Feedforward Control of a Crane Manipulator with Four Load Chains

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Abstract

Metal sheets can be formed by means of a so-called ship building press in a cold plastic forming process. For positioning under the forming tool, the metal sheet is suspended by four chain hoists mounted on trolleys of an overhead crane with two bridges each with two trolleys. Bridges, trolleys and chain hoists are independently controllable to achieve the desired workpiece position. In addition to the flexibilty of the workpiece itself the four chain attachment points at the plate are flexible in order to isolate the crane gear from process forces.
For controller design a simple model of the flexible plate with one elastic degree of freedom η, describing only the torsional deflection of the metal sheet, is used. Compared to other occurring deflection modes of the sheet, the torsional mode is predominant for the suspension chain force distribution. The controller design model is schematically shown in **Fig. 1**.

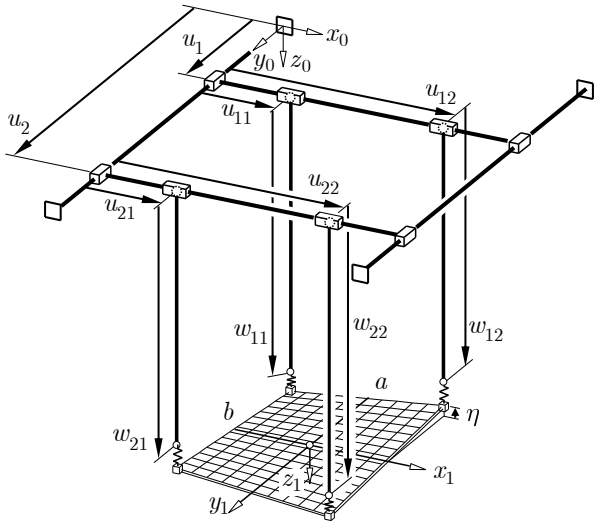

Fig. 1 Cable manipulator with four load chains suspending a flexible rectangular metal sheet.

The objective of the flatness-based control is to determine the actuator coordinates

$$\boldsymbol{u} = [u_1 \quad u_2 \quad u_{11} \quad u_{12} \quad u_{21} \quad u_{22}]^{\mathrm{T}} \quad \text{and} \quad \boldsymbol{w} = [w_{11} \quad w_{12} \quad w_{21} \quad w_{22}]^{\mathrm{T}} \tag{1}$$

of the crane in such a way that the metal sheet is moved between predefined rest positions without undesired sway motions. For this purpose, the dynamics of the system has to be taken into account. The position coordinates are summarised in the 7-vector

$$\hat{\boldsymbol{r}} = \begin{bmatrix} \boldsymbol{r}_1^{\mathrm{T}} & \boldsymbol{\varphi}^{\mathrm{T}} & \eta \end{bmatrix}^{\mathrm{T}} \tag{2}$$

as well as their time derivatives $\hat{\boldsymbol{v}}$ and $\dot{\hat{\boldsymbol{v}}}$. In [1] the nonlinear equations of motion of the crane manipulator were derived in the form

$$\boldsymbol{M}\dot{\hat{\boldsymbol{v}}} = \boldsymbol{k}^{\mathrm{c}}(\hat{\boldsymbol{v}}) + \boldsymbol{k}^{\mathrm{e}}(\hat{\boldsymbol{r}}, \boldsymbol{u}, \boldsymbol{w}) + \boldsymbol{k}^{\mathrm{el}}(\hat{\boldsymbol{r}}). \tag{3}$$

The mass matrix $\boldsymbol{M}$ and the generalised centrifugal and Coriolis forces $\boldsymbol{k}^{\mathrm{c}}$ from (3) have the structure

$$\boldsymbol{M} = \begin{bmatrix} m\boldsymbol{E} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\Theta}_1 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \frac{1}{9}m \end{bmatrix}, \qquad \boldsymbol{k}^{\mathrm{c}} = \begin{bmatrix} \boldsymbol{0} \\ -\tilde{\boldsymbol{\omega}}\boldsymbol{\Theta}_1\boldsymbol{\omega} \\ 0 \end{bmatrix}. \tag{4}$$

The vector of generalised external forces on the plate $\boldsymbol{k}^{\mathrm{e}}$ in (3) can be written as

$$\boldsymbol{k}^{\mathrm{e}} = \begin{bmatrix} \boldsymbol{k}_f^{\mathrm{e}} & \boldsymbol{k}_\tau^{\mathrm{e}} & \boldsymbol{k}_\eta^{\mathrm{e}} \end{bmatrix}^{\mathrm{T}}. \tag{5}$$

Here $\boldsymbol{k}_f^{\mathrm{e}}$ is the resulting force of the gravity force and the four suspension forces, $\boldsymbol{k}_\tau^{\mathrm{e}}$ is the resulting moment of the suspension forces and $\boldsymbol{k}_\eta^{\mathrm{e}}$ is the generalised force on the elastic coordinate η due to the suspension forces. The generalised elastic force of the plate $\boldsymbol{k}^{\mathrm{el}}$ is related to the bending stiffness of the plate K under consideration of its length a, width b as well as thickness h, Young's modulus E and Poisson's ratio ν [2],

$$\boldsymbol{k}^{\mathrm{el}} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & k_\eta^{\mathrm{el}} \end{bmatrix}^{\mathrm{T}} \quad \text{with} \quad k_\eta^{\mathrm{el}} = -c_{\mathrm{f}}\eta, \quad c_{\mathrm{f}} = \frac{32K(1-\nu)}{ab}, \quad K = \frac{Eh^3}{12(1-\nu^2)}. \tag{6}$$

The flatness property of the system is exploited to derive a feedforward control model. A flat system has the property that the state variables and control inputs can be algebraically expressed in terms of the so-called flat outputs and their time derivatives [3]. According to (1) and (2) there are ten independently controllable actuator coordinates but only seven position coordinates, the six rigid-body coordinates and the coordinate η describing the elastic degree of freedom of the plate. Thus, the problem is kinematically triple redundant. Technically advantageous solutions can be found by optimisation, for example by minimising the chain lengths.
A general movement in space and the results for the ten actuator coordinates are shown in **Fig. 2**. The metal sheet is moved along a desired trajectory within a given time interval, and the actuator coordinates are algebraically calculated from the equations of motion from (3).

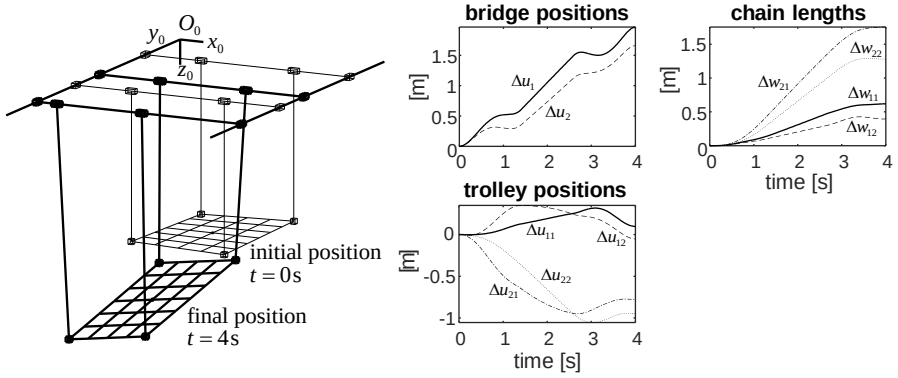

Fig. 2 Motion between rest positions and time trajectories of the actuator coordinates.

The realization of the feedforward controller on the basis of the nonlinear equations of motion requires the iterative solution of a nonlinear constrained optimization problem being computationally expensive and not directly suitable for implementation into a plant controller. Therefore the linearized equations of motion

$$\boldsymbol{M}\Delta\ddot{\boldsymbol{r}} + \boldsymbol{K}\Delta\boldsymbol{r} = \boldsymbol{H}_u\Delta\boldsymbol{u} + \boldsymbol{H}_w\Delta\boldsymbol{w} \tag{7}$$

with the actuator coordinates $\boldsymbol{u}$ (bridges and trolleys) and $\boldsymbol{w}$ (chain lengths) from (1) were formulated. They are obtained by successively linearizing all calculations during formulation of the nonlinear equations of motion (3).
The results for the actuator coordinates calculated from the nonlinear and also from the linearized equations of motion were transmitted to a Simpack multibody model of the crane manipulator. The system reaction on the determined actuator coordinates was satisfactorily simulated, resulting in only minor sway motions. A prototype system being under construction will be used for experimental validations.

Literatur

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