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Control of Non-linear and Non-holonomic Sheet Registration Devices

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***Abstract*—In Xerographic printers, one important quality metric to customers is the image to paper registration. This metric measures how well the image is positioned on the paper on the finished print, relative to its intended position.**

In the media path the sheet registration device, located immediately upstream from the image transfer section, is responsible for aligning the sheet with the image. In modern, high-speed printers these devices are most often mechatronic devices utilizing sophisticated sensors and active feedback control. This paper gives an overview of registration goals and constraints, several existing technologies, and control approaches. The differential drive registration nip and current state of the art control approach are explained in detail.

I. INTRODUCTION TO SHEET REGISTRATION DEVICES

XEROGRAPHIC printers and copiers printing on pre-cut sheets need to register, i.e. align the image and the sheet, before transferring the image onto the sheet. This is required in order to have the image be transferred to the desired location on the sheet. In most applications, the image location is fixed on the image-carrying device, a photo-sensitive drum or belt, which is constrained to travel at a constant velocity due to xerographic constraints. Therefore, only the option of registering the sheet to the image is available.

Since sheets are constrained to travel along a plane in the media path by baffles, they only have three degrees-of-freedom. They are driven by sets of rotating roller pairs called nips that pinch the sheet between them. The sheet has to be registered along these three degrees of freedom (DOF): process direction (direction of travel), cross-process direction (perpendicular to the direction of travel) and skew.

Several registration technologies exist. Some are purely mechanical, for example stalled nip registration which performs process direction and de-skew by transporting the sheet lead edge into a stalled (non-rotating) nip. A buckle is allowed to form which absorbs any skew the sheet has before starting the stalled nip and continuing to drive the sheet. Others are mechatronic and utilize a combination of DC and stepper motors to drive the sheet and various sensors to sense its position.

An example registration device is [1] which is used in Xerox Nuvera Digital Production System printers. As shown in Figure 1b, it utilizes a split nip shaft where each drive nip is driven by a separate motor. The whole shaft assembly can move in the cross-process direction. This gives three degrees of freedom to the registration device.

Another example is the registration device used in the Xerox iGen3 Digital Production Press, see [2] and [3]. It utilizes a split nip shaft similar to [1], see Figure 1a. There is however no cross-process direction movement available. With only two degrees of freedom the device is non-holonomic, necessitating the use of a trajectory planner to generate the reference trajectory for the sheet and the reference velocities for each drive nip in order to control a sheet along its three degrees of freedom. This device will be the focus of this paper.

Another interesting registration device is [4], utilizing a pair of spherical balls and backer balls at each contact point. The device, shown in Figure 1c, utilizes four identical motors to drive two spherical balls. Each ball is driven by two motors with their drive capstans contacting the balls at a 45 degree angle to the process direction. This arrangement allows for symmetric velocity limits and identical dynamics for the velocity vector at each contact point. The 45 degree angle configuration also avoids having any motor stop at zero velocity for sheet transport along the nominal process direction hereby avoiding stick-slip friction disturbances. This enables the device to remove any type of registration errors equally efficiently and easily perform large sheet movements such as sheet rotations and offseting sheets from center to edge registration.

Interestingly enough, despite such a variety of sheet registration devices, a majority of them contact the sheet at two points and have three or more degrees of freedom. This paper presents the dynamics and constraints of such devices, with special focus on the differential drive registration used in iGen3 digital press.

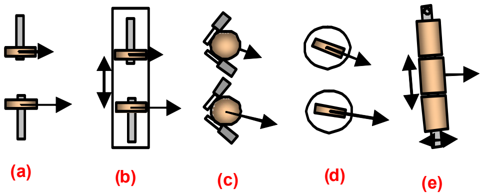

Fig. 1. Various registration devices which can be modeled as two contact point devices for paper position control.

Most sheet registration devices contact a sheet at two points, points A inboard and B outboard (or a contact line or patch that kinematically is equivalent to two points), as shown in figure 1. For this class of registration devices, the

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kinematic equations defining the relationship between the contact point velocities and the sheet velocity at its center of mass are derived in the following section. Figure 2 shows the registration device / sheet geometry.

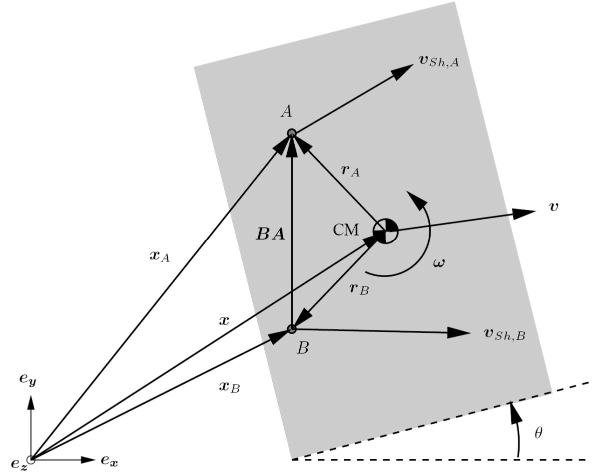

Figure 2. Two contact point registration device geometry.

Equation 1 shows the basic relation between the velocity at the contact point and sheet motion (*P* and *Q* are matrices dependent upon the registration device geometry and the location of the two contact points).

$$\begin{bmatrix} v_{Sh,A,x} \\ v_{Sh,A,y} \\ v_{Sh,B,x} \\ v_{Sh,B,x} \end{bmatrix} = P^{-1}Q \begin{bmatrix} v_x \\ v_y \\ \omega \\ \dot{\delta} \end{bmatrix} \tag{1}$$

Here δ represents the buckle building up between the two contact points. In this paper, we assume that the registration device is controlled not to introduce any buckling in the sheet, hence $\dot{\delta}$=0. The following section expands on the relationship between sheet and contact point dynamics. Then, in Section III, we describe the registration technology in the iGen3 digital press in greater detail. Simulation and experimental results using this differential drive registration nip are given in Section IV. Finally in Sections V and VI, we discuss some future extensions and conclusions.

II. SHEET KINEMATICS

This section outlines the relationship between the two contact point velocities, $v_{Sh,A}$ and $v_{Sh,B}$, and the sheet velocity at its center of mass (CM), v and *ω*.

Assuming the sheet is a rigid body, the velocities of the two contact points A and B of the sheet in contact with the registration device are governed by rigid body kinematics:

$$\begin{aligned} v_{Sh,A} &= v + \omega \times r_A \\ v_{Sh,B} &= v + \omega \times r_B \end{aligned} \tag{1}$$

To calculate the relationship between the sheet velocities at contact points A and B, $v_{Sh,A}$ and $v_{Sh,B}$, and the sheet angular velocity *ω*, subtract the two contact point velocities:

$$v_{Sh,A} - v_{Sh,B} = \omega \times (r_A - r_B) = \omega \times (x_A - x_B) = \omega \times BA \tag{2}$$

On component form, the above can be written as

$$\begin{bmatrix} v_{Sh,A,x} - v_{Sh,B,x} \\ v_{Sh,A,y} - v_{Sh,B,y} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} \times \begin{bmatrix} BA_x \\ BA_y \\ 0 \end{bmatrix} = \begin{bmatrix} -\omega BA_y \\ \omega BA_x \\ 0 \end{bmatrix} \tag{3}$$

Depending on the location of contact points A and B, the sheet angular velocity can be calculated using one of the following formulae, selecting the one that avoids dividing by zero:

$$\omega = \begin{cases} \dfrac{v_{Sh,A,y} - v_{Sh,B,y}}{BA_x} \text{ if } BA_x \neq 0 \\ \dfrac{v_{Sh,A,x} - v_{Sh,B,x}}{BA_y} \text{ if } BA_y \neq 0 \end{cases} \tag{4}$$

To determine the relationship between the sheet velocities at contact points A and B, $v_{Sh,A}$ and $v_{Sh,B}$, and the sheet velocity *v*, add the two contact point velocities:

$$v_{Sh,A} + v_{Sh,B} = 2v + \omega \times (r_A + r_B) \tag{5}$$

This can now be solved for the sheet velocity *v*:

$$v = \frac{1}{2}\left[v_{Sh,A} + v_{Sh,B} - \omega \times (r_A + r_B)\right] \tag{6}$$

III. THE CURRENT STATE OF THE ART: iGEN3 DIFFERENTIAL DRIVE REGISTRATION SYSTEM

As described in section I, the Xerox iGen3 Press uses a differential drive nip for sheet registration. As shown in figures 3 and 4, it consists of a split nip shaft where the inboard and outboard nips are driven by their own separate DC motor. This registration device has only two degrees-of-freedom and can only apply velocity vectors in the process direction at the two contact points. The specific kinematics and dynamics of the differential drive nip device imposes non-holonomic constraints between the two directly controllable sheet states; sheet process direction position (x) and sheet skew sheet (θ); and the in-directly controllable state cross-process direction position (y).

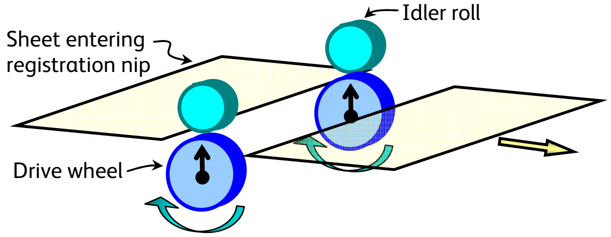

Fig. 3 Schematic of iGen3 differential drive registration device.

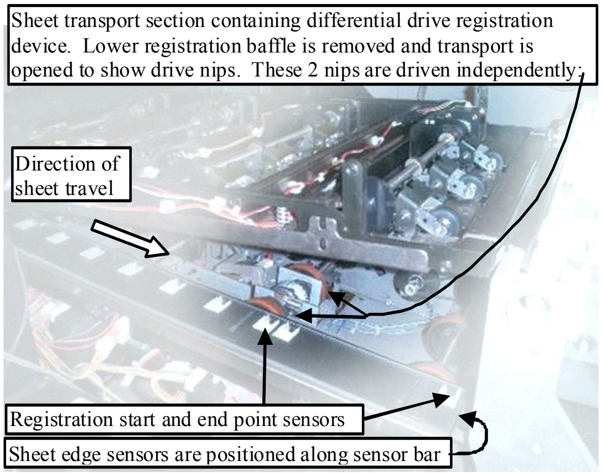

Fig. 4 iGen3 differential drive registration device.

To be able to register the sheet in the cross-process direction, the device has to be controlled to steer the sheet during forward motion in the process direction such that the sheet moves the desired amount in the cross-process direction before reaching the image transfer zone. Similar motion planning is performed by a driver when parallel parking a car. This control in the iGen3 printing press is determined by an open-loop motion planning algorithm [6].

The planning algorithm uses a measurement of the incoming sheet position, $x(0)$, $y(0)$ and $\theta(0)$ as the starting point and the desired final sheet position (with the sheet aligned to the image) as the end point. It utilizes an approach that uses polynomials of sufficiently high order to find the trajectories for a "control point", P, on the sheet, with coordinates $x(t)$ and $y(t)$ as well as the sheet skew, $\theta(t)$. First, trajectories for $x(t)$ and $\theta(t)$ that satisfy the end point constraints of desired initial and final positions, velocities and accelerations are determined. Second, using the dynamic equations for the registration system and end point constraints a trajectory for $y(t)$ can be determined. Lastly, the two nip velocity trajectories $v_{Sh,A}(t)$ and $v_{Sh,B}(t)$ can be determined from the control point trajectories and the sheet skew trajectory.

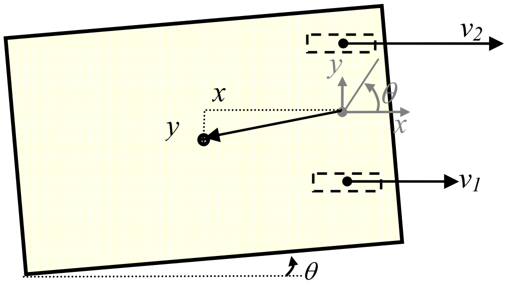

Fig. 5 The 3 DOF, x, y, θ of a sheet being registered by the differential drive nip velocity vectors v_1 and v_2 applied..

A. Differential drive nip path planning

Path planning for the differential drive registration system is designed to deliver the sheet from its starting position as it enters the registration nip to its final position as it leaves the registration nip and enters the downstream nip. In this case, $v_{Sh,A,y} = v_{Sh,B,y} = 0$, $v_{Sh,A,x} = v_2$ and $v_{Sh,B,x} = v_1$, as shown in Figure 5.

Assuming L is the distance between the wheels, and using a reference frame fixed to the registration system with its origin centered between the two nips, we can write the following state equation for the motion of point P on the sheet:

$$\begin{aligned} & L = \|BA\| \\ & \dot{y} = x\dot{\theta}, \\ & \dot{x} = -y\dot{\theta} + \frac{v_1 + v_2}{2}, \\ & \dot{\theta} = \frac{v_2 - v_1}{L}, \end{aligned} \tag{7}$$

Re-writing this in the form of a velocity constraint equation gives:

$$\begin{aligned} & \dot{y} - x\dot{\theta} = 0 \\ & v_1 = \dot{x} + \dot{\theta}\left(y + \frac{L}{2}\right) \\ & v_2 = \dot{x} - \dot{\theta}\left(y + \frac{L}{2}\right) \end{aligned} \tag{8}$$

The start and end conditions of a sheet during registration move are given by:

$$\begin{array}{lll} x(0) = x^o, & y(0) = y^o & \theta(0) = \theta^o, \\ x(t_r) = x^f, & y(t_r) = y^f, & \theta(t_r) = \theta^f, \\ \dot{x}(0) = V_x^o, & & \dot{\theta}(0) = \omega^o, \\ \dot{x}(t_r) = V_x^f, & & \dot{\theta}(t_r) = \omega^f, \end{array} \tag{9}$$

Finally, to ensure smooth delivery and acquisition to and from the nips, a zero acceleration condition is also enforced at the boundaries.

$$\begin{array}{ll} \ddot{x}(0) = 0, & \ddot{\theta}(0) = 0, \\ \ddot{x}(t_r) = 0, & \ddot{\theta}(t_r) = 0 \end{array} \tag{10}$$

Let the solutions for x and θ be expressed as 5th and 6th order polynomials as follows:

$$x = \alpha_0 + \sum_{i=1}^{5} \alpha_i t^i, \quad \theta = \beta_0 + \sum_{i=1}^{6} \beta_i t^i \tag{11}$$

where the α_i and β_i are undetermined coefficients. Substituting Eqs. (11) into Eq. (8a) and integrating results in the following solution for y:

$$y = \gamma_0 + \sum_{i=1}^{11} \gamma_i t^i \tag{12}$$

where γ_0 is the integration constant and

$$\gamma_j = \begin{cases} -\dfrac{1}{j}\displaystyle\sum_{k=0}^{j-1}(j-k)\alpha_k\beta_{j-k}, & j = 1,\ldots,6 \\ -\dfrac{1}{j}\displaystyle\sum_{k=j-6}^{5}(j-k)\alpha_k\beta_{j-k}, & j = 7,\ldots,11 \end{cases} \qquad (13)$$

Equations (11) and (12) include a total of 14 unknown coefficients. To solve for these coefficients, the 14 different boundary conditions in Eqs. (9) and (10) are used.

B. *Learning Algorithm*

There are several disturbance effects during sheet registration. Some are external to the sheet like drag due to friction, drive roll run out and velocity variations, nip wear, measurement error, etc. Other disturbances are related to media properties like weight, size, thickness coating, etc. In order to compensate for such known and unknown disturbances, a learning algorithm is used which fine tunes the target final position for the path planning algorithm to achieve the desired final registration. In order to do this, sensors measure media position as the sheet exits the registration nip. This information is used to adjust the targets for the next incoming sheet as shown below.

$$\begin{aligned} x_k^f &= x_{k-1}^f + K^x\left(T^x - x_k^m\right), \\ y_k^f &= y_{k-1}^f + K^y\left(T^y - y_k^m\right), \\ \theta_k^f &= \theta_{k-1}^f + K^\theta\left(T^\theta - \theta_k^m\right) \end{aligned} \qquad (17)$$

where k is the sheet number index, x_k^f, y_k^f, and θ_k^f are the reference values for process, cross-process and skew used for sheet k by the path planner, x_k^m, y_k^m, and θ_k^m are the values for process, cross-process, and skew that are measured at the exit of Registration for sheet k, T^x, T^y, and T^θ are the given target values for process, cross-process, and skew at the exit of registration, and K^x, K^y, and K^θ are given adjustment gains for the process, cross-process, and skew directions.

C. *Sensing System*

The iGen3 registration device uses several process edge sensors (point sensors) as well as side edge detection devices (CCD sensors) to track the position of the sheet as it enters and leaves the registration region. In addition, motor encoders are used to measure the drive nip angular velocities.

The process edge sensor is an optoelectronic sensor that detects the position of either the lead edge or trail edge of the media. The sensor consists of a light emitting diode light source and a phototransistor detector. As the lead/trail edge of the media passes between the sensor and a reflective surface mounted opposite and perpendicular to the sensor, a change in light condition is detected indicating the presence of the media (referred to as the trip point)

The CCD sensor is an optoelectronic sensor that measures the absolute position of the cross-process edge of the media. The primary components for the sensor include a detector, a light source, and a focusing lens. The detector for this sensor is a linear charged coupled device of size 2048 pixels by 1 pixel, where each pixel is 14 μm by 14 μm. Its light source consists of 12 infrared light emitting diodes. Roughly speaking, the sensor operates as follows: Light from this light source reflects off a reflective surface above the media path and is focused onto the CCD detector using a SELFOC lens array. When media is present between the sensor and the reflective surface, a portion of the light is blocked and an image of the edge of the media is projected onto the CCD array.

In iGen3 registration subsystem, sheet errors are recorded as each sheet enters and leaves the registration nip. To enable this, a process edge sensor is located just downstream of the nip, and another one at the registration exit. Three CCD sensors are located along the registration edge. Two of these sensors are used at a time to measure the cross-process position as well as skew of the sheet. By taking a reading of the sheet edge using two CCD's as the sheet lead edge reaches the lead edge sensor, we can fully define the position of the sheet. A similar reading is taken at the end of each sheet registration to provide the final sheet positions for the learning controller.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The simulation and experimental results for a sheet entering the iGen3 sheet registration device with a process error of 10.2 mm, cross-process error of -4.2 mm and a skew error of 9.4 mrad are shown in figures 6 – 10. Figure 6 shows the differential drive nip velocities during sheet registration. Actual, experimental nip velocities are shown as solid lines, the desired velocities are shown as dashed lines. An additional function that many registration devices perform is to slow down the sheets from a higher sheet transport velocity to the image velocity which is generally lower. In the iGen3 printer, the sheets enter the registration device at a velocity of 1.025 m/s and exit at the photoreceptor velocity of 0.468 m/s. The available nominal registration time is 170 ms.

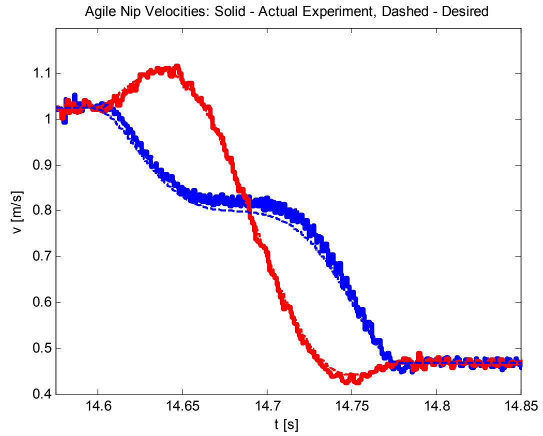

Figure 6. iGen3 registration device nip velocities (solid – actual experimental velocities, dashed – desired velocities).

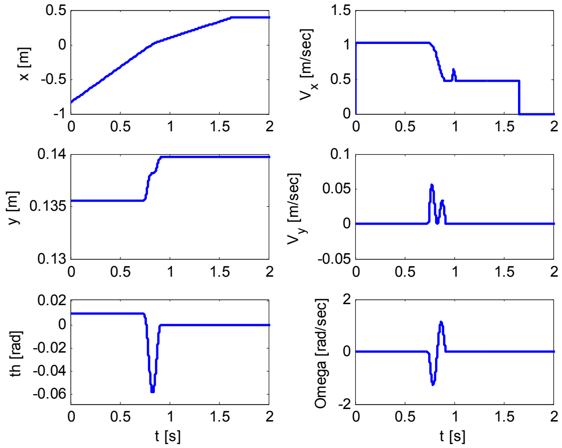

Figure 7. Positions and velocities of the sheet's center of mass during registration..

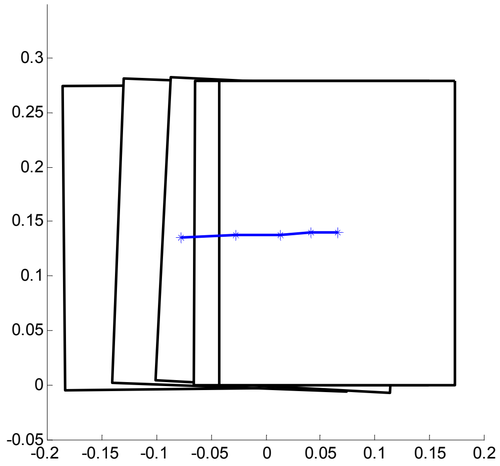

Figure 8. Outline of the sheet edges and center of mass trajectory during sheet registration.

Figure 7 shows the sheet states (sheet center of mass position and velocities) during registration. As can be seen, the cross-process position is corrected by approx. 4 mm (to its target of approximately 0.140 m). Notice that during the registration move, due to the non-holonomic constraints, the planned trajectory "wags" the sheet upwards of 58 mrad, much more than the incoming error of 9.4 mrad. The skew error is however corrected to 0 at the end of the registration move.

Figure 8 shows the outline of the sheet and the motion of the center of mass during the sheet registration move. The sheet "wag" is clearly visible as is the cross-process position correction at the center of mass. Figures 9 and 10 show the experimental results from a 15 sheet print job and illustrate the performance of the learning portion of the control algorithm.

Figure 9 shows the incoming sheet cross-process position errors (o) and the final cross-process position errors at transfer (+) for sheets 1–15. As can be seen, the learning algorithm converges to a zero average cross-process error. Figure 10 shows the corresponding performance of the learning controller for sheet skew.

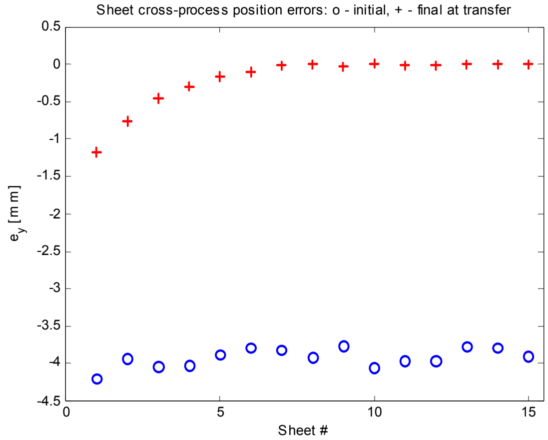

Figure 9. Sheet cross-process errors at entry (o) and exit (+) of registration nip for a 15 sheet print job.

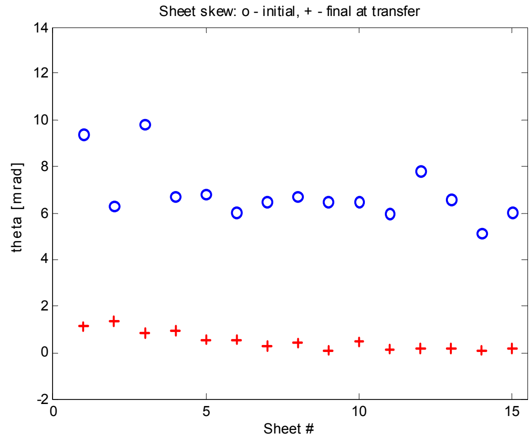

Figure 10. Sheet skew at entry (o) and exit (+) of registration nip for a 15 sheet print job.

V. FUTURE WORK AND EXTENSIONS

Current and future research directions include increased sheet registration performance, both for side 1 of the sheet for simplex (one sided) printing and additionally for side 1 to side 2 (show through registration performance) for duplex (double sided) sheets.

The open-loop path planning method for the iGen3 registration system is of course sensitive to disturbances affecting the sheets during registration. Learning addresses repeating disturbances and noises. Some recent research to address errors due to non-repeating disturbances and noises by closing the loop on the actual sheet position during registration has been carried out at Xerox [7]. Closed loop sheet registration for three and four DOF sheet registration devices has also received attention, both at Xerox [8] and at UC Berkeley [9–11].

VI. CONCLUSION

This paper gave an overview of several sheet registration technologies used in today's xerographic printers. Special focus was given on the differential drive nip registration device and the current state of the art control approach towards this non-holonomic and non-linear system. Simulation and experimental results are shown to demonstrate the current performance. The paper concludes with a brief overview of current and future research topics in this area.

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