A FLEXURE-BASED HIGH-THROUGHPUT ROLL-TO-ROLL PRINTING SYSTEM

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In this paper, we present the design of a fully automated flexure-based high-throughput, roll-to-roll (R2R) printing system with multiple degrees of freedom misalignment correction capability for implementing several nanometer resolution contact printing techniques such as Microcontact Printing (MCP) and Nanoimprint. The completed system will be used to fabricate transparent metal grids as electrodes for organic photovoltaic cells and diffraction gratings with pitches of a few hundred nanometers.

ULTRA PRECISE R2R PRINTING

Although compatibility with R2R processes is the main driving force for many flexible electronics and organic photovoltaic devices (when compared with conventional inorganic semiconductor devices fabricated through lithographic processes), there is a common misperception that this high throughput, low-cost process produces devices of lower resolution and quality. This will not be true if we implement contact printing techniques such as Microcontact Printing [1,2] or Nanoimprint to properly designed R2R platforms. In fact, the printing resolution can be significantly better than lithographic processes as contact printing is not limited by diffraction. Complex high resolution patterns of tens of nanometers have been repeatedly demonstrated by the aforementioned techniques at laboratory scale [2]. However, it is not practical to directly scale up and apply these techniques to present state-of-the-art R2R systems, e.g. gravure printing and flexographic printing, which have approximately 15 micron print resolution.

To utilize a R2R process for precision printing, we must address the machine’s repeatability and accuracy issue. A R2R machine must possess nanometer repeatability in order to create patterns with submicron resolution. However, current state-of-the-art R2R systems mostly use conventional bearings to guide the printing motion and lack the required repeatability and precision. Additionally, current systems lack alignment features to compensate the "yaw" and "roll" errors (rotational errors in $\theta_Y$ and $\theta_X$ respectively, shown in Figure 1). This leads to non-uniform distribution of pressure during the printing process and pattern distortions.

![FIGURE 1: Illustration of misalignments between impression roller and print roller.](image)

DESIGN CONCEPT

We have been developing a flexure-based R2R printing system for generating submicron resolution metal patterns. This is achieved through precise position control between the web and the print roller that the stamp is attached to. Figure 2 shows a conceptual flexural mechanism design, where two monolithic blocks of compliant mechanisms are used to support the two ends of the print roller. This arrangement generates 4 degrees of freedom error correction capability, i.e. $x$, $y$, $\theta_X$ and $\theta_Y$. Each flexure block provides decoupled motion guidance capability in two independent axes. The arrows in Figure 2 indicate the placement locations of four positioning actuators; the stepper motor can be connected to the shaft of the print roller with an elastomeric coupler.

Figure 3 presents simulated results of the monolithic flexure subjected to an input displacement of 2mm in $x$ direction and -2mm in $y$ direction. By comparing these results, one can conclude that the cross-axis coupling errors are
minimized and will be eliminated when manufacturing tolerance is zero.

FIGURE 2: Conceptual design of the flexure-based roller positioner.

FIGURE 3: Simulated results of decoupled motion generated by the monolithic flexure stage. Motions in X (A) and Y (B) direction.

SYSTEM INTEGRATION
Figure 4 shows the core design of the R2R system (not including collection, intermediate guiding rollers). The two flexure blocks are driven by H2W’s voice coil actuators (y direction) and PI’s stepper motor actuators, i.e. M230.10S, (x direction) respectively. Their positions are monitored by 2 pairs of capacitance probes and eddy current sensors. These sensors provide high bandwidth (15 kHz) real-time position feedback for implementing closed-loop control.

The position of the web is controlled by a custom-designed web-guiding module. The module consists of four rollers, and two of the upper rollers are affixed to a rotary stage controlled by a stepper motor. The actual position of the web is detected by two infrared edge sensors. When the rollers in the upper frame are rotated, the unbalanced friction force causes the web to move in the lateral (z) direction. This arrangement insures the web path can be corrected within a short distance with minimized stress in the web.

To insure stable operation, air bearings are used to guide the motions of both the impression and print roller. Two load cells are also installed by the print roller to monitor the printing force in real time. Closed-loop web tension control is achieved through the use of a magnetic particle break/clutch and tension sensor.

FIGURE 4: CAD model of the partial R2R system; sensors and actuators are implemented for error motion sensing and correction.

To adapt the MCP process for R2R operation, we replace the normal glass substrate with 4” wide gold coated PET rolls. In the printing process, the web tension, printing load, substrate-stamp wrap angle, and print roller position need to be precisely controlled. For stamp preparation, PDMS stamps are fabricated by the injection molding procedure, following which the stamp is attached to a flexible steel plate that is then mounted to the motor-driven print roller.

CONCLUSION
We are developing a fully-automated flexure-guided high-throughput roll-to-roll (R2R) printing system. Upon completion, we will characterize the static and dynamic characteristics and performance of the system and adapt the Microcontact Printing technique to this R2R platform for manufacturing submicron precision photonic devices, e.g. diffraction gratings and transparent metal grids, on flexible substrates. The system will be able to produce high resolution, large area prints at the speed of 100-300 ft/min.

REFERENCES