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Robust control of piecewise linear systems: A case study in sheet flow control ☆

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Abstract

This paper presents a control design approach for robust sheet control in a printer paper path. By splitting up the control problem into low level motor control loops and a high level sheet control loop, a hierarchical control structure is obtained. Based on the piecewise linear model of the high level sheet dynamics, the control design is formulated in the H_∞ framework. The resulting dynamic output feedback controllers guarantee stability and performance of the closed-loop system. To show the effectiveness of the control design approach in practice, the robust sheet controllers are successfully implemented on an experimental paper path setup.

Keywords: Piecewise linear systems; Hierarchical control; Robust control; Linear matrix inequalities

1. Introduction

High productivity and good printing accuracy are two of the main requirements for high volume cut sheet document handling systems. One of the dominating factors in satisfying these requirements is the reliable transportation of the sheets through the paper path. An example of such a paper path is shown in Fig. 1. Sheets enter the paper path at the paper input module, here referred to as PIM. After the sheets have been transported through the preheater units to obtain the desired temperature required for printing, the sheets go to the image transfer station (ITS) where they meet their corresponding images. For the purpose of backside printing, sheets can re-enter the paper path via the so-called duplex loop. Eventually, sheets are transported to the finisher (FIN) where they are collected. The transportation of the sheets is realized via so-called pinches. These pinches consist of a driven roller and a non-driven roller. The task of the non-driven roller is to apply sufficient normal force in order to prevent the sheet from slipping in the pinch. As can be seen from Fig. 1, these pinches can either be driven by one motor individually or they can be grouped into sections.

In order to achieve a good printing quality, the sheet transportation system must deliver the sheets on time at the ITS and maintain the right sheet velocity in order to prevent misplaced or blurred images. In today's cut sheet printers the transportation of the sheets mainly relies on event-driven closed-loop sheet control in combination with time-driven closed-loop motor control. Together with a high precision mechanical design with small manufacturing tolerances, this ultimately results in a predictable sheet flow. At discrete points in the paper path, i.e. where the optical sheet sensors are located, the presence of a sheet is detected. Based on this information, the reference velocities of the motor can be adjusted in order to correct for possible errors. A drawback of this event-driven closed-loop sheet

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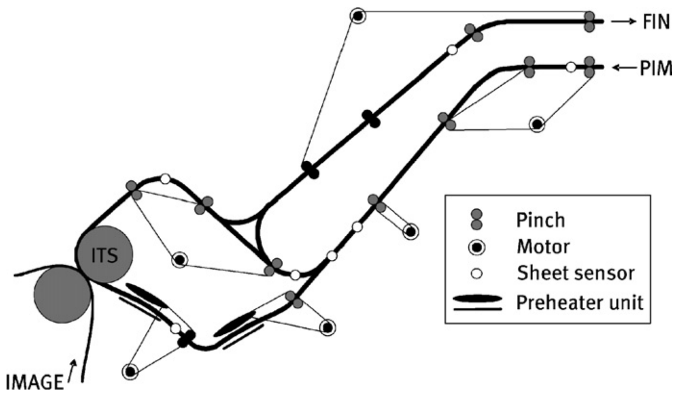

Fig. 1. Example of an industrial printer paper path.

control approach is the limited robustness against uncertainties and disturbances. Furthermore, high precision mechanics are needed to obtain the desired predictability in the sheet flow, which leads to a relatively high cost of goods. An alternative for tackling the sheet feedback control problem is to exploit the power of closed-loop sheet feedback control (Bukkems, de Best, van de Molengraft, & Steinbuch, 2006; Bukkems, 2007; Cloet, 2001; Kruciński, 2000; Rai, 1998). In the closed-loop approach, the tolerances in the mechanical design are allowed to be larger, since in this case active sheet feedback control is used to react on disturbances and uncertainties present in the printer paper path. To implement sheet feedback control, it is necessary to have knowledge of the sheet position. This can, for example, be realized by adding (cheap) position sensors, possibly in combination with model-based observer techniques.

The design of closed-loop sheet feedback control is mostly based on dynamic paper path models. In Cloet (2001) and Kruciński (2000), the dynamics are split up into low level section dynamics and high level sheet dynamics. The section dynamics map the motor currents to the angular velocities, implying that these dynamics are basically described by integrators. The high level sheet dynamics map the section velocities to the sheet position, which is described by a switching integrator. The combination of the finite state machine describing the sheet dynamics and the integrators describing the section dynamics leads to a hybrid dynamic model, and the control problem is formulated in a hybrid hierarchical control setup, in which the spacing between the sheets is controlled. However, in Kruciński (2000) and Cloet (2001) the control design is based on intuition and verified only by simulation. Stability of the closed-loop system is not proven and disturbances and uncertainties present in the printer paper path are not taken into account in the proposed control design.

In this paper a model-based feedback control design procedure is proposed that does guarantee stability and performance of the closed-loop system subject to disturbances and uncertainties. As in Cloet (2001) and Kruciński (2000) the control problem is split up into two levels, namely in low level motor control loops and a high level sheet control loop. For the control design of the high level sheet controller the low level motor control loops are assumed to be ideal. As a result, the high level sheet dynamics are described by switching integrators, which will be formulated in the piecewise linear (PWL) modeling formalism (Heemels, Schutter, & Bemporad, 2001; Sontag, 1981). As such, the control problem at hand is transformed into a tracking control problem for PWL systems. An H_∞, or more precise, an $\mathscr{L}_2$ gain approach will be adopted to tackle this problem. Known results from literature regarding H_∞ control of piecewise affine systems can be found in Rantzer and Johansson (2000) and Feng (2002a), in which *state* feedback controllers are used. Extensions for controlling *uncertain* PWL systems via state feedback are presented in Feng (2002b) and Chen, Zhu, and Feng (2004). In this paper, extensions of these existing works will be presented and apply these within the sheet feedback control application. The first contribution is a controller synthesis technique that is based on *output* feedback as opposed to the results in Feng (2002b), Chen et al. (2004), Rantzer and Johansson (2000) and Feng (2002a), that all are based on state feedback. In particular, for carrying out the controller synthesis, LMI-based approaches for linear systems known in literature, e.g. Gahinet and Apkarian (1994), Gahinet (1996) and Scherer, Gahinet, and Chilali (1997), are extended to the PWL case. Secondly, frequency domain weighting filters will be used (as commonly used in the linear case) to shape the closed-loop dynamics of the PWL sheet flow model. The novelty here lies in the fact that this is the first paper in which the classical linear H_∞ loop shaping techniques (Skogestad & Postlethwaite, 2005) using weighting filters is combined with stability and performance requirements for the overall PWL system. Allowing for frequency dependent weighing of the performance variables, defined in the sheet feedback control problem as the weighted sheet tracking error or the weighted sheet position, in combination with the weighted controller output, is important because performance can now be enforced where it is needed most. Moreover, with the use of weighting filters, an ability is created to include additional dynamics in the controller, like for example a high frequency roll-off for the individual subsystems. The third contribution of this paper is the practical demonstration of the control design theory. Experiments will confirm the robustness for parametric model uncertainties of the closed-loop PWL system. It will be shown that the desired tracking performance is realized using the presented control design approach.

The remainder of this paper is organized as follows: in Section 2, the system under consideration will be discussed in more detail and the problem statement will be given, together with the control goal. In Section 3, the nominal control design approach (without uncertainties) is discussed, whereas in Section 4 the control design is presented in case the uncertainties are included. In Section 5, the experimental setup, that is used to validate the proposed control design will be discussed. The results of these experiments are given in Section 6, which at the end are followed by the conclusions and recommendations.