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Printer Media Path Closed Loop Control

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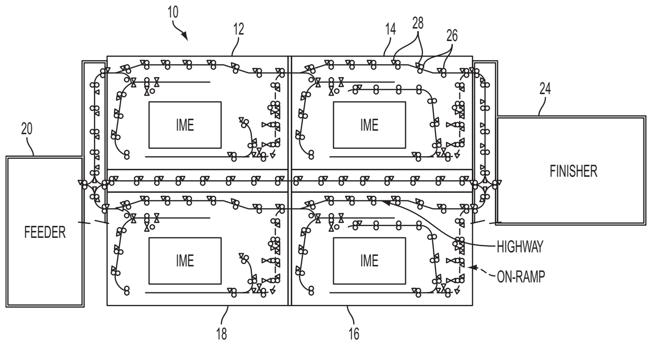

Fig. 1. Overview of a parallel printer architecture. Multiple print engines printing concurrently offer print speed scalability and redundancy. The required large and complex media path presents novel controls challenges.

Abstract— **The invention of parallel cut-sheet printing system architectures could potentially revolutionize the approach to building reliable, high-speed printers. Instead of speeding up an existing printer or designing a new, higher speed printer, a printing system is built utilizing multiple print engines printing in parallel, increasing speed and reliability.**

To connect the multiple printers with sheet feeders and finishers large and complex high-speed media paths are necessary to route and transport the sheets through the system.

These media paths require precise sheet position and velocity control in order to precisely and reliably transport a large number of sheets concurrently through the media path during parallel printing operation.

A closed loop control algorithm for large media paths with independently driven transport nips has been developed and successfully implemented. The performance has been verified both in simulations and experimentally.

I. Introduction

During the last decade, an increased interest in the design, modeling and control of printer media paths has emerged, addressing the challenges of increased size, complexity and speeds of modern printers. Early work at the University of California at Berkeley and Xerox Corporation started in 1996 and was published in several conference proceedings and dissertations, see [12], [10], [7], [11], [6], [14].

In Europe reserchers at the Embedded Systems Institute in Eindhoven and the Eindhoven University of Technology in cooperation with OCÉ Technologies BV have addressed the media path design and control challenges in the BODERC project [3], [2], [1]. [5], [15], [4].

Recently the Xerox research community has explored an alternative approach for building high-speed cut-sheet printers. Instead of trying to speed up an existing printer, which poses great challenges in the xerographic and fusing sub-systems, or designing a new, faster printer, printing systems composed internally of two or more print engines printing concurrently have been proposed and explored. An overview of such an example system is shown in figure 1.

The advantages of this approach are multiple: easy scaling of the printing speed of such systems for a given application, the ability to mix monochrome and color print engines for mixed-mode printing on one system (monochrome prints are often cheaper than color prints) and the inherent redundancy of such systems. If one print engine fails, the system can still continue to print while the failed engine is repaired or replaced.

The concept of increasing performance and redundancy by using multiple units of a certain device is well known and accepted in many other technological areas. Examples include multiple cylinders in a car engine, multiple engines on a jet airliner, computer RAID disc storage systems and multi-core / multi-processor computer CPU's.

This approach however presents a serious challenge as compared to traditional printers. It requires complex, large, high-speed media paths to transport the cut sheets from the sheet trays in the feeder to multiple print engines and to transport the printed sheets to the finisher as can be seen in figure 1. The media path however, is among the most reliable sub-systems of a printing system. Hence having a large and complex media path will not affect system reliability in a negative way.

A single print engine system has a simpler media path, usually a direct path from the feeder, through the print engine and to the finisher, with a loop back to the print engine entrance for duplex (double-sided) printing.

Commercial systems exists where a common print server splits up large jobs and prints them concurrently on several standard printers, so called cluster printing. For these systems, the media path is simpler in each printer but there are many disadvantages, among them the requirement for manual collation and assembly of the outputs, no automatic option to mix cheap monochrome and more expensive color pages in a single document in order to minimize cost (color prints are more expensive) and no automated recovery and guarantee of job integrity in the event of failures.

The proposed parallel printing systems perform automatic job collation, exception handling in the event of failures and guarantee job integrity. Additionally, sensors for sensing print image quality and color properties (often expensive), that are used for calibration and closed loop control of the xerographics and image processing sub-systems, can be shared among all the print engines in the printing system by

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placing them in a module where sheets from the different print engines can be routed and sensed.

II. Media path requirements

Some of the requirements of the media path in a multiple print engine parallel printing system are:

- transport sheets from one or several feeders to one or several print engines to arrive on time for printing
- transport sheets from the print engines to one or several finishers
- avoid sheet collisions and mis-routings despite various disturbances affecting the sheets

Some of the disturbances affecting the sheets being transported are timing variations in the feed time of the feeders, variations in effective media path length due to sheet properties, bends, differences in modeled media path geometries versus actual geomtries (e.g. module docking tolerances, sensor location tolerances etc.), sheet to baffle friction, sheet static cling, nip drive train dynamics, nip roller wear etc.

In order to successfully operate a parallell printing system, the sheets have to arrive at the image transfer zone in the print engines at the exact specified times so that the toner images formed inside the print engines are accurately placed and transferred onto the sheets.

Additionally, to reliably route sheets into different paths, gates; media path guide members that route the sheet to one of two possible media paths; need to actuate in between two consecutive sheets. This requires the inter-sheet spacing to be close to the desired spacing, otherwise the gate may interfere during switching with the trail edge or a lead edge of a sheet and jam it. At the merge points in the media path, where sheets from various modules merge into one common path, sheets need to be accurately position controlled in order to avoid sheet collisions.

Another requirement is to perform velocity changes of the sheets that are being transported. Since the common media path portions, e.g. the entry point into the media path from the feeder in figure 1, operate at a higher capacity in terms of sheets per minute than the print engines in the system, the required velocities in these paths, called *highways*, are often higher than the entry and exit velocities of the print engines. The media paths routing sheets from the highways to the print engines, called *off-ramps* (note similarity with common automotive highway nomenclature) and the media paths routing sheets from the print engines back onto the highways, called *on-ramps* need to perform velocity changes to match the different velocities at their starting and ending points.

In summary, the above requirements require the media path controls to accurately control the *positions* and *velocities* of all sheets being transported in the media path, as well as the accurate position control of all the gates used for sheet routing in the media path.

III. Media path architectures — grouped nips and independent nips

Media paths are often comprised of *nips*, pairs of opposing rollers that drive the sheets forward, often called *pinches* in the European litterature. These are represented by the pair of circles in figure 1. The sheets are guided from one set of nips to the next by baffles which constrain the sheet motion to a plane, sometimes curved plane in media path bends etc.

For cost reasons, several nips are often grouped together and driven by one motor by timing belts, gears etc. The dynamics of a media path with grouped nips is governed by a hybrid system which can also be described as a switched linear system, as outlined in [11]. This complex dynamics makes control design difficult but several algorithms have been developed [11]. Among those, ISSC—InterSheet Spacing Control has been the most promising [13], [8], [7], but it does not give the control performance that independent nips and the proposed ARTC control algorithm in section IV provides.

By using independently driven nips, i.e. one motor per nip, the system dynamics can be simplified considerably by applying an appropriate, state-dependent control input transformation which decouples the system dynamics into N independent linear systems. This input transformation is peformed by the *Nip Selector* component as described in section IV.

IV. Proposed Control Algorithm : Absolute Reference Tracking Control — ARTC

ARTC - Absolute Reference Tracking Control is a closed loop control methodology that enables robust and accurate sheet position and velocity control in media paths of arbitrary size and complexity, and at very high velocities. Especially in large printers with extensive media paths and the proposed parallel printing systems. The ARTC algorithm enables the control of the positions and velocities of all sheets in the printer / system media path with millimeter precision. ARTC requires nips in the media path to be independently controlled (i.e. one motor per nip). Even if not all nips in the media path are independently controlled, ARTC can be utilized in the portions of the media path where nips are independently driven.

The ARTC algorithm is based upon generating desired sheet position reference trajectories $\boldsymbol{x}_d$ for each sheet entering the system. The control algorithm then controls all actuators in the system (nip motors, gates etc.) such that each sheet position $\boldsymbol{x}$ closely follows its intended reference trajectory, see figure 2.

ARTC enables robust operation of these systems despite varying sheet properties, feeder variations, wear and other disturbances, noises and uncertainties, exceptions etc. since all sheets are under closed loop control and are continuously controlled to track their desired trajectories, despite these disturbances.

ARTC also enables much easier design of sheet trajectories, fulfillment of timing constraints and the implementation

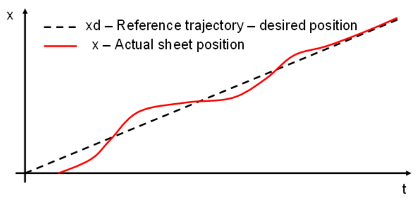

Fig. 2. ARTC — each sheet controlled to track its reference trajectory.

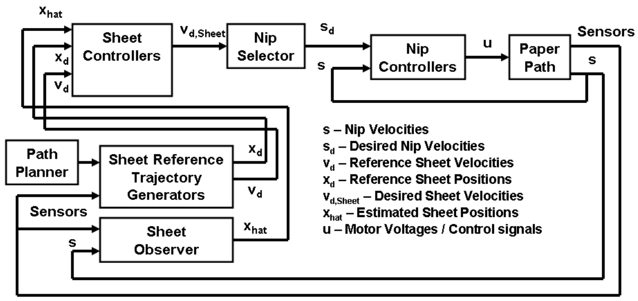

Fig. 3. Overview of the ARTC control architecture.

of the controls to ensure sheets track the reference trajectories, since the trajectories can be designed without worrying about any considerations as to what nips are executing the desired motion profile at any given time.

The ARTC algorithm consists of two main feedback control loops connected in a cascade control structure, as shown in figure 3.

1) **Sheet control feecback loop**: For each sheet entering the media path, a desired reference trajectory is generated depending on the operations to be performed on the sheet and the path it needs to travel ($\boldsymbol{x}_d$ — dashed in figure 2). Sheet position estimators (sheet observers) are also activated for each sheet and provide the estimated sheet position ($\hat{\boldsymbol{x}}$ — solid) to the sheet controller. The sheet controller then calculates the desired velocity to ensure each sheet transported in the media path tracks its desired reference trajectory.
2) **Nip control feedback loop**: The desired sheet velocities are mapped through a nip selector to desired velocities for each nip in the media path. Local nip velocity controllers control each nip to ensure each nip velocity follows the desired velocity. The nip controllers also operate in different modes depending on if they are in contact with sheets or not.

The ARTC implementation consists of these blocks:

1) **Sheet Reference trajectory generator** - generates desired sheet trajectories (positions $\boldsymbol{x}_d$ & velocities $\boldsymbol{v}_d$) for each sheet that enters the system using information from a system-wide planner (routing & scheduling algorithm). The reference trajectories are designed to provide desired velocity matching between various locations in the media path, see figure 1 for the on-ramp and highway locations. On-ramp trajectories start at printer exit velocity and end at highway velocity.

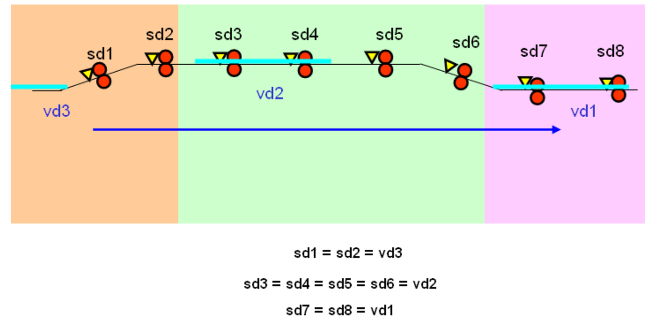

Fig. 4. Nip selector algorithm — assigns desired nip velocities for the various nips based upon sheet positions and desired sheet velocities. Nips that touch a sheet get assigned that sheet's desired velocity, empty nips get assigned the incoming (up-stream) sheet's desired velocity.

2) **Sheet observer** - generates estimates of the positions and velocities ($\hat{\boldsymbol{x}}$ & $\hat{\boldsymbol{v}}$) of all sheets in the media path system utilizing a model-based estimator, all control signals (motor voltages, motor currents, step motor pulses, gate actuation signals etc.) and all sensor signals (encoder, tachometer and sheet sensor signals from optical or mechanical point sensors or array sensors (CCDs)).
3) **Sheet Controller** - generates appropriate control signals, in this case desired sheet velocities — $\boldsymbol{v}_{d,sheet}$, to ensure that all sheets stay on track and follow their respective reference trajectories. The control action is determined as a function of the reference trajectories and the actual sheet positions and velocities, as determined by the Sheet Observer. Theoretically, it has been shown that proportional control with velocity feed-forward is a suitable controller due to its stability, zero steady state tracking error and ease of tuning [11]. The desired sheet velocities are calculated as follows:

$$\boldsymbol{v}_{d,sheet} = K_P\,(\boldsymbol{x}_d - \hat{\boldsymbol{x}}) + \boldsymbol{v}_d \tag{1}$$

where K_P is the controller proportional gain, $\boldsymbol{x}_d$ is the current reference trajectory position, $\hat{\boldsymbol{x}}$ is the current estimated sheet position and $\boldsymbol{v}_d$ is the current reference trajectory velocity.
4) **Nip selector** - utilizes the desired sheet velocities from the sheet controllers and the estimated sheet positions from the sheet observer to generate desired velocities for each nip in the media path. See figure 4 for an overview of the nip selector functionality.
5) **Nip controllers** - utilizing the desired nip velocity from the nip selector and the actual or estimated nip velocity from nip motor sensors / step motor pulses, each nip controller generates the nip motor control signals (voltage, current or step motor pulses) to ensure that the nip velocity tracks the desired nip velocity.

V. Experimental Results

The ARTC algorithm has been used extensively to control the media path in various parallel printing system prototypes. One of the prototypes using four print engines is shown in

Fig. 5. Four print-engine parallel printing system at the Xerox Research Center, Webster, NY, U.S.A.

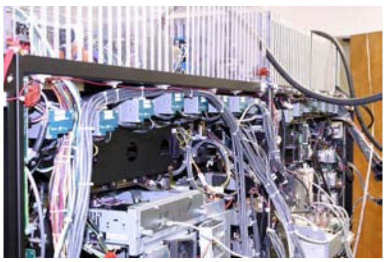

Fig. 6. Close-up of nip motors driving the upper highway nips.

figures 5–7. The total length of media path under ARTC control is around 17 m, with 132 independently controlled nips (driven by 132 DC motors).

The ARTC algorithm has been develop using the Mathworks Model Based Design (MBD) tool-chains for modeling, simulation, rapid control prototyping and auto-code generation toolchains (Matlab, Simlink, Stateflow and xPC Target). A total of 8 xPC Targets were used for the real-time implementation of the ARTC control algorithm.

Experimental results of the ARTC control algorithm in the upper left container on-ramp, from the print engine exit to

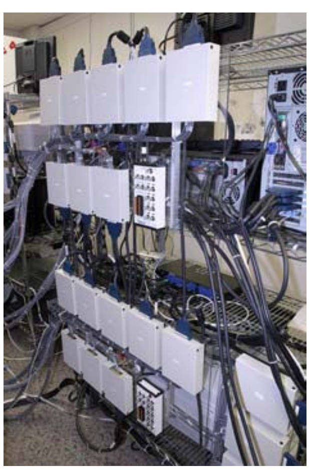

Fig. 7. Hardware implementation of ARTC media path controls utilizing 8 xPC Targets and associated harnessing.

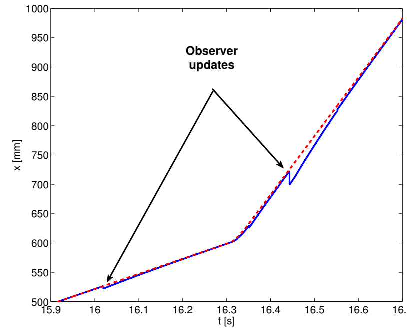

Fig. 8. Experimental results of the ARTC algorithm performing closed loop sheet control in the printing system on-ramps. Figure shows the sheet lead edge desired reference trajectory (dashed) and estimated position (solid). Notice how the estimated position is controlled to track the desired whenever a sheet sensor updates the estimated sheet position.

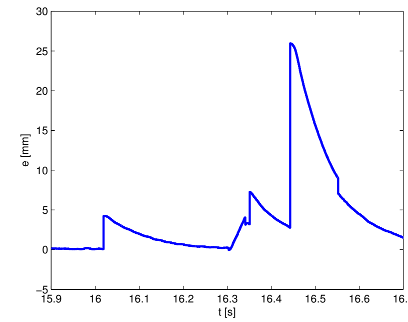

Fig. 9. Experimental results showing the tracking errors from the previous figure, i.e. the difference between the desired sheet LE position ($\boldsymbol{x}_d$) and the estimated position ($\hat{\boldsymbol{x}}$) for the on-ramp ARTC controls. All tracking errors are continuously being removed by the ARTC algorithm.

the upper highway, are shown in figures 8 and 9.

In order to evaluate the robustness of the proposed ARTC algorithm to varying media properties, the following experiments were performed on the printing system. Three print jobs consisting of 10 monochrome prints, all printed in the upper left monochrome print engine were set up. Job 1 consisted of 10 sheets of 4024 media, 75 gsm (grams per square meter) media only. To illustrate how different media types affect the induced disturbances to individual sheets transported along the media path and how the ARTC algorithm handles these, jobs 2 & 3 were printed on mixed sheets with basis weights from 60–216 gsm. Media with different properties will experience different effective path lengths in the media path, especially when being transported through bends in the media path.

To illustrate the performance of the ARTC control algorithm, the media path control algorithm in the Output Module, see figure 10 (the right-most module of the media path in figure 5), was switched between open loop and ARTC sheet control as follows:

1) Job 1 - Open Loop sheet control, standard media (4024, 75 gsm). With this control algorithm, the nips were closed loop velocity controlled to run at a the nominal

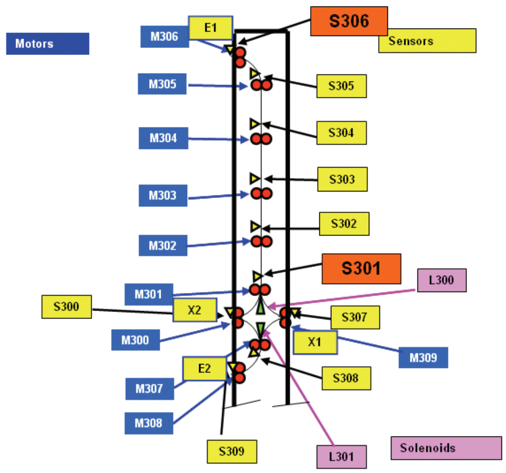

Fig. 10. Output Module used for ARTC performance characterization. Sheets entered output module at entry E1 (upper left) and exited at exit X1 (lower right).

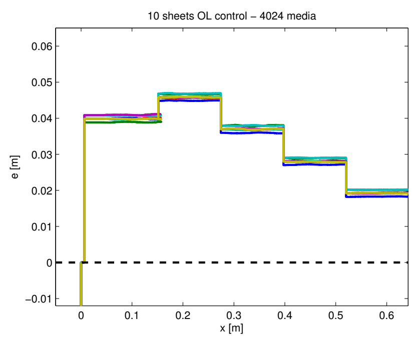

Fig. 11. Sheet tracking errors for Job 1: *4024 - 75 gsm media*, utilizing open loop control. No removal of errors, range of tracking errors remains the same along media path.

highway velocity of 1.000 m/s.

2) Job 2 - Open Loop sheet control, mixed media.
3) Job 3 - Closed Loop Sheet Control using ARTC control algorithm, mixed media.

As a measure of the control performance, the sheet tracking errors, i.e. the difference between the reference position ($\boldsymbol{x}_d$) and the estimated sheet position ($\hat{\boldsymbol{x}}$) have been captured and plotted, from the entry E1 of the Output Module to just slightly up-stream of the S301 sensor. The media path traversed by the sheets includes one 90 degree bend and is approximately 0.6 m long.

A. *Experimental results* without *ARTC (open loop)*

Figures 11 and 12 show the sheet tracking errors vs. sheet position with open loop sheet control. The errors are updated by the sheet observers at the sheet sensor locations, x = 0.005 m (S306), 0.151 m (S305), 0.274 m (S304), 0.397 m (S303) and 0.520 m (S302). Figure 11 shows the sheet tracking errors for Job 1, which consisted of 10 sheets of 4024 - 75 gsm media. The arrival time errors into the Output Module at entry E1 (difference between expected arrival times and actual arrival times) are around 40 ms. This error was introduced on purpose to show how large incoming errors into a module (from feeders, print engines, open-loop controlled modules etc.) are effectively removed by the ARTC algorithm. The arrival time errors in ms correspond to position errors in mm in figures 11 and 12 since the highway velocity is 1.000 m/s. The range of these arrival time errors (the maximum - the minimum error) is 2.0 ms, essentially within +/- 1 ms which is the implemented sampling period of the ARTC controller.

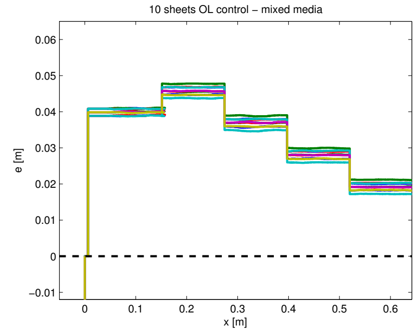

Fig. 12. Sheet tracking errors for Job 2: *Mixed media*, utilizing open loop control. No removal of errors, range of tracking errors increases from 2.0 to 4.0 mm after 1st bend, at x = 0.151 m, this range is not decreased along the media path.

Essentially, at each sensor location, as the estimated sheet positions are updated, the mean error changes by some amount. This is due to the difference between the actual and nominal (as supplied by CAD drawings) sensor trip point positions. Note that the errors in between sensor updates remain constant, both their mean and range is not affected by the open loop sheet control (some slight variation can be seen due to sheet disturbances).

Figure 12 shows the sheet tracking errors for Job 2, which consisted of 10 sheets of mixed media as described previously. The interesting phenomenon to observe is that the range of the errors increases from 2.0 to 4.0 mm after the 1st bend in the media path, at around x = 0.151 m. This is due to the fact that media with varying properties have different effective path lengths along bends. So the natural, random spread of 2.0 mm that the sheets enter with increases to 4.0 mm in the bend due to the properties of the sheets in this job being different. This increased range remains as the sheets are transported open loop along the Output module. Various experiments [9] have shown an effective media path length variation in each 90-degree bend of up to 5 mm due to media basis weight variations from 50 to 300 gsm. Also, transporting sheets at varying velocities along a media path introduces path length variations. Since, e.g. the on-ramps connecting slower speed print engines with higher speed highways, utilize variable move times due to timing constraints, the velocities along certain media path segments can vary for each individual sheet. This will affect the effective path length of certain media paths that the sheet experiences, even for sheets with identical properties.

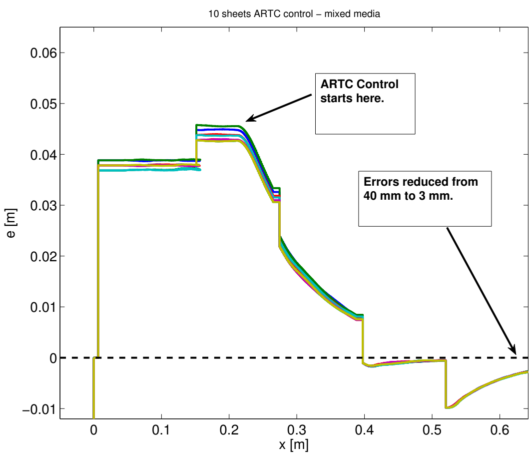

Fig. 13. Sheet tracking errors for Job 3: *Mixed media*, utilizing ARTC control. Both the mean as well as the range of the tracking errors are actively decreased throughout media path by the ARTC algorithm. Compare with figure 13 that utilizes open loop sheet control. On average, incoming errors were reduced from 40 mm to 3 mm and their range was reduced from 4 to 1 mm.

Experiments have shown a 6 mm variation in path length per 90-degree bend as speed varies from 1.5–4.5 m/s.

Since the printing system was designed to operate with a minimum inter-sheet spacing of 40 ms these variations are decreasing the margins available to avoid sheet collisions and operate gates properly. Also note that these position errors shown in these plots build up in a small part of the media path, in only one 90-degree bend, over a distance of 0.643 m. Keep in mind that the printing systems consists of approximately 17 m of media path and multiple bends.

B. *Experimental results* with *ARTC closed loop control*

Figure 13 shows the sheet tracking errors for Job 3, which consisted of 10 sheets of mixed media with the Output Module under ARTC closed loop control. The interesting observation that can be made is that as soon as the sheet is fully inside the Output Module, and becomes controllable, the ARTC algorithm starts to decrease the errors to zero, continuously as the sheets travel through the media path. Additionally, the range of the errors is effectively decreased, from 2.0 mm incoming, then 4.0 mm after the 1st bend down to effectively 1.0 mm (the controller sampling time is 1.0 ms so this translates to a position resolution at the sensors of 1.0 mm, so errors within +/- 0.5 mm are detected as 0.0 mm). The mean of the errors also approach zero, and are decreased from +40 to -3 mm throughout the Output Module. The mean errors would have reached zero had the media path portion been slightly longer or had a more aggressive controller gain been used in the ARTC control algorithm. Compare the continuous removal of errors by the ARTC algorithm in figure 13 with the constant errors remaining in figures 11 and 12. Note that the ARTC control algorithm in the Output Module reduced mean errors from 40 mm to 2.8 mm, and reduced the range of errors from 4.0 mm to 1.0 mm) over a distance of approx. 0.5 m.

VI. Conclusions

ARTC closed loop sheet control has been successfully demonstrated experimentally. It is able to control sheets with millimeter accuracy in very large and complex media paths and is a crucial enabler for reliable operation of large printer media paths and parallel printing systems. The author would like to thank the Xerox Research Center Webster parallel printing team members that were crucial for this project's success: Jack Elliot, Saurabh Prabhat, Marina Tharayil, Marc Daniels, Chinmaya Patil, Ron Root, Alex Brougham, Steve Moore, Tom Wyble, Bob Lofthus, Tom Scheib, Roy Daniel and Lynn Glanton. Also, big thanks goes to our research partners at PARC who provided the routing and scheduling algorithms used and general discussions on media path design and controls: Markus Fromherz, Wheeler Ruml, Haitham Hindi, Lara Crawford, Minh Doh and Rongh Zhou.

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