Feedforward control of a crane manipulator

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Crane manipulators are appropriate for handling large and heavy payloads in space. The application standing behind the present investigation is three-dimensional cold forming of steel or aluminium plates by means of so-called ship building presses. For appropriate positioning of the workpiece under the press table it is suspended by four chain hoists of an overhead or gantry crane with two bridges each with two trolleys (Fig. 1a). The bridges, trolleys and chain hoists are independently controllable with coordinates y_i, x_{ij}, s_{ij}, $i, j \in \{1,2\}$ to achieve the desired workpiece position. Passive degrees of freedom are the sway angles φ_{ij}, ψ_{ij} of the chain hoist units that are swivel-suspended under the trolleys, the six rigid-body degrees of freedom of the plate due to the spring travels of the four lifting attachments and the sway motion of the plate and elastic plate deformations, in Fig. 1a described by the torsion coordinate w belonging to the shape function of a plate with four point-like supports. A basic task for crane control is to move the plate from a given rest position into another desired rest position without residual sway motions by means of synchronized actuation of the drives.

For the special case of a motion between two horizontal rest positions of the plate in y-direction at different heights z, the two bridge coordinates $y_i(t)$ as well as the four chain lengths $s_{ij}(t)$ are synchronized. Here the problem can be reduced to the control of the double pendulum (sway angles $\boldsymbol{\varphi} = [\varphi_1 \ \ \varphi_2]^{\mathrm{T}}$) shown in Fig. 1b. The upper pendulum body (length l_{H}, mass m_{H}, inertia moment θ_{H}) corresponds to the hoist units, and the lower mass-point pendulum represents load mass m_{L} with neglected chain mass. The overall pendulum length l_{C} is the sum of the chain length and the constant travel of the attachment springs in the static equilibrium. Dynamic travel of the springs during motion is neglected as it is assumed to be approximately decoupled from the sway motion. The trolley coordinate $y(t)$ and pendulum length $l_{\mathrm{C}}(t)$ are kinematically prescribed. The equations of motion of the system are

$$\mathbf{M}(\boldsymbol{\varphi},t)\,\ddot{\boldsymbol{\varphi}} = \mathbf{k}(\boldsymbol{\varphi},\dot{\boldsymbol{\varphi}},t) + \mathbf{B}(\boldsymbol{\varphi})\,\ddot{y} \tag{1}$$

with the explicit time dependence in $\mathbf{M}$ and $\mathbf{k}$ resulting from the prescribed function $l_{\mathrm{C}}(t)$.

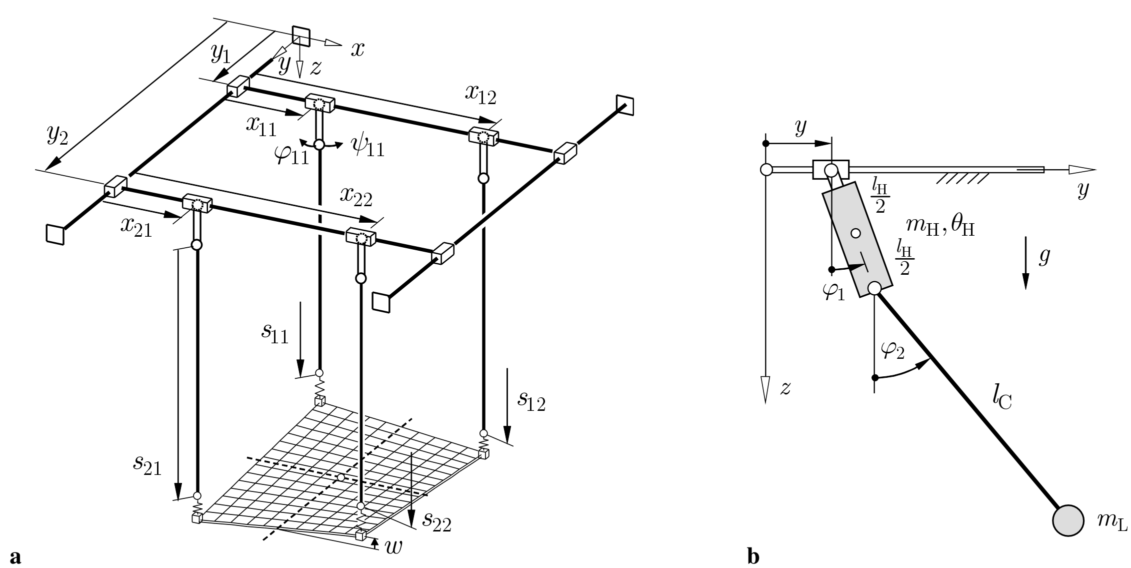

Fig. 1: Idealized crane models. **a** Crane manipulator with four chain hoists. **b** Double pendulum crane.

The objective is to find feedforward controls $y(t)$ and $l_C(t)$ that move the load mass within the time intervall $[0,T]$ from a rest position at $y_L(0) = y(0)$ and $z_L(0) = l_H + l_C(0)$ into a desired rest position at $y_L(T) = y(T)$ and $z_L(T) = l_H + l_C(T)$. Analysis of the equations of motion (1) shows that a flat output being much favourable for feedforward control design [1, 2] cannot be achieved due to the rotational inertia of the hoist units. This issue is also discussed in [3]. An approach for solving the control task that is relatively flexible with respect to the structure of the underlying equations of motion is described in [4]. Here a time trajectory of the actuated coordinate $y(t)$ is calculated in such a way that the boundary conditions

$$y(0) = 0\,, \quad \dot{y}(0) = 0\,, \qquad y(T) = y_T\,, \quad \dot{y}(T) = 0\,, \tag{2}$$

$$\boldsymbol{\varphi}(0) = \mathbf{0}\,, \quad \dot{\boldsymbol{\varphi}}(0) = \mathbf{0}\,, \qquad \boldsymbol{\varphi}(T) = \mathbf{0}\,, \quad \dot{\boldsymbol{\varphi}}(T) = \mathbf{0}\,, \tag{3}$$

according to the desired initial and final rest positions are fulfilled. Hereby a smooth transition of the pendulum length between the rest position values $l_C(t)$ from $l_C(0)$ into $l_C(T)$ is prescribed.

A solution is obtained by defining a shape function for $y(t)$ that fulfills the boundary conditions (2) and includes four additional design parameters p_i to fulfill the boundary conditions (3). A possible shape function is the polynomial form [4]

$$y(t) = \sum_{i=1}^{5} a_i \left(\frac{t}{T}\right)^i + \sum_{i=1}^{4} p_i \left(\frac{t}{T}\right)^{i+5}. \tag{4}$$

It fulfills the initial condition $y(0) = 0$ in (2) and contains five parameters $a_1, \ldots, a_5$ to meet the three other initial conditions in (2) and the additional conditions $\ddot{y}(0) = \ddot{y}(T) = 0$ in order to achieve continuous trolley acceleration at $t = 0$ and $t = T$. By this the parameters $a_1, \ldots, a_5$ are expressed in terms of the four remaining design parameters $p_1, \ldots, p_4$. These parameters are then determined in such a way that the equations of motion (1) with $\ddot{y}(t)$ expressed by the second-order time derivative of (4) fulfill the four boundary conditions in (3) at $t = T$. This boundary value problem is numerically solved by means of the Matlab function `bvp4c`. The trolley motion $y(t)$ and their time derivatives $\dot{y}(t)$, $\ddot{y}(t)$ are reference functions for the motion controller of the trolley.

For the parameters $l_H = 0.5\,\text{m}$, $m_H = 100\,\text{kg}$, $m_L = 200\,\text{kg}$, $\theta_H = 15\,\text{kg}\,\text{m}^2$, $T = 4\,\text{s}$, $y(T) = 0.1\,\text{m}$ Fig. 2 shows the time trajectories of trolley motion variables $y(t)$, $\dot{y}(t)$, $\ddot{y}(t)$, sway angles $\varphi_1(t)$, $\varphi_2(t)$ and pendulum length $l_C(t)$. The transition from $l_C(0) = 3\,\text{m}$ to $l_C(T) = 2.9\,\text{m}$ is interpolated by a prescribed smooth polynomial function.

While feedforward control is intended to contribute the major part of the control signal, model incertainties and disturbances are to be compensated by an additional feedback controller. Together with control of spatial motions this is part of ongoing work.

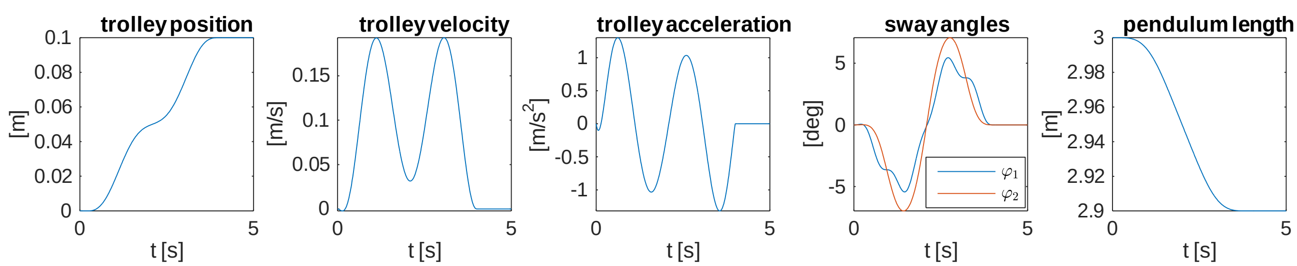

Fig. 2: Time trajectories of trolley motion variables $y(t)$, $\dot{y}(t)$, $\ddot{y}(t)$, sway angles $\varphi_1(t)$, $\varphi_2(t)$ and pendulum length $l_C(t)$.

References

[1] T. Heyden and C. Woernle, "Dynamics and flatness-based control of a kinematically undetermined cable suspension manipulator," *Multibody System Dynamics*, vol. 16, pp. 155–177, 2006.

[2] R. Seifried, *Dynamics of Underactuated Multibody Systems, Modeling, Control and Optimal Design*. Cham: Springer, 2014.

[3] R. Seifried and W. Blajer, "Analysis of servo-constraint problems for underactuated multibody systems," *Mechanical Sciences*, vol. 4, no. 1, pp. 113–129, 2013.

[4] K. Graichen, *Feedforward control design for finite time transition problems of nonlinear systems with input and output constraints.* Aachen: Shaker Verlag, 2006.