \tag{10}$$

The operator $L_{\mathbf{f}}$ represents the LIE derivative along the vector field $\mathbf{f}$ and $L_{\mathbf{g}}$ along the vector field $\mathbf{g}$, respectively.

A relative degree of $r = 2$ is obtained with the real output (8). Because the order of the simplified nonlinear model is 4, y is not a linearizing output. But with a new output

$$y^* = h^*(\mathbf{x}) = x_1 + l_S x_3 \tag{11}$$

a relative degree of $r = 4$ is obtained. Assuming that only small radial rope angles occur, the difference between the real output y and the flat output y^* can be neglected.

Because the simplified system representation is differentially flat an exact linearization can be done. Therefore a new input is defined as $v = \ddddot{y}^*$ and the linearizing control signal $u_{l,lin}$ is calculated by

$$u_{l,lin} = \frac{-L_{\mathbf{f}}^r h^*(\mathbf{x}) + v}{L_{\mathbf{g}}L_{\mathbf{f}}^{r-1}h^*(\mathbf{x})} = \frac{g\sin x_3 x_4^2 - g\cos x_3\left(-\frac{g}{l_S}\sin x_3 + \frac{a}{l_S}x_2^2 + \frac{b}{l_S}x_2\right) + v}{\frac{gm}{l_S}\cos x_3} \tag{12}$$

In order to stabilize the resulting linearized system a feedback of the error between the reference trajectory and the derivatives of the output y^* is derived.

$$u_l = \frac{-L_{\mathbf{f}}^r h^*(\mathbf{x}) + v - \sum_{i=0}^{r-1} k_i\left(L_{\mathbf{f}}^i h^*(\mathbf{x}) - y_{ref}^{(i)*}\right)}{L_{\mathbf{g}}L_{\mathbf{f}}^{r-1}h^*(\mathbf{x})} \tag{13}$$

The feedback gains k_i are obtained by the pole placement technique.

4 Trajectory generation

The trajectory generation problem is formulated as a constrained, open-loop optimal control problem for the linearized system including the state feedback. Because of the relevant calculating time for solution of the optimal control problem the model predictive trajectory generation operates with a non-negligible sample time. Likewise the numerical solution procedure itself introduces a discretization of the time axis, see below. But for the sake of simplicity, the open-loop optimal control problem is stated in continuous time in the following.

The model equations are given by

$$\begin{aligned} \dot{\mathbf{x}}_{lin} &= \mathbf{A}_{lin}\mathbf{x}_{lin} + \mathbf{b}_{lin}u_{lin}, \quad \mathbf{x}_{lin}(t_0) = \mathbf{x}_{lin,0} \\ \mathbf{y}_{lin} &= \mathbf{C}_{lin}\mathbf{x}_{lin} \end{aligned} \tag{14}$$

The state variables $\mathbf{x}_{lin}$ are the states of the integrator chain forming the linearized system as well as the state variables of the integrator chain for the output reference trajectory. Additional state variables are introduced to generate a smooth input v. The initial state $\mathbf{x}_{lin,0}$ is derived from the state of these integrators and the current system output and system output derivative measurements. The outputs $\mathbf{y}_{lin}$ of the linear system (14) are the variables corresponding to the flat output y^* (eqn. (11)) and its first and second derivative that approximate the load position, velocity, and acceleration.

The objective functional

$$J_c = \frac{1}{2}\int_{t_0}^{t_f} \left((\mathbf{y}_{lin} - \mathbf{w})^T \mathbf{Q} (\mathbf{y}_{lin} - \mathbf{w}) + r\dot{u}_{lin}^2 \right) dt \tag{15}$$

is a standard form evaluating quadratically both the deviations of the predicted outputs $\mathbf{y}_{lin}$ from their reference predictions $\mathbf{w}(t)$ and the rate of change of the input variables u_{lin}. The optimization horizon $t_f - t_0$ and the symmetric and positive semi-definite weighting matrix $\mathbf{Q}$ and the weighting coefficient $r > 0$ are essential tuning parameters of the model predictive trajectory generator.

The optimization horizon $t_f - t_0$ should cover the essential dynamics of the process. These are defined by the period of the load sway (up to 18 s for the crane under consideration). Practical experience shows that a horizon of 10 s is sufficient.

Reference predictions $\mathbf{w}(t)$ are generated from the crane operator's hand lever signals (velocity targets) for the load position, velocity and acceleration. The prediction takes into account velocity reductions if the load approaches the radial boundaries.

The model predictive trajectory generation algorithm incorporates restrictions on the process variables as constraints of the open-loop optimal control problem.

$$u_{lin,\min} \leq u_{lin} \leq u_{lin,\max}, \qquad \mathbf{y}_{lin,\min} \leq \mathbf{y}_{lin} \leq \mathbf{y}_{lin,\max} \tag{16}$$

Input rate constraints are applied to avoid high-frequency excitations of the system.

$$\dot{u}_{lin,\min} \leq \dot{u}_{lin} \leq \dot{u}_{lin,\max} \tag{17}$$

Therefore, the change rates $\dot{u}_{lin}$ are to be considered as the control variables in the optimal control problem formulation.

The reference trajectory generation forms an outer control loop. Therefore stability results from model predictive control are applicable. Conditions for guaranteed stability of the closed loop system under nominal conditions usually require stabilizing constraints of the state variables at the end of the optimization horizon together with a suitable evaluation of the final state [15]. This is approximated by a quadratic penalty term with symmetric, positive definite weighting matrix $\bar{\mathbf{Q}}$ which extends the original objective functional.

$$J = J_c + \frac{1}{2}\left(\mathbf{x}_{lin}(t_f) - \mathbf{x}_{lin,f}\right)^T \bar{\mathbf{Q}}\left(\mathbf{x}_{lin}(t_f) - \mathbf{x}_{lin,f}\right) \tag{18}$$

The continuous-time constrained linear-quadratic optimal control problem (14)-(18) is discretized on the grid

$$t_0 = t^0 \leq t^1 \leq \ldots \leq t^K = t_f$$

$$\begin{aligned} \mathbf{x}_{lin}^{k+1} &= \mathbf{A}^k \mathbf{x}_{lin}^k + \mathbf{b}^k u_{lin}^k, \quad k = 0, \ldots, K-1 \\ \mathbf{x}_{lin}^0 &= \mathbf{x}_{lin,0} \\ \mathbf{y}_{lin}^k &= \mathbf{C}_{lin}^k \mathbf{x}_{lin}^k, \quad k = 0, \ldots, K \end{aligned} \tag{19}$$

Here $\mathbf{x}_{lin}^k$, u^k, and $\mathbf{y}_{lin}^k$ denote the values of the respective variables in the grid points t^k. The matrices and vectors $\mathbf{A}^k$, $\mathbf{b}^k$, and $\mathbf{C}^k$ are obtained from $\mathbf{A}$, $\mathbf{b}$, and $\mathbf{C}$ via solution of the transition equation in $[t^k, t^{k+1}]$.

The objective functional (18) and the constraints (16), (17) are discretized accordingly.

In this way the continuous-time optimal control problem is approximated by a quadratic programming problem (QP) in the control and state variables $[\mathbf{x}_{lin}^k, u_{lin}^k]$ of the discretized problem which can be solved by a standard interior point algorithm [16], [17]. Within this algorithm, the structure of the discrete-time model equations (19) is utilized in a RICCATI-like approach to obtain a solution of the NEWTON step equation with $\mathcal{O}\left(K(m^3 + n^3)\right)$ operations, i. e. the computational effort grows linearly with the prediction horizon K and cubically with the number of control (m) and state (n) variables. For further details see [18], [19].

Non-uniform sample intervals $\Delta T^k = t^{k+1} - t^k$ within the prediction horizon of the MPC help to limit the dimension of the optimization problem. In this schema, the initial sample steps are determined by the trajectory generation loop and the length of the sample intervals increases linearly within the prediction horizon.

5 Measurement results

In this section, measurements of the boom crane LIEBHERR LHM 322 are presented. The rope length l_S is 57 m and the load mass is 3.5 t for all experiments. The flatness based nonlinear controller and the optimal trajectory generation is implemented on a rapid prototyping system dSPACE DS1103. The sample time of the model-based trajectory generation is 100ms.

Fig. 4 shows the load velocity given by the crane operator's hand lever and the optimized reference trajectory generated by the model-based trajectory generator. The upper bound for the load velocity depends on the radial load position. The acceleration constraint is $|\ddot{r}_{LA}| \leq 0.45\,\mathrm{m/s^2}$.

Fig. 5 compares this reference trajectory with the load velocity measurement. The flatness based controller tracks the reference trajectory and the trajectory generation compensates model uncertainties by planning a model based reference trajectory. This results in a fast and damped motion of the load with nearly no overshoot.

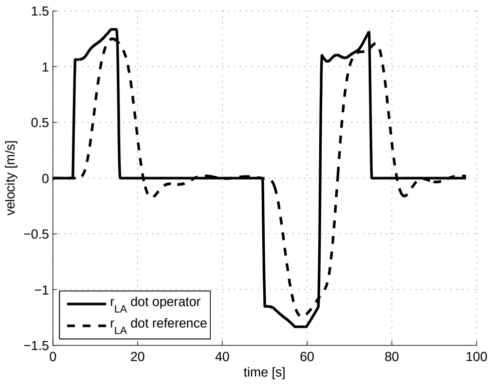

Figure 4: Load velocity reference trajectories.

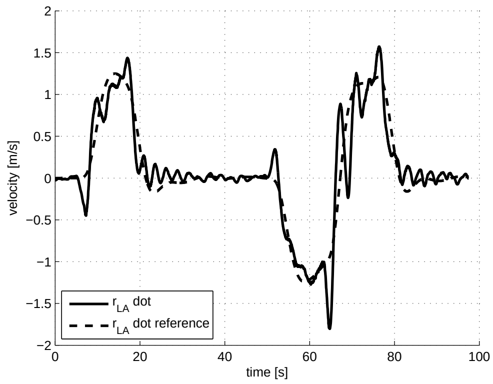

Figure 5: Load velocity: reference trajectory and measurement.

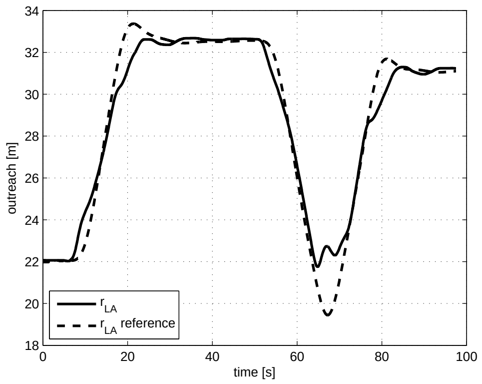

Figure 6: Load position: reference trajectory and measurement.

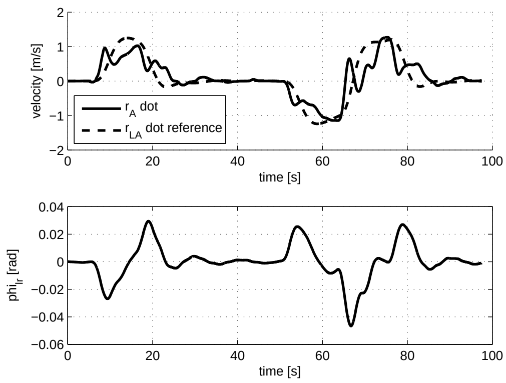

Figure 7: Radial rope angle φ_{Sr}.

The corresponding load position trajectories are shown in Fig. 6.

The control system damps the load sway by suitable compensating movements of the boom during and at the end of each maneuver. The resulting rope angle φ_{Sr} is less than 0.05 rad (≈3°), see Fig.7.

The actual calculation time for the online solution of the linear-quadratic optimal control problems is between 54ms and 66ms.

6 Conclusion

In this paper a nonlinear model for a rotary boom crane is developed utilizing the method of Newton-Euler. Dominant nonlinearities such as the kinematics of the hydraulic actuator (hydraulic cylinder) are considered. A nonlinear, flatness based controller is developed using a flat output that coincides with the load position for small rope angles. A model-based optimal trajectory generator provides feasible and sufficiently smooth reference trajectories. The optimal control problem to be solved online takes into account the linearized system including the state feedback as well as input and state constraints. The control system is implemented at the LIEBHERR harbor mobile crane to obtain measurement results. These results validate the exact tracking of the reference trajectory with reduced load sway.

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