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Model-based feedforward register control of roll-to-roll web printing systems

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ABSTRACT

Roll-to-roll (R2R) printing press provides a continuous printing process to print the multi-color patterns onto a web. To correctly print patterns on webs without the register error, it is necessary to regulate the web tension and transport velocity. In this paper, a mathematical model is built for R2R web printing system, and a model-based feedforward PD (MFPD) control method is proposed to reduce the effects of interaction in adjacent print units whose print cylinders are driven by electrical line shafts and is compared with other control methods. The proposed control method is applied to an industrial 7-color gravure printing register system. The register error can be controlled in the range of ± 0.1 mm at a steady high speed, which meets the requirement of modern industrial application.

1. Introduction

Roll-to-roll (R2R) printing press is a multi-axis system which offers support, transport and control for elastic material in a continuous, flexible strip form, called “web”, such as plastics, film, belt, foil, and fabric. The R2R printing press has been widely applied in film processing, newspaper pressing, web printing and so on since it allows mass production with high speed and low cost (Dong, Lévine, Jo, & Choi, 2013). Print registration in a printing process is to align successively print patterns on the material to ensure the print quality through appropriately controlling various web handling variables, such as web transport velocity, web tension, web strain, etc. (Seshadri & Pagilla, 2013; Seshadri, Pagilla, & Lynch, 2013). The register error is the position misalignment between the two adjacent overlapped patterns. Product with acceptable register error shall be classified as conforming product, otherwise it will be classified as nonconforming product. The example of register error is given in Fig. 1 to illustrate a properly and an improperly registered print pattern.

In order to produce an eligible product, the web requires successive and appropriate spacial positioning through accurate angular synchronization of print cylinders. The accurate angular synchronization, namely register control, depends on the transport conditions, web tension, web material properties and machine installation properties, such as web transport velocity, roller size and span length between rollers. The register control makes use of the regulation of web tension and web transport velocity to decrease the register errors. In this paper, the transport velocity and web tension is regulated by gravure cylinders.

Nowadays, traditional proportional derivative (PD) approach and the operators' experience are adopted in register control in industrial application, which cannot achieve the satisfactory performance (Koc, Knittel, De Mathelin, & Abba, 2002). With faster printing speed and higher printing precision required in modern industrial factories, it is necessary to develop a new control method to solve the coupling, time delay and nonlinear problems (Choi, Thanh, & Kim, 2009). Much research has been done to build dynamic mathematical models of R2R web register systems and to develop control methods on basis of the models. Whitworth and Harrison proposed a dynamic model to predict the change of span tension, which formed the basis for almost all the subsequent work on span tension dynamics (Whitworth & Harrison, 1979). Lynch et al. designed an online nonlinear tension observer for web machines (Lynch, Bortoff, & Röbenack, 2004). Some web tension control methods were proposed in Fletcher (2010), Lee, Kang, and Shin (2012), and Kang, Lee, Shin, and Kim (2011). Pagilla et al. put forward a dynamic model for R2R web processing lines, and designed a decentralized state feedback controller for the regulation of web velocity and tension (Pagilla, Siraskar, & Dwivedula, 2007). It improved the regulation performance of web tension compared

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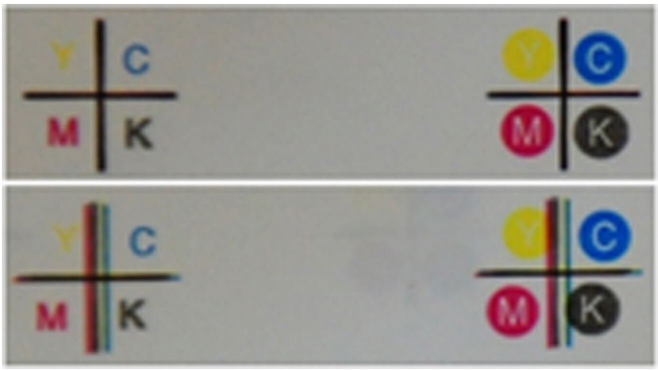

Fig. 1. Example of a properly (up) and an improperly(down) registered print pattern.

with existing industrial decentralized proportional-integral (PI) strategy. A dynamic tension compensation method was proposed to use in the unwind process (Shi & Zheng-Bing, 2011). Considering the existence of non-ideal rollers, a control algorithm of web tension and velocity was proposed in Branca, Pagilla, and Reid (2012), which could predict the periodic oscillation of the web tension and velocity and help to observe the dynamics of the system. Moreover, Hur et al. built a mechanical model for the R2R plastic film system and proposed a model-based Cross-Directional (CD) controller which improve both dynamic and static performance of the system (Hur, Katebi, & Taylor, 2011). Koc et al. applied a robust control and a linear parameter varying (LPV) strategy to control the tension and velocity of elastic materials (Koc et al., 2002). Abjadi et al. proposed a sliding-mode feedback linearization method for a multi-motor web-unwinding system and a robust nonlinear tracking controller (Abjadi, Soltani, Askari, & Markadeh, 2009). Benlatreche et al. presented multivariable controllers with one or two degrees of freedom (DOF) to improve the tracking and anti-disturbance performance (Benlatreche, Knittel, & Ostertag, 2008). However, register control is not researched directly in these works.

For multi-axis printing systems, since it involves the continuous multi-stage R2R printing, it is necessary to design longitudinal closed-loop control strategy to reduce register error with high precision (Choi et al., 2010; Yoshida, Takagi, Muto, & Shen, 2011). Early work on mechanical models describing the longitudinal dynamic characteristics of the elastic materials was found in Whitworth and Harrison (1979). Pagilla and Knittel gave an overview of the longitudinal control technology (Pagilla & Knittel, 2005). To avoid complicated math equations, Xin and Hoang used position and vision sensor to measure the longitudinal displacement and adopted a fuzzy logic for the longitudinal closed-loop control (Xin & Hoang, 2011).

However, the work mentioned above do not involve the register control of the coupled R2R system. Jeon et al. proposed a decoupling controller for bridle rolls of the steel mill drive system, and it was proved to be valid in controlling the tension and speed of metal strip without any coupling effects (Jeon, Kim, Jung, Sul, & Choi, 1997). Since the dynamic characteristics of the speed and tension of bridle rolls of steel mill drive system are quite different from the R2R web printing systems, this decoupling controller is not applicable in R2R systems. In Yoshida, Takagi, Muto, and Shen (2008a), analyzed the dynamic characteristics of R2R register system at low steady speed,developed mathematical models of web tension and register error, and presented a crude decoupling PD control approach. Although its register accuracy was somewhat improved compared with PD approach, the register error could not be completely compensated since only the coupling of the adjacent printing units is considered in this approach, so it would bring additional disturbance to subsequent print units. A nonlinear control method was proposed in Yoshida, Takagi, Muto, and Shen (2008b). And this method had some effect on reducing register error caused by the coupling effect, but it required on-line tension data, which could not be provided in practice because of high cost and installation difficulties. Similar with Yoshida et al. (2008b), Choi et al. presented a nonlinear feedback controller based on the assumption of existence of a lot of tension sensors (Choi et al., 2010). The method had good performance in fast computation and register accuracy, but it was also difficult for industrial application since the controller parameters searched by genetic algorithm were sensitive to initial value and required high-performance computing devices. Moreover, as the number of printing units increases, the coupling complexity of this method increases greatly.

In recent years, more and more R2R systems are driven by electrical line shafts instead of traditional mechanical shafts, especially for printed circuit production. In hybrid roll-to-roll printing systems which combine gravure and inkjet printing, a mathematical modeling of the register was derived in Kang and Baumann (2014). For the implementation of multilayered flexible printed circuitries through the R2R mass production, a high resolution of register control should be achieved to prevent electrical leakages and short circuitries. The mathematical models of machine directional (MD) register and cross direction register and control methods were suggested in Kang, Lee, and Shin,.. (2013) and Kang, Lee, and Shin,..... (2010), the effect of tension was discussed in Kang and Lee (2015), and the dynamic model of thermal characteristic of register was analyzed in Lee, Shin, and Lee (2015).

Because the motors of electrical line shafts are driven individually and synchronized electrically, the register control performed upstream leads to register error and tension fluctuation downstream. The position difference with respect to the downstream cylinders changes with upstream position difference. In this paper, a Model-based Feedforward PD (MFPD) control algorithm is proposed to reduce register fluctuations downstream. The upstream control input is fed forward and register fluctuations is compensated by the model-based feedforward control. A new concept "decoupling depth" is introduced to quantify the number of print units with register control performed upstream. The proposed control method is applied to a 7-color gravure printing press. According to the industrial application, the proposed method can quickly eliminate the initial error and reduce register fluctuations downstream efficiently.

2. Mechanical model

The technological nomenclature used in this section and following sections can be referred in Table 1.

The structure of R2R web printing system is shown in Fig. 2. There are three sections in the R2R system, including the infeed section, multi-color printing section and the outfeed section. Each gravure cylinder corresponding to a color is driven by an individual motor and all motors are required to be electrically synchronized. Driven by the unwind motor, the web enters the infeed section and the tension is controlled. When the web goes into the multi-color printing section, it is compressed between the impression roll and gravure cylinder, a pattern and its color mark will be printed on the web. Register errors are measured by a registration sensor. Then the web is dried in the bake oven before entering the next printing unit. After all colors are printed, the web enters the outfeed section.

The two adjacent printing units in R2R web system are shown in Fig. 3, in which T_i and l_i represent web tension and web length between the No. i and the No. $(i+1)$ gravure cylinder respectively,