COMPARISON OF CONTROL STRATEGIES FOR ROLL-TO-ROLL PRINTING PRESSES

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ABSTRACT

Flexible printed electronics is touted to be a significant part of the future of the roll-to-roll (R2R) printing industry. Electronic devices, such as RFID tags, low-cost displays and lighting devices, polymer solar cells, sensors, etc., can be manufactured on a flexible substrate using roll-to-roll machines. In recent years there has been a significant focus towards printing electronics on a flexible substrate using R2R printing methods. These studies have primarily dealt with the feasibility of printing electronic components such as thin metal lines, electrodes, capacitors, thin film transistors, etc., on the flexible substrate. In order to realize the goal of low cost printing of electronics on a flexible substrate using R2R techniques, the web handling aspects related to R2R printing have to be addressed adequately. This paper focuses on the web handling aspects related to R2R printing by analyzing the print registration process using mathematical models and by studying control schemes to improve print registration.

NOMENCLATURE

$\dot{(\ )}$	Derivative with respect to time
δ_{v_q}	Relative surface velocity between impression roller and q^{th} print cylinder
ϵ_1, ϵ_2	Web strain in spans upstream and downstream of print cylinder 1
ϵ_{21}	Strain difference between the downstream and upstream spans of a print cylinder ($\epsilon_2 - \epsilon_1$)
$\tilde{\epsilon_i}$	Strain above/below nominal strain
γ_{1_q}	Doctor blade contact angle at q^{th} print cylinder
θ_1, ω_1, r_1	Angular position, velocity and radius of print cylinder 1
θ_2, ω_2, r_2	Angular position, velocity and radius of print cylinder 2
θ_m, ω_m	Angular position and velocity of print section motor
θ_q, ω_q	Angular position and velocity of common shaft at q^{th} position
$\theta_{pr_q}, \omega_{pr_q}$	Angular position and velocity of q^{th} print cylinder
$\theta_{dr_q}, \omega_{dr_q}$	Angular position and velocity of q^{th} doctor blade crank arm
ω_{Im_q}	Angular velocity of q^{th} impression roll
τ_1	Time constant for the web to travel from upstream print cylinder to downstream print cylinder
τ_2	Time constant for the web to travel from compensator roller to downstream print cylinder
b_{dr_q}, J_{dr_q}	Viscous friction and moment of inertia of q^{th} doctor blade crank arm
b_{Im_q}, J_{Im_q}	Viscous friction and moment of inertia of q^{th} impression roll
b_{pr_q}, J_{pr_q}	Viscous friction and moment of inertia of q^{th} print cylinder
e_r	Registration error
E	Modulus of elasticity of web
F	Friction force
F_{pr_q}	Friction force opposing print cylinder motion at q^{th} print cylinder
F_{dr_q}	Friction force opposing doctor blade motion at q^{th} print cylinder
F_{c_q}	Coulomb friction coefficient at q^{th} print cylinder
F_{v_q}	Viscous friction coefficient at q^{th} print cylinder
F_{D_q}	Load on the doctor blade at q^{th} print cylinder
F_{t_q}	Force due to tension differential at q^{th} impression roll
F_{f_q}	Force due to friction contact at q^{th} impression roll
F_{N_q}	Net normal force at q^{th} impression roll
F_{ni_q}	Nipping force at q^{th} impression roll
F_{nw_q}	Reaction force due to tension differential at q^{th} impression roll
K, K_{gr}	Transmission shaft and print unit gear box stiffness
l	Nominal span length in a print unit (an integer multiple of upstream print cylinder circumference)
$\tilde{l}$	Change in span length from the nominal span length
M_{dr_q}	Mass of the doctor blade assembly at q^{th} print cylinder
n_{dr_q}	Transmission ratio between print section motor and doctor blade crank arm at q^{th} print cylinder
n_{dr_q}	Transmission ratio between print section motor and q^{th} print cylinder
r_{pr_q}, r_{Im_q}	Radius of q^{th} print cylinder and q^{th} impression roll
r_{dr_q}	Radius of q^{th} doctor blade crank arm
T_1, T_2	Web tension in spans upstream and downstream of print cylinder 1

T_{i_q}, T_{i+1_q}	Web tension in spans upstream and downstream of q^{th} print cylinder
v_s^*	Steady-state web velocity at the print cylinder
x_{dr_q}	Linear position of the doctor blade at q^{th} print cylinder
Subscripts	
q	print unit number; $q = l_1, \ldots, l_4,\ r_1, \ldots, r_4$

INTRODUCTION

In recent years there has been a significant focus towards printing electronics on a flexible substrate using R2R printing methods since printing of functional materials on a substrate is cost effective compared to conventional photo-lithography techniques [1–12]. The feasibility of printing low-cost electronics using inkjet technology is presented in [1]; this work also motivates the possibility of using gravure printing as a viable option for printing electronics on a flexible substrate. Because of the preliminary nature of the work the printing was carried out on a stationary substrate and the research primarily concentrates on printing technologies and materials used in printing rather than the roll-to-roll aspects of printing. In [2] the viability of gravure printing technology to pattern conductive lines was explored using a laboratory gravure sheetfed printer developed in [4] which does not have continuous processing capabilities; [6] extends previous work and provides a first systematic study on gravure printing technique as a viable option for printing nanoparticle lines using a sheetfed gravure printer. Roll-to-Roll nanoimprint lithography on a flexible substrate was used in [3] to deposit a single layer of polymer patterns with 70 nm feature size using a coating roller followed by a nanoimprint roller; even though small feature sizes were achieved by this process, registration or layering of successive patterns was not addressed in the work.

The possibility of printing polymer solar cells using R2R techniques was explored in [5]. Several different steps of printing and coating were involved in the manufacturing process with two printing steps: an initial screen printing of etch resist material (R2R process) and a final screen printing of silver electrodes (bath or non-R2R process). The feature sizes in the solar panels were in millimeters and no layer to layer registration using R2R techniques were used in the manufacturing process. A study that quantifies the limits on print registration capabilities and the scalability of gravure-printed electrodes on plastic foils using commercially available R2R gravure system is presented in [7]. A commercial two unit gravure printing press was employed to print electrodes with feature width of about 300 μm. It is found that the overlay printing registration accuracy was about 40 μm in the machine direction and less than 20 μm in the cross-machine direction. The paper studied the limits of the R2R gravure printing system to evaluate the registration accuracy, line widening effects, thickness, surface roughness of the print, waviness of the print, etc., based on the type of ink used, the speed of transport of the material, the aspect ratio of the gravure cells in the print cylinder, etc. A R2R printed RFID tag using two gravure print units for printing the precursors, the bottom electrodes and the dielectric layer, is presented in [8] where the remaining components of the RFID were printed using inkjet and pad printing methods; because of the limits on the R2R gravure print registration capabilities the feature sizes were in excess of 200 μm and the registration requirement was not stringent because the large size of the dielectric layer. Polymer solar cell fabrication using full R2R processing was demonstrated in [9] where two flatbed screen printing R2R lines were employed to print an UV curable etch resist followed by the printing of the silver black electrode. The first etch resist layer is registered with the second silver back electrode layer based on a registration hole punched in the first R2R line. Even though the system is capable of printing continuously, the flatbed screen printing requires the stoppage of the line to print the layers. R2R printed radio frequency tag with two layers printed using gravure printing and the final layer printed using inkjet printing is reported in [10]. The first layer that includes the coil and the capacitor bottom electrodes is grauvure printed and registered with the large second dielectric insulating layer while the final small feature layer is inkjet printed. The overall circuit is designed to tolerate registration errors between successive layers and hence have a large capacitor bottom electrodes (width = 0.5 to 2 mm).

In spite of the progress in printing electronics on a flexible substrate using R2R techniques in laboratory environments there are many more challenges that have to be overcome before an industrially viable economic manufacturing process can be achieved. Majority of the advances have led to the appropriate selection of ink properties, material properties, printing process parameters, etc. and very little work has been done to improve the web handling aspects to increase the efficiency of the R2R manufacturing process specifically for printed electronics applications. A reason for this is noted in [11]: "One is often met with the argument that roll-to-roll processing is technical and not at the forefront of science." But with proper machine and process design, based on the behavior of the flexible substrate during transport, one could improve and enable efficient manufacturing of printed electronics to an industrial scale, which is also noted by the authors in [11] as: "We would hold the opposite argument and claim that it (roll-to-roll processing) both enable and provides considerably more control over and insight into complex phenomenon." Instead of settling with limitations of existing machinery and designing the processes for printing electronics around the existing limitations, efforts towards improving the capabilities of machines can provide significant benefits towards the realization of the goal to commercially manufacture flexible electronics using R2R techniques.

In this paper we provide an overview of how the R2R aspects of printing, specifically machine design, process design and control design can be improved in order to meet the stringent registration requirements for R2R printed electronics applications. The overview is based on a new model for print registration using a new tool for analyzing disturbance propagation behavior or interaction within R2R systems. Data from conventional printing presses are also analyzed to provide recommendations for improving print registration quality. Finally, recommendations for registration control design are provided based on dynamic stability analysis, ease of control design and implementation, and interaction or the disturbance propagation behavior between successive print units.

MODEL FOR PRINT REGISTRATION

R2R printing involves transport of web through print units where the required pattern is printed on the material. Several types of R2R printing technologies, such as offset-printing, flexo-printing and rotogravure printing, are available. For printed electronics applications gravure printing has gained a lot of traction because of the simplicity of the printing process. In R2R printing, the web is transported through one or more printing rollers (also called as print cylinder) where the image/pattern on the print cylinder(s) is transferred onto the web material. A schematic of a print section with two gravure print units is shown in Figure 1.

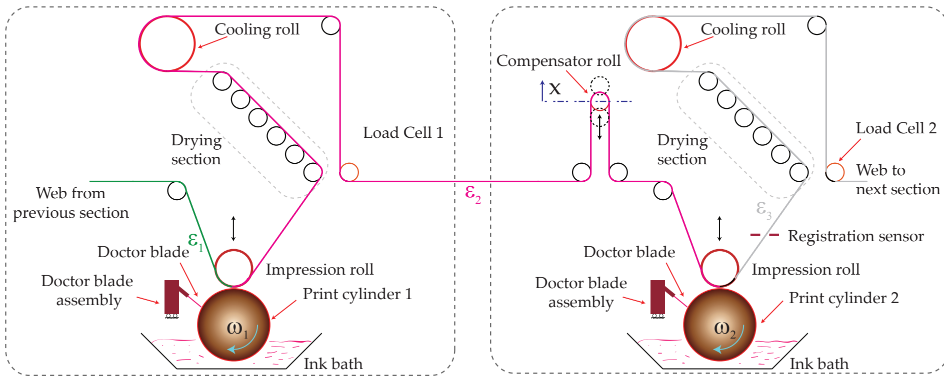


Figure 1: A schematic showing the web between two successive print cylinders; some of the idle rollers are ignored.

The quality of the print output depends on maintaining appropriate web transport conditions, such as regulation of web tension and web transport velocity [13]. Apart from maintaining web tension and web transport velocity – to minimize transport related web defects, such as wrinkling, creasing, or even web breakage – printing requires spatial positioning of the web. When multiple print cylinders are used to print a complex multicolor pattern, it is critical to have successively printed patterns to align appropriately on top of each other; this in addition to maintaining web tension at desired value presents additional challenges in R2R printing.

Two types of control strategies are typically used to control the printing quality in R2R printing. A compensator roll based control strategy is typically employed in print units with mechanical line shafts where the registration error is controlled by changing the web path length between the two print cylinders. With the advent of electronic line shafts (ELS), the angular positions of the print cylinders are actively controlled, in addition to controlling the angular velocity, to minimize registration error. By using ELS, fine control over print cylinder velocities is achieved, and it is generally argued that there is no longer a need for a compensator roller to correct registration error. A better understanding of the registration process and the substrate behavior as it is transported in a printing press is necessary to design appropriate control algorithms for either control strategies.

There has not been much fundamental work reported in the literature on modeling of print registration other than the models given in [14] and [15]; further, there has been no experimental corroboration of the proposed models. In [16,17] the modeling approach given in [14] and [15] is used for designing controllers to minimize registration error. A mathematical model for the print registration process in an offset printing press is developed in [14]. A governing equation for the registration error is obtained by taking into account the elongation (or strain) experienced by the web as it passes through two successive print units and the difference of the actual web strain and its nominal value for each print unit span is used in the governing equation. A similar model, but considering the actual strain in each print unit span, is developed in [15]. In these existing models it is assumed that the print cylinder angular positions are synchronized and that the print cylinders rotate at a constant velocity. These assumptions are acceptable for conventional printing applications where the registration requirements are in few millimeters but may not be valid for printing electronics on a flexible substrate where the registration requirements are in the order of few micrometers.

A new mathematical model for print registration that considers the effect of relative web strain, angular position of print cylinders and the effect of compensator motion presented in [18] is given by:

$$e_r(t) = l - \underbrace{\int_{t-\tau_1}^{t} \frac{r_1\omega_1(\tau)}{1+\bar{\epsilon}_{21}(\tau)} d\tau}_{\text{effect of relative strain}} - \underbrace{\left[r_2\theta_2(t) - \frac{r_1\theta_1(t-\tau_1)}{1+\bar{\epsilon}_{21}(t)} \right]}_{\text{effect of print cylinder velocities}} + \underbrace{\int_{t-\tau_1}^{t-\tau_2} \dot{\tilde{l}}(\tau) d\tau}_{\text{compensator motion}} \quad \{1\}$$

As the web strains within the span of the print unit, the printed image is elongated. This changes the path length the printed image needs to travel and hence affects print registration. Unlike the existing registration models, the model in Equation {1} uses relative strain within print units whereas absolute strain is used in [15] and strain over nominal value is used in [14]. This is because as long as the upstream and downstream span strains are the same ($\epsilon_1 = \epsilon_2$), the printed image is not elongated further after printing and hence will not affect the registration error; even if both ϵ_1 and ϵ_2 are not at their nominal values. Production run data from conventional print presses reveal that the web strain between print units are seldom the same and moreover web strain during a single production run is seldom maintained the same. Hence a registration process characterized by models that use absolute web strain [15] and strain over nominal value [14] are inaccurate whereas the relative strain model [18] sufficiently captures the dynamics of the print registration process. The comparison of three print registration models based on actual production run data is presented in [18] where the inaccuracies in existing models are quantified.

Apart from just considering the effect of web strain the new model also includes the effect of print cylinder angular position as well as the effect of compensator motion on print registration. If the angular position and velocity of the two print cylinders in the print unit are exactly the same, the printed image from print cylinder one will overlay exactly over the printed image from print cylinder two if the span length variations and strain variations are neglected. But if the print cylinder velocities are not the same then the registration error is a function of the angular position difference between the two print cylinders. This is accounted for by the second term in Equation {1}. Similarly the motion of the compensator increases or decreases the total path length the printed pattern needs to travel from the upstream print cylinder to the downstream print cylinder. The last integral term in Equation {1} accounts for that effect. These effects were not validated from the production run data because of the inability to instrument in the explosion proof environment around the print cylinders and the compensator roller position measurements are also not available from the original equipment manufacturer. In spite of neglecting these effects the relative strain registration model is able to capture the average characteristics of the registration process (see Figure 2). This is because data from a number of production runs support the fact that relative strain between two adjacent print unit spans is a primary cause of registration error (see Figure 3).

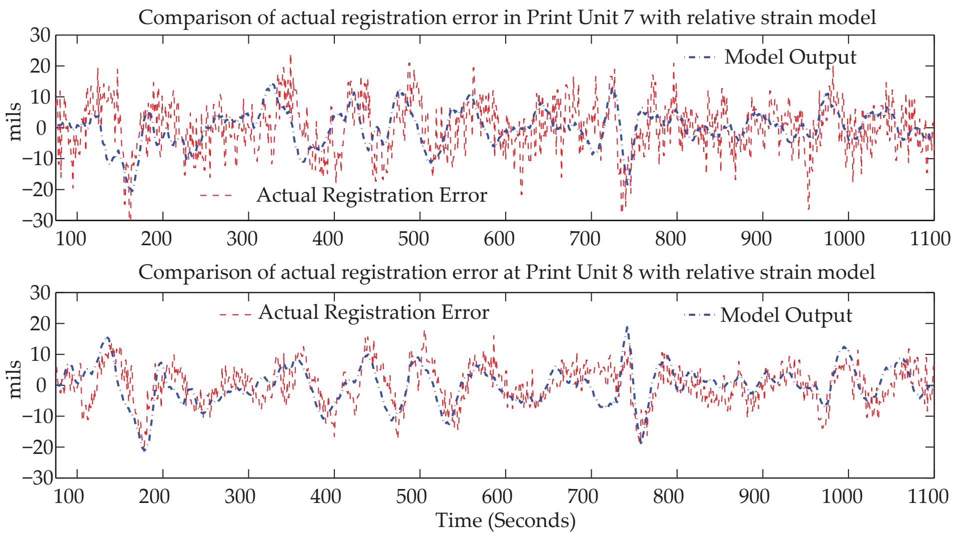


Figure 2: Comparison of relative strain registration error model output and actual production run data from an industrial printing press.

It is clear from the analysis presented in [18] that one of the primary requirement for achieving good registration for printed electronics applications is to maintain web strain or web tension at desired value without variations within print units. But in practice, strain is seldom actively controlled within the print units. Apart from control of web strain it is also necessary to minimize the creation and propagation of tension disturbances within print units due to improper machine design, control design and process design. In printing presses with mechanical line shafts, independent control of print cylinder velocities is not possible; hence compensator rollers are used to compensate for registration error. But the motion of the compensator roller causes strain variations in the print unit. Similarly, direct control of each print cylinder angular position also results in strain variations within the print unit. The governing equation for strain given below clearly shows the effect of print cylinder velocities and compensator motion on web strain.

$$\dot{\epsilon}_2(t) = \frac{1+\epsilon_2(t)}{\quad} \qquad \left. \frac{\quad}{1+\epsilon_1(t)} \right] \qquad \{2\}$$

With strain transport tension disturbances occurring in spans preceding the print units are likely to cause strain variations in succeeding print units. Machine induced disturbances in the print units, such as eccentric or out-of-round rollers, may also cause strain variations that can affect registration error. Hence, control

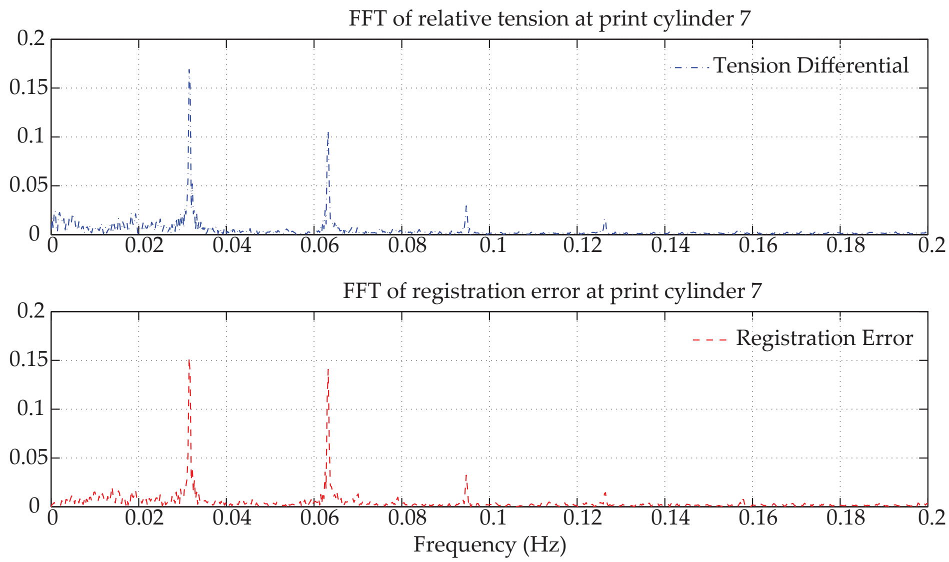


Figure 3: The plot shows the Fast Fourier Transform of the registration error and tension signal measured in an industrial printing press during a production process. From the frequency domain comparison there is a strong correction between the tension and registration error in the print unit.

strategies have be designed such that both strain variations and registration error are minimized simultaneously.

IMPROVING PRINT REGISTRATION QUALITY

Apart from improving print registration by using advanced registration control algorithms, it is also necessary to employ passive methods to reduce the creation and propagation of disturbances within print units. Proper machine design can reduce the creation of tension disturbances and with a proper process design the propagation of tension disturbances within print units can also be minimized. In this section some examples on how machine design and process design can affect print registration is discussed and recommendations for minimizing their effect on print quality are provided.

Minimization of Disturbances by Proper Machine Design

Proper machine design is critical to minimize the sources of disturbances in R2R systems and is especially important for R2R flexible printed electronics applications. Nonideal effects such as time varying span length due to accumulator motion, rotating turret winder or dancer motion, eccentric rollers, out-of-round material roll, backlash and belt transmission compliance can significantly affect web tension [20–22]. Apart from these nonideal effects that influence web tension in any R2R system, other machine design aspects specifically related to R2R printing can affect registration error. For example, the motion of the doctor blade can affect print registration if not properly designed [18].

The doctor blade is a device that is used in most rotogravure printing presses to wipe excess ink off the print cylinder so that only the region of the gravure cylinder with the pattern contains the ink and the rest of the region is devoid of ink. The doctor blade is pressed against the print cylinder to wipe excess ink as shown in Figure 4. Pneumatic cylinders, housed on the doctor blade assembly frame, are used to apply pressure on the doctor blade holder such that adequate pressure is applied at the contact between the doctor blade and the print cylinder surface to wipe off excess ink.

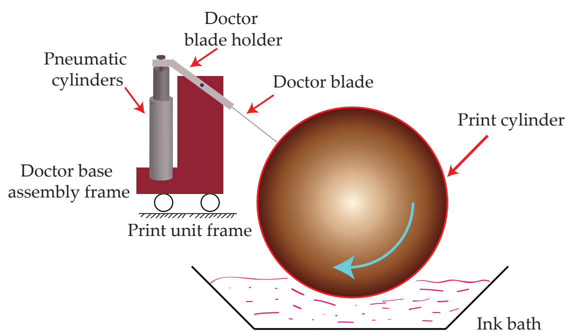


Figure 4: A side view of the doctor blade assembly and the print cylinder.

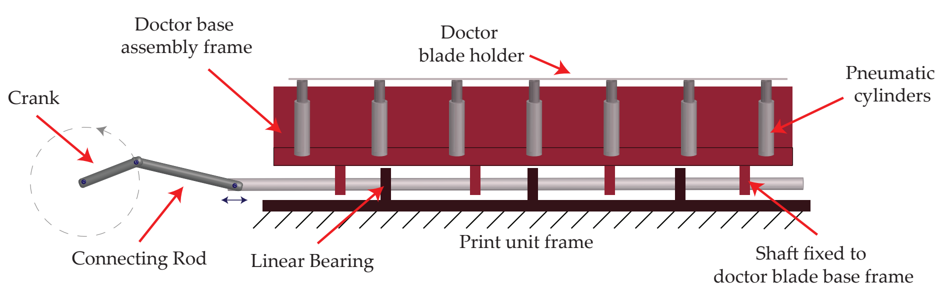


Figure 5: Doctor Blade Assembly

In order to produce even wear on the doctor blade, the doctor blade is made to oscillate back and forth on the print cylinder as it wipes the ink off. To facilitate the rocking motion the entire doctor blade assembly is moved back and forth. A linear bearing facilitates the oscillating motion of the doctor blade assembly and a crank mechanism as shown in Figure 5 provides the power for the motion. For the sake of simplicity some printing presses use the power from a single motor to drive both the print cylinder as well as the doctor blade crank assembly using a gearbox. Whenever the print cylinder is engaged by the clutch mechanism, the doctor blade assembly oscillates; but the doctor blade makes contact with the print cylinder only when the pneumatic cylinders are engaged. The frequency of oscillation of the doctor blade assembly is based on the gearing ratio and is usually fixed; the stroke length may be varied based on the crank radius. Since the same gear box drives the print cylinder and the doctor blade assembly, the motion of the doctor blade assembly will affect the print cylinder velocity dynamics due to mechanical compliance. The governing equation for the doctor blade motion that affects print cylinder velocity given in [18] is

$$\begin{aligned} \underbrace{\left(M_{dr_q} f_q(\theta_{dr_q}) + J_{dr_q}\right)} \qquad \qquad \frac{\qquad}{n_{dr_q}} - \theta_{dr_q} \Bigg) - \underbrace{\frac{1}{2} M_{dr_q} \frac{\partial f_q(\theta_{dr_q})}{\partial \theta_{dr_q}} \dot{\theta}^2_{dr_q}}_{W_{dr_q}} \\ - F_{dr_q} g_q(\theta_{dr_q}) + b_{dr_q} \underbrace{g_q(\theta_{dr_q}) \dot{\theta}_{dr_q}}_{-\dot{x}_{dr_q}} \end{aligned} \tag{3}$$

where

$$g_q(\theta_{dr_q}) = \left[r_{dr_q} \sin\theta_{dr_q} + \frac{r^2_{dr_q} \sin\theta_{dr_q} \cos\theta_{dr_q}}{\sqrt{l^2_{dr_q} - r^2_{dr_q} \sin^2\theta_{dr_q}}} \right], \quad f_q(\theta_{dr_q}) = g_q(\theta_{dr_q})^2. \tag{4}$$

Note that the equivalent inertia $J_{eq_{dr_q}}$ and the input disturbance W_{dr_q} are functions of the crank angle and the doctor blade motion causes velocity variations at the print cylinder due to variations in equivalent inertia and load disturbance; which may be reduced by reducing the stroke length of the doctor blade assembly.

Experimental results and data from production runs clearly show the detrimental effect of improper doctor blade motion design on registration [18]. The stroke length of oscillation of the doctor blade should be small in order to minimize the print cylinder velocity variations which affect registration. If the doctor blade assemblies in multiple print units are coupled mechanically then the phase of oscillation of the doctor blade assembly needs to be designed appropriately to minimize their effect on registration error. The effect of doctor blade motion on registration can be minimize by using an independent actuator to provide linear motion of the doctor blade assembly. Even with an independent actuator, the doctor blade motion needs to designed such that the stroke length and the velocity of oscillation of the doctor blade is small to minimize the effect of print cylinder velocity variations due to frictional contact. Excessive contact force between the doctor blade and print cylinder can also influence registration error, and hence suitable doctor blade loading force needs to be maintained.

Web slip between the print cylinder and the impression roller in a rotogravure print unit can also result in poor printing quality. Print units that employ electronic line shafts are especially affected if excessive angular position correction is introduced. A slip model based on various frictional forces that affect this slippage is presented in [18]; a free body diagram of the print cylinder-impression roller contact is shown in Figure 6. From the model it is evident that arbitrary correction to the angular velocity of the print cylinder or the compensator motion can result in large strain differential at the print cylinder-impression roller contact. This strain differential can result in web slippage and poor print quality if adequate nipping force is not maintained at the contact region.

Apart from minimizing the sources of disturbances, it is also important to minimize the propagation of disturbances by proper machine design, process design and control design. The following section outlines ways to minimize the propagation

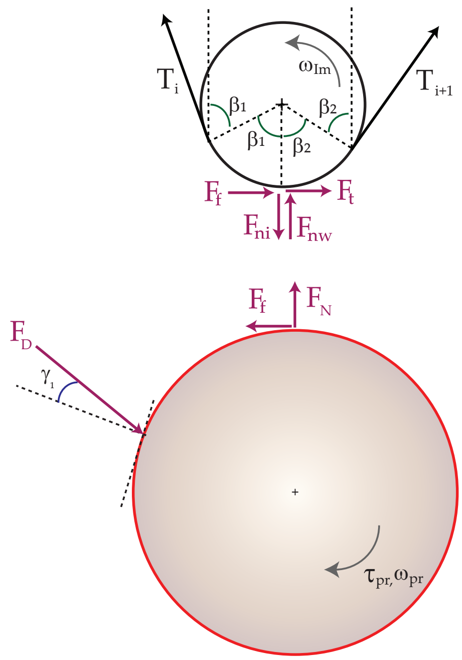


Figure 6: Free body diagram with frictional forces between the print cylinder and the impression roller.

of disturbances in a R2R system.

Minimization of Propagation of Disturbances

The interaction between machine dynamics and web dynamics occurs as the web is transported through processing machinery, and it is an active topic of research in web handling. Apart from machine-web interaction, interaction between tension zones in a R2R system is inevitable because of the physical connection created by the flexible substrate. This interaction results in transport of tension disturbances both upstream and downstream of the tension disturbance source because of strain transport. Understanding this disturbance propagation behavior and thereby minimizing this interaction can significantly improve the print registration quality since web strain or web tension variation is the primary cause of registration error in R2R printing presses.

To study the disturbance propagation behavior, a new interaction metric applicable to R2R applications was introduced in [19]. The metric is based on the Perron-Frobenius theory of nonnegative matrices and is used to quantify interaction in any large-scale interconnected system that employ decentralized control structure such as a R2R processing system. The Perron Root based Interaction Metric (PRIM) is a frequency dependent metric that quantifies the disturbance propagation behavior based on the longitudinal web dynamics which is influenced by machine configuration parameters, such as span lengths, roller inertia, radius of the rollers, friction coefficient, and process conditions, such as mechanical and physical properties of the flexible material, nominal web transport velocity and nominal web tension. Figure 7 shows the PRIM plot for an experimental platform, (schematic of the platform is shown in Figure 8) for a particular transport condition with Tyvek web material. Since PRIM is an interaction metric, a smaller value indicates smaller magnitude of disturbance propagation and if the PRIM is zero then it implies that there is no interaction between tension zones. From the figure it is evident that at low frequencies the disturbance propagation behavior is higher than at other frequencies. PRIM indicates the overall interaction in the R2R system and if the magnitude is greater than or equal to one it implies that disturbance created in one tension zone is magnified because of the dynamics and process conditions of the R2R system. Apart from analyzing the disturbance propagation behavior with a particular process condition, the metric can be used to find the optimal design parameters for the R2R machine as well as the optimal process parameters for the processing conditions so that the tension disturbances are attenuated between tension zones.

Figure 7: Perron root interaction metric for an experimental R2R system (shown in Figure 8) with a certain type of web material under certain processing condition.

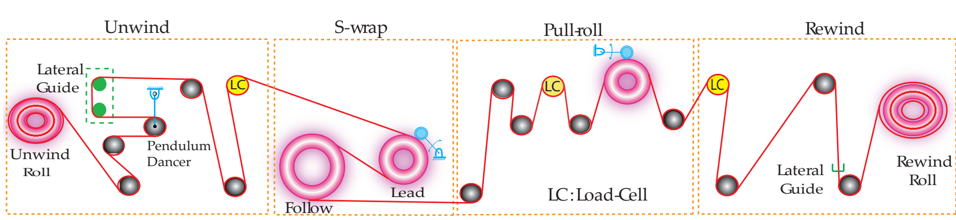


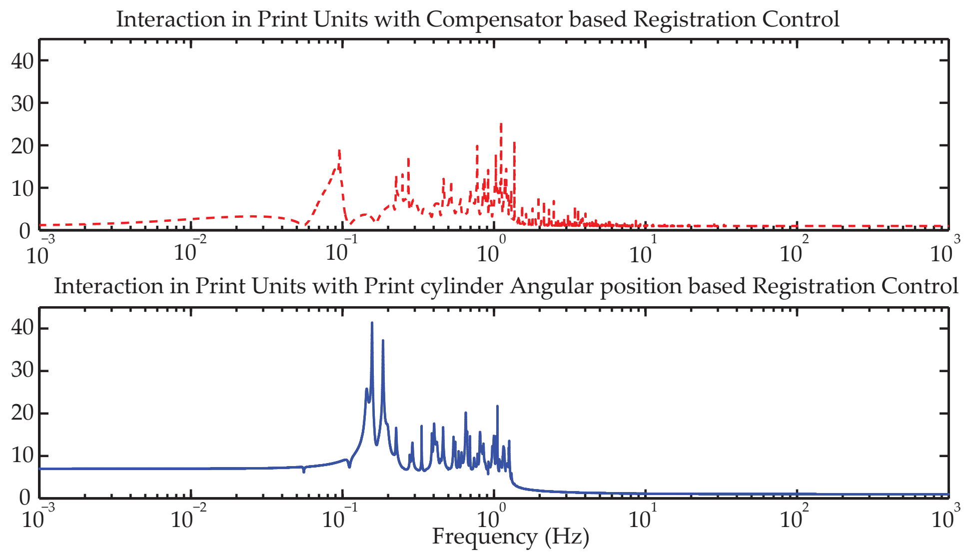
Figure 8: Schematic of an experimental R2R system used in computing the PRIM.

Like any other R2R process, printing involves more than one print unit and hence R2R printing machines can be considered as a large scale interconnected system with several subsystems, the subsystems being the print units or the tension zones between the driven print cylinders. Because of the interconnections due to web transport, tension disturbances propagate between different tension zones. Since the registration error is affected primarily by tension disturbances, it is important to understand and control propagation of tension disturbances within the R2R system in order to achieve the stringent registration requirements for flexible printed electronics.

Two types of control strategies are typically used in control of registration error in R2R printing. A compensator roll based control strategy (CRC) is typically employed in print units with mechanical line shafts where the registration error is controlled by changing the web path length between the two print cylinders. With the advent of Electronic Line Shafts (ELS), the angular positions of the print cylinders are actively controlled, in addition to controlling the angular velocity, to minimize registration error. By using ELS, fine control over print cylinder velocities is achieved, and it is generally argued that there is no longer a need for a compensator roller to correct registration error. The analysis presented in [18] indicates that a compensator provides an additional degree of freedom to control both registration error and web strain. A systematic comparison of the compensator based registration control strategy and Print cylinder Angular position based Registration Control (PARC) strategy will enable selection of an appropriate control strategy for R2R flexible printed electronics applications.

Motion of both the compensator roller and the print cylinder, with CRC and PARC strategies, can affect web strain in the print unit as well as adjacent print units because of strain transport [18]. Hence, control of registration error in one print unit causes tension disturbances or strain variations in adjacent print units which affect registration in adjacent print units. Therefore, it is necessary to understand the interaction behavior in print units that employ CRC and PARC to determine a suitable high performance control strategy for R2R flexible printed electronics applications. Based on the print registration model developed in [18] and using the PRIM developed in [19] a systematic comparison of print units employing CRC and PARC is presented in [23].

From the simulation results and the PRIM analysis presented in [23] it is concluded that print units employing CRC strategy will result in smaller magnitude of tension and registration error propagation when compared to print units employing PARC strategy. Figure 9 shows a comparison of CRC and PARC strategy using PRIM. This is because of the manner in which strain is transported within print units. As the compensator is positioned to reduce the registration error in one print unit, the motion of the compensator directly affects web strain within that span. This strain variation affects the velocity dynamics of print cylinders adjacent to that span and which in turn affect web strain in adjacent spans. Therefore, the motion of the compensator has an indirect effect on web strain in adjacent spans. But for print units using PARC, the control of angular position or the angular velocity of a print cylinder directly affects web strain in the spans upstream and downstream of that print cylinder. Therefore, the magnitude of interaction is larger for PARC when compared to CRC.



The most effective method to improve print registration quality is by employing active closed-loop control systems for print registration. When compared to the passive methods discussed in the previous sections, active control of registration is necessary to significantly improve print quality. But relying completely on an active registration control system without preventing the various sources of disturbances and propagation of disturbances using passive methods will be counterproductive and may not meet the stringent registration requirements for the flexible printed electronics applications.

The main challenge in controlling print registration in a R2R printing press arise due to the time delay involved in the registration process due to the transport of the printed web from one print cylinder to the next print cylinder; generally it is difficult to stabilize a closed-loop system in the presence of system delays. Existing registration control algorithms in the literature are developed predominantly for PARC with one or two print units [15, 17, 24, 25]. These control algorithms involve communication of measurements such as web speed and tension between print units and also require past values of these measurements to stabilize the system. Moreover, propagation of disturbances due to registration error correction in one print unit with PARC affects other print units and this disturbance propagation is often minimized using a cooperative control strategy where the control input from one print unit is fed forward to the subsequent print unit [17, 25]. Even the existing CRC algorithms in literature require a centralized control structure with exchange of information between print units and storage of past measurements [16, 26].

Typical industrial controllers for web tension and velocity regulation are simple, decentralized controllers based on measurements from the respective tension zones. A centralized or a cooperative controller is seldom used because of the complexity involved in data communication between different sections in a R2R machine, and more importantly, because of erroneously providing control corrections in those sections of the web line where compensation is not required.

Even though the use of compensator for registration control reduces propagation of disturbances, the complexity of the control system is increased since the compensator motion introduces additional delay in the control system; whereas a PARC strategy has a simpler system dynamics. In order to choose a suitable control strategy for printed electronics applications it is also necessary to understand the ease of control design and implementation, stabilizability and performance of either control strategies. Such a comparison is provided in [27] where the dynamic stability analysis, control design and model simulations are presented based on the print registration model developed in [18]. The results from [27] suggest that the added degree of freedom with a CRC strategy does provide added benefits in spite of the increased complexity due to the compensator motion. It is found that the CRC strategy can stabilize the print section dynamics with a decentralized state feedback control law based on current state measurements with minimum propagation of disturbances. A decentralized state feedback law is simple to implement and hence would be an ideal choice for commercial registration controllers. Even though the control design for PARC presented in [27] stabilizes the system, the interaction or the propagation of disturbances, deteriorates the performance when the print section has multiple print units. The stability analysis also provides some insights on selection of design parameters, such as registration error correction rates, for both CRC and PARC strategies in order to ensure closed-loop stability. The results also show that a CRC strategy can accommodate larger correction rates than a PARC strategy. This is because the correction provided by the compensator motion has an indirect and smaller effect on web strain variations in adjacent print units whereas the angular correction provided to the print cylinder has a direct and larger effect on web strain in adjacent print units which tends to destabilizes the closed-loop system.

From these preliminary results it is evident that a compensator based registration control strategy has some added benefits over a print cylinder angular position based registration control strategy. Hence it would be worthwhile to investigate the possibility of using a CRC strategy in commercial printing presses for flexible printed electronics applications.

CONCLUSIONS

Realizing the goal of mass printing of electronics on a flexible substrate not only involves research in advanced materials and processes but also research on the web handling aspects involved in printing on a flexible substrate. This paper highlights various aspects of R2R printing that can be improved to meet the registration requirements for flexible printed electronics applications. Since variation in web strain is the primary cause for poor print quality, it is important to understand how proper machine design, process design and control design can minimize the sources and propagation of tension disturbances within print units.

It is concluded that print quality using R2R printing can be improved by using print cylinders driven by tightly controlled electronic line shafts that regulate the web velocity, and a compensator based control strategy for registration control. With electronic line shafts, machine induced disturbances due to compliant transmission can be avoided and with a CRC propagation of registration error between print units can be minimized. The registration performance can be further improved by using an independent actuator for doctor blade motion, actively regulating web tension within the print units, choosing process conditions, such as transport velocity, web tension, web span length, web material properties, etc., based on PRIM analysis of the model in order to minimize the tension propagation behavior within print units. Moreover, pre-filters designed to minimize propagation of tension disturbances will possibly improve registration performance.

Commercial production on an industrial scale requires significant improvement in printing quality which cannot be achieved just by designing advanced registration control algorithms; an overall approach that involves proper machine design, process design and control design based on the web behavior in a R2R system is necessary.

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