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Steering Control of Metal Strips Using a Pivoted Guide Roller

A. Steinboeck * **A. Kugi** †

* *Automation and Control Institute, Vienna University of Technology, Gußhausstraße 27-29, 1040 Vienna, Austria (e-mail: andreas.steinboeck@tuwien.ac.at)*

† *Christian Doppler Laboratory for Model-Based Control in the Steel Industry, Automation and Control Institute, Vienna University of Technology, Gußhausstraße 27-29, 1040 Vienna, Austria (e-mail: kugi@acin.tuwien.ac.at)*

Abstract: Controlling the lateral position of moving metal strips is a frequent task in the metal industry. For production lines with a guide roller at the entry, a dynamical model is developed and validated by measurements from an industrial plant. A reduced-order state observer is designed to estimate unmeasurable states. As the system is open-loop unstable, output-feedback controllers, state-feedback controllers, and a constrained model predictive controller are developed. Their performance is compared in a simulated example problem.

Keywords: Strip steering, lateral dynamics of moving web, double integrator, reduced-order observer, output-feedback control, state-feedback control, constrained model predictive control

1. INTRODUCTION

In the metal industry, lateral steering of metal strips is a frequent control task. For instance, it occurs in continuous strip processing lines and strip transport facilities. Paper making, printing, coating, and the production of printed electronic devices are other typical industrial applications, where lateral guidance of moving strips, often referred to as *webs*, is of central interest.

Shelton and Reid (1971a,b) provided a comprehensive analysis on modeling techniques for idealized and real moving webs. Here, the term *idealized* means that the material properties of the web are neglected and the web is considered as an inelastic membrane with zero shear stiffness and longitudinal fibres that are straight between the guide rollers. Modeling a *real* web means that the elastic properties of the material are taken into account. Hence, the web may undergo elastic deformation in the form of lateral bending (non-uniform stretch and bending of longitudinal fibres). Shelton and Reid (1971a) showed that the lateral beam bending problem (without consideration of shear deflection) can be analytically solved. The dynamical models of both idealized and real moving webs are linear and can be expressed by first- or second-order transfer functions.

Figure 1 shows the two most commonly used web steering systems, i. e., a remotely-pivoted guide and an offset-pivot guide (Seshadri and Pagilla, 2011). In the former case, only one guide roller (roll 2 in Fig. 1a) is pivoted. Elastic deformation of the strip occurs mainly between the two rollers adjacent to the pivoted guide (between rolls 1 and 3 in Fig. 1a). In the latter case (Fig. 1b), two guide rollers (rolls 1 and 2 in Fig. 1b) are carried by a pivoting frame. Elastic deformation of the strip occurs mainly in the vertical spans of the strip. Both systems are typically used as intermediate web guides, i. e., in continuous processing lines with uniform up- and downstream strip tension. The different situation shown in Fig. 2 is considered in this paper. There is no tension in the strip section upstream of the pivoted guide (roll 1 in Fig. 2), which is the first roll after a looping pit. Generally, this guide roller is connected to an electric drive that operates in generator mode. A pressure roll on top of the guide roller avoids or minimizes slip between the strip and the roll.

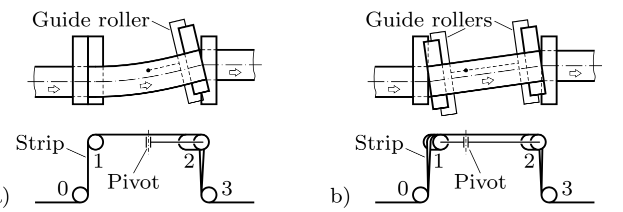

Fig. 1. Web steering systems, a) remotely-pivoted guide, b) offset-pivot guide.

Shin et al. (2004) used PI-control with and without disturbance feedforward for the second-order system of a real

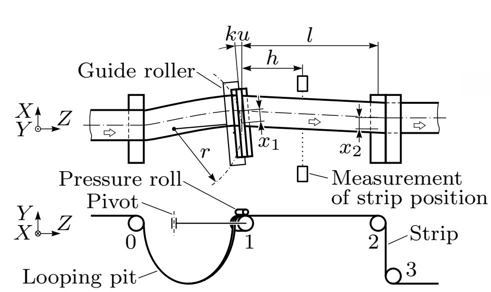

Fig. 2. Web steering systems after looping pit.

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moving web steered by an offset-pivot guide. For the same system, Ho et al. (2008) simulated the use of PID-control. Wang et al. (2005) used PI-control and a Smith predictor with PI-control for the second-order model with time delay of a real moving web steered by a pivoted roller. The time delay accounts for the spatial offset of a downstream position measurement. Seshadri and Pagilla (2011) argued that fixed gain controllers are not suitable for systems with unknown or changing model parameters. Hence, they proposed an adaptive controller for web guiding systems based on a generic second-order reference model. This controller can be used for both offset-pivot guides and remotely-pivoted guides but requires several design parameters to be tuned. Seshadri and Pagilla (2011) conducted laboratory experiments for this parameter tuning process.

All models and control solutions mentioned so far are parameterized in terms of the time. If the longitudinal velocity of the web varies, these models are thus time-variant, which implies that control parameters have to be updated, e. g., by gain scheduling (Wang et al., 2005) or adaptive control (Seshadri and Pagilla, 2011). Schulmeister and Kozek (2009) presented a dynamical model of the lateral position of an endless steel strip, i. e., a process belt, where the strip traveling distance rather than the time is used as an independent variable. The advantage of such a *time-free* formulation is that it is invariant with respect to changing strip velocities. Therefore, this time-free formulation is also used in this paper.

In most published models, the strip tension is considered to be uniform along both the up- and downstream direction and the lateral position at upstream rollers (e. g., roll 0 in Fig. 1) is assumed to be a known system input. The configuration considered in this paper (cf. Fig. 2) is different: The lateral position at roll 0 is unknown and irrelevant. The strip tension varies from zero in the looping pit to full tension after roll 3.

Another fundamental assumption of most published models of moving webs is zero slip between the web and the guide rollers. However, it is not clear whether the zero-slip assumption is tenable for the longitudinal direction if the shear and the lateral bending stiffness of the moving web is high, which is characteristic for wide metal strips.

In view of the existing strip steering solutions and the special requirements of strip steering after a looping pit (cf. Fig. 2), the objective of the current paper is to develop a mathematical model and controllers for the lateral strip position of the considered system. The paper is organized as follows: In Section 2, a dynamical model of the system is derived, parameterized, and validated. A state observer and various controllers are designed in Sections 3 and 4, respectively. The control performance is demonstrated in an example scenario in Section 4.

2. IDEALIZED LATERAL STRIP MOTION

Consider the web steering system outlined in Fig. 2. The angular position ku of the pivoted entry roller is controlled by a hydraulic cylinder, which has the position u. Here, k is a geometric constant. Subordinate control loops are considered as ideal and u is a system input. The steering system should ensure that the strip enters the downstream section of the processing line at a laterally centered position.

2.1 Mathematical Model

A dynamical model of the lateral strip position is developed based on the following assumptions for the strip section between the rollers 1 and 2 in Fig. 2:

- A1) The strip has a flat and wrinkle-free shape.
- A2) The centerline of the strip (dash-dotted line in Fig. 2) rolls over the guides 1 and 2 without slip at the upper vertices. All other points of the strip may experience slip along the direction Z as they pass these vertices.
- A3) The centerline of the strip is straight.
- A4) Acceleration forces and lateral vibrations are negligible, i. e., a purely kinematic model is considered.
- A5) For the angular position of the guide roller, $|ku| \ll 1$ holds. The lateral displacement of the strip is small compared to $\min\{r, l\}$. Hence, geometrically linear relations can be used and displacements of the center point of the guide roller along the direction Z can be neglected.

In particular, assumption A2) is different compared to existing models of moving webs (cf. Section 1). Assumption A2) seems reasonable because of the tensile force in the strip, the effect of the pressure roll, and the high stiffness of the strip against shear and lateral bending.

The distance between the center point of the guide roller and the pivot axis is $r = 2.06\,\mathrm{m}$. The rolls 1 and 2 have the longitudinal distance $l = 4.14\,\mathrm{m}$. The lateral strip position y at a distance $h = 1.68\,\mathrm{m}$ from the guide roller is the system output and is optically measured.

Let w be the accumulated strip length, which serves as the independent variable of the dynamical model (instead of the time t). Derivatives with respect to w are abbreviated in the form $(\cdot)' = \mathrm{d}(\cdot)/\mathrm{d}w$. The lateral distances between the centerline of the strip and the center points of the rolls 1 and 2 serve as system states $x_1(w)$ and $x_2(w)$, respectively, and are assembled in the vector $\boldsymbol{x} = [x_1, x_2]^T$. Whenever confusion is ruled out, the argument w is omitted. The centerline of the strip between the rolls 1 and 2 and the axis Z span the angle $(x_2 - (x_1 + rku))/l$, which is equivalent to $-x_2'$, i. e., the negative change of x_2 per unit accumulated strip length. Similarly, the rate of change of x_1 is equivalent to the angle $ku + (x_1 + rku - x_2)/l$. Hence, the state-space representation of the dynamical model follows in the form

$$\boldsymbol{x}' = \frac{1}{l}\begin{bmatrix} 1 & -1 \\ 1 & -1 \end{bmatrix}\boldsymbol{x} + \frac{k}{l}\begin{bmatrix} r+l \\ r \end{bmatrix} u \qquad \forall\, w > 0 \tag{1a}$$

with the initial state $\boldsymbol{x}(0) = \boldsymbol{x}_0$ and the output equation

$$y = \frac{1}{l}\,[l-h \;\; h]\,\boldsymbol{x} + \frac{rk}{l}(l-h)u. \tag{1b}$$

This system is linear, independent of the strip velocity $\mathrm{d}w/\mathrm{d}t$, and invariant with respect to w. The system features direct feedthrough and its transfer function

$$\frac{\tilde{y}(\bar{s})}{\tilde{u}(\bar{s})} = \frac{((l-h)\bar{s}+1)(r\bar{s}+1)k}{l\bar{s}^2} \tag{2}$$

shows that it is a double integrator, i. e., it is unstable. In (2), $\tilde{}$ labels a signal in the continuous Laplace domain and $\bar{s} \in \mathbb{C}$ is the Laplace variable with the unit 1/m.