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Simultaneous analysis and design based optimization for paper path and timing design of a high-volume printer[☆]

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ABSTRACT

The design of a high-volume printer for professional use is rather complex. The design of the paper path and the timing of sheets is frequently reengineered as the design of the printer components progresses. This paper presents an optimization model for the combined paper path and timing design problem. The paper path is an optimal physical dimensioning problem, while the timing is an open-loop optimal control problem. The coupled optimization problem is formulated as a simultaneous analysis and design (SAND) problem using a direct transcription of the optimal control problem. Benefits of the chosen formulation for industrial application are the ease of setting up the optimization model for arbitrary printer configurations, and the short computation times. Results of an industrial case are presented.

1. Introduction

A printer is an electromechanical device capable of transferring an image to a sheet of paper. Various types of printers are on the market, ranging from printers for home use to high-volume printers for professional applications. This paper considers the design of a high-volume printer. In particular, an optimization model is developed to support the design of the, so-called, paper path and timing for such a printer.

Inside the printer, sheets are transported through a metal track. Along their route through the track, sheets visit several modules, which typically includes a paper input module, an image transfer station, a turn track for duplex (two-sided) printing, and a finisher. The paper path represents the physical layout and dimensioning of the metal track with the various printer modules. The timing is the envisioned position of sheets along the paper path with respect to time.

Design of the paper path and timing is a coupled problem. A change in the design of the paper path affects the timing. The other way around, a change in timing typically requires the paper path to be re-designed. This leads to a lot of rework due to the constant changing design in the early phases. Moreover, many changes are induced due to the multidisciplinarity of the design of a printer: each discipline introduces their own specific requirements. All in all, this leads to a highly iterative design process. Creating a paper-path layout with accompanied timing typically takes a lot of time.

A model-based engineering approach may be taken to address this challenge. For instance, Cloet et al. [1] developed a computational model to calculate collision free transportation of sheets through the paper path, assuming simplex (one-sided) printing and homogeneity of the print job, i.e. every paper sheet excites the same dynamics shifted in time. Kruciński [2] and Bukkems et al. [3] addressed media path design and related control challenges in the context of high-speed printers, including single and multiple print engine systems. Additionally, Beckers et al. [4] and Heemels and Muller [5] presented a model that enables the visualization of the flow of papers along the paper path. Given a paper path and timing, the paper flow can be simulated and inspected for possible collisions. Stamps et al. [6] studied the timing design for duplex printing jobs, assuming homogeneity of the print job. They developed a numerical optimization model that includes the duplex printing cycle and the merging of the stream of paper sheets from the duplex loop with the input stream.

Also in other engineering domains, literature may be found that considers related problems. For instance, Cao et al. [7] investigated model-predictive control for the path generation of merging automated vehicles. The vehicles on the ramp merge with the vehi-

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cles on the main road. The method is intended for online vehicle collision avoidance. The focus of timing design for printers is different: one seeks the timing of each sheet such that system performance (e.g. paper throughput) is maximized while guaranteeing that sheets do not collide.

The timing design problem in the printer relates to trajectory optimization in the field of optimal control (open-loop control). For instance, see Betts [8] for an overview of algorithms for trajectory optimization problems. Balesdent et al. [9] present a survey of multidisciplinary optimization (MDO) methods in launch vehicle design, where trajectory optimization is one of the disciplines. They compare various single-level and multi-level MDO methods for application in the launch vehicle design. Herein, single-level refers to centralized optimization, and multi-level to distributed decision making. For classifications of single-level and multi-level MDO methods, one is referred to Cramer et al. [10], Balling and Sobieszczanski-Sobieski [11], Alexandrov and Lewis [12], Tosserams et al. [13], De Wit and Van Keulen [14], and Martins and Lambe [15]. Allison and Herber [16] review MDO methods specifically for dynamic systems design. They advocate the development of dedicated MDO methods for dynamic systems with balanced consideration of physical and control system design. Examples of papers developing methods for the optimal design and control codesign problem in the context of mechatronic systems design include Ravichandran et al. [17], Affi et al. [18], and Peters et al. [19].

We aim to develop an optimization model for the combined design of the paper path and the timing. Given the application in industry, it is required that the optimization model can be solved using off-the-shelf optimization software. Preferably in an environment such as MATLAB. Solving times of the optimization runs are preferably small to allow rapid prototyping. What is more, the model setup should be such that the paper path configuration can be easily adjusted. This paper describes the model that we have developed.

The timing design is viewed as an open-loop optimal control problem, while the paper path design is a physical system optimal design problem. The key concept in our model development is to treat the coupled system in an all-at-once fashion by incorporating a direct transcription of the optimal control problem Betts [8], Hargraves and Paris [20], Biegler [21] into a simultaneous analysis and design (SAND) formulation of the combined paper path and timing design problem Allison and Herber [16], Haftka [22], Arora and Wang [23]. That is, the equations of motion are discretized and included as algebraic equality constraints, while the decision variables include the physical lengths of the segments of the paper path, the state variables due to the discretized equations of motion, and the control input variables (segment accelerations). This is a different approach compared to the commonly employed nested analysis formulation (NAND) which defines the paper path dimensions and the segment accelerations as decision variables. For each evaluation of the objective function the state variables follow from a nested solution of the equations of motion.

The SAND formulation allows the modular setup of the optimization model for arbitrary paper path configurations; the optimization model can be assembled from the components given a certain paper path configuration. This presents a significant advantage compared to Stamps et al. [6], where a NAND approach was used. With this specific method, a new configuration required a new model to be derived.

The paper is organized as follows. First, the design problem is described. Subsequently, the optimization problem is formulated, which includes the mathematical representation of the various paper path components and the accompanying derivation of design goals, design constraints, and state equations. Then, the industrial case is presented to demonstrate the model-based optimization framework. Finally, some concluding remarks are offered.

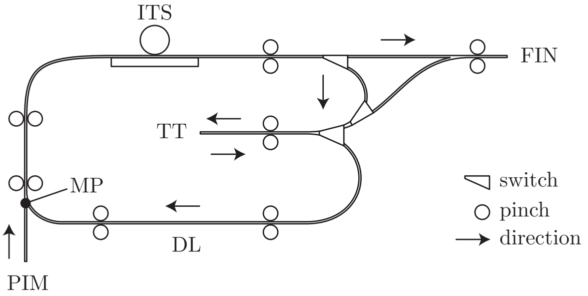

Fig. 1. Schematic layout of a paper path.

2. Design problem

The paper path and timing are leading in the design of the various components that make up the printer. The design of the paper path and the timing is frequently revisited. In this section, the paper path and timing design problem is explained in further detail.

2.1. Paper path

The paper path of a printer is defined as the path sheets can follow in the printer. The paper path comprises the various components that perform actions on the sheets. Generally, a paper path includes a track, an *image transfer station* (ITS), a *turn track* (TT), multiple switches, and numerous pinches. In some printer configurations also a cooling station is included, after the ITS.

In Fig. 1, a typical paper path is depicted. Sheets are fed to the paper path by means of a *paper input module* (PIM), via a standardized interface. The sheets move inside the metal track, where pinches actuate the sheets by means of frictional forces. Pinches can either be controlled as a group or individually. If pinches are coupled, the same velocity must be imposed by each pinch in the same group. At intersections, switches are used to guide sheets into a specific direction.

The (digital) image is transferred to one side of the sheet at the ITS. This is typically done at a pre-defined constant velocity, to achieve high quality prints and prevent smudging. In the case that both sides are to be printed, in a two-sided (duplex) job, a sheet passes the ITS two times. To this end, sheets are reversed (turned) in the turn track and guided to the *duplex loop* (DL). The stream of sheets from the duplex loop is merged with the stream of sheets from the paper input module at the *merge point* (MP).

After the printing process for a sheet is finished, the sheet leaves the paper path via another standardized interface to the *finisher* (FIN). The finisher can be any external module, which post-processes sheets or stores sheets.

2.2. Timing

The timing is the envisioned displacement of the leading edge of a sheet with respect to time. Each sheet has, in general, its own characteristic timing, as the properties of sheets may differ. However, it is assumed that every sheet has the same size and the same timing, shifted in time, i.e. a homogenous job.

The determination of the timing can be viewed as the offline calculation of the optimal time-displacement profiles of subsequent sheets to achieve maximum printer performance (open-loop optimal control problem).

In Fig. 2, an exemplary timing is (partially) given for three sheets. The solid lines represent the position of the leading edge of a sheet. The dashed lines represent the position of the trailing edge of a sheet. The combination of a solid and dashed line of one particular color, represents the timing of one sheet. The green, shorter,