Integrated Hardware, Software, and Sensor Design for Control of a Scalable, Continuous Roll-to-Roll Microcontact Printing Process

by

Scott T. Nill

B. Eng. Mechanical Engineering
Vanderbilt University, 2012

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

Master of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2014

© Massachusetts Institute of Technology 2014.
All rights reserved.

Signature redacted

Author...

Signature redacted

Department of Mechanical Engineering
May 20, 2014

Signature redacted

Certified by...

Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Thesis Supervisor

Signature redacted

Accepted by...

Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Graduate Officer
Integrated Hardware, Software, and Sensor Design for Control of a Scalable Continuous Microcontact Printing Process

by

Scott T. Nill

Submitted to the Department of Mechanical Engineering
on this 20th day of May, 2014, in partial fulfillment of the requirements for the degree of Master of Science

ABSTRACT

Soft lithography has been a long-time candidate for altering the landscape in micromanufacturing. Such processes promise lower cost in equipment and processed products while showing substantial gains in throughput and maximum dimensions. These distinct advantages allow for new advances in production ranging from inexpensive, fully flexible electronics to higher efficiency batteries and improved water purification systems.

Microcontact printing (μCP), a particular form of soft lithography, scales the rubber stamp concept down to the micron range. Past work has demonstrated sub-nanometer resolutions attainable with μCP. Currently, microcontact printing is usually performed with a flat stamp and substrate thus limiting the process to batch processing. Recent advancements have enabled conversion of the plate process to a roll-to-plate configuration through in-depth understanding and control of the stamp contact.

The transition to full roll-to-roll manufacturing, on increasingly larger scales, presents new challenges for sensing and control of this contact. In the past, the roll-to-roll printing process the control loop has not been closed around the actual contact and transfer process.

This thesis presents a new method for sensing, in real-time, this contact process that can be used in roll-to-roll, high-throughput production. Second, the design and implementation of an integrated control and automation system, integrating the novel sensing, is presented. Finally, an overview of the design and production of a precision machine incorporating the sensing, control and automation is given.

Thesis Supervisor: David E. Hardt

Title: Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
ACKNOWLEDGEMENTS

There are numerous individuals, far too many to name here, whose combined influence has led me to this point. There are, however, a few individuals I would like to individually recognize:

- First, I thank my family, mom and dad, Marshall and Grant, and Grandma Huser. Thank you for enabling me on all my endeavors and putting up with the occasional roller coaster in the garage.
- I thank my advisor Dave Hardt for his wisdom and guidance, and his shared curiosity and love for building things.
- Larissa and Adam, as the rest of the μFLEX team, they've made this project such a fun adventure, thank you.
- To Maia, Caitlin, Melinda, Joe, as fellow members of the Hardt Lab, thank you for your support and camaraderie.
- To all the outstanding colleagues of the LMP, especially Stephanie, Josh, Brandon, Adam, and the rest of the 135, my thanks for the great innovation, inspiration, and fun you contribute.
- Thank you to Leslie Regan and Michael Goldfarb whose encouragement and assistance brought me to MIT in the first place.
- To Molly, Alan, Anna, and Sarah, who remind me that Grudge Terrace is home, my deepest thanks
- Thanks are owed to the Center for Clean Water and Clean Energy as a joint program between KFUPM and MIT for supporting the work

Finally, I wish to give this work a special dedication to my grandfather, Robert Raymond Huser. Through the people, stories, and equipment he left behind, I learned firsthand what mechanical engineering and machine building truly are.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>3</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>5</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>7</td>
</tr>
<tr>
<td>List of Figures</td>
<td>11</td>
</tr>
<tr>
<td>List of Tables</td>
<td>15</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>17</td>
</tr>
<tr>
<td>1.1 Microcontact Printing</td>
<td>17</td>
</tr>
<tr>
<td>1.1.1 Configurations for Microcontact Printing</td>
<td>18</td>
</tr>
<tr>
<td>1.1.2 Inks</td>
<td>18</td>
</tr>
<tr>
<td>1.1.3 Stamp</td>
<td>22</td>
</tr>
<tr>
<td>1.1.4 Precision Printing</td>
<td>29</td>
</tr>
<tr>
<td>1.1.5 Printing Systems</td>
<td>31</td>
</tr>
<tr>
<td>1.1.6 Sensing and Metrology</td>
<td>35</td>
</tr>
<tr>
<td>1.1.7 Summary</td>
<td>36</td>
</tr>
<tr>
<td>1.2 Scaling</td>
<td>36</td>
</tr>
<tr>
<td>1.2.1 Scalable Configuration</td>
<td>36</td>
</tr>
<tr>
<td>1.2.2 Process Control</td>
<td>37</td>
</tr>
<tr>
<td>1.3 Contributions of the Thesis</td>
<td>37</td>
</tr>
<tr>
<td>2 Sensing Contact</td>
<td>41</td>
</tr>
<tr>
<td>2.1 Contact Sensing for Process Control</td>
<td>41</td>
</tr>
<tr>
<td>2.2 Prior Art in Contact Sensing</td>
<td>41</td>
</tr>
<tr>
<td>2.2.1 Contact Sensing in Research and Industry</td>
<td>41</td>
</tr>
<tr>
<td>2.2.2 Contact Sensing for Soft Lithography</td>
<td>44</td>
</tr>
<tr>
<td>2.3 Actuating Contact</td>
<td>46</td>
</tr>
<tr>
<td>2.4 Developing Sensing for Continuous µCP Using Fluorescent Stamps</td>
<td>47</td>
</tr>
<tr>
<td>2.4.1 Establishment of Functional Requirements</td>
<td>47</td>
</tr>
</tbody>
</table>
2.4.2 Concept Generation and Selection .......................................................... 52
2.4.3 Proof of Concept Testing ........................................................................ 55
2.4.4 Tool Fabrication ...................................................................................... 60

2.5 Deploying Fluorescent Contact Imaging ...................................................... 62
  2.5.1 System Model .......................................................................................... 62
  2.5.2 System Design .......................................................................................... 64
  2.5.3 Implementation ......................................................................................... 68
  2.5.4 Algorithm Development .......................................................................... 70
  2.5.5 Sensor Testing .......................................................................................... 76

2.6 Sensing for Control ...................................................................................... 82
  2.6.1 Methods for Control .............................................................................. 82
  2.6.2 Balance Sensing and Control ................................................................ 84
  2.6.3 Contact Length Sensing and Control ....................................................... 87
  2.6.4 Application to Closed-Loop Contact Control .......................................... 89

2.7 Conclusions and Future Work in Contact Sensing ...................................... 93
  2.7.1 Proof of New Sensing Concept ............................................................... 93
  2.7.2 Sensing for Process Control ................................................................. 93
  2.7.3 Future Work on Contact Imaging Physics ............................................... 94
  2.7.4 Future Work on the Optical System ....................................................... 94
  2.7.5 Future Work on the Image Processing Algorithms .................................. 94
  2.7.6 Application to Closed-Loop Control ..................................................... 94
  2.7.7 Conclusion .............................................................................................. 95

3 A Machine for Continuous μCP ..................................................................... 97
  3.1 Commercially Available Equipment ......................................................... 97
    3.1.1 Commercial Printing Press Construction ............................................. 97
    3.1.2 Control of Commercial Printing Presses .............................................. 99
  3.2 Roll-to-Roll Micro-fabrication ..................................................................... 100
    3.2.1 Machines for the Laboratory ............................................................... 101
    3.2.2 Commercial Machines ......................................................................... 103
5.1.2 Scalable Machines for Continuous Microcontact Printing Research and Production. 141
5.2 A Case Study in Deployment.......................................................... 142
5.3 Future Work.................................................................................. 144
  5.3.1 Sensing for Contact-Based Control ........................................ 144
  5.3.2 Control for Continuous Microcontact Printing....................... 144
5.4 Outlook....................................................................................... 144
LIST OF FIGURES

Figure 1.1: Traditional plate-to-plate microcontact printing process: ........................................ 17
Figure 1.2: Three basic configurations of the microcontact printing process: ..................... 18
Figure 1.3: Simplistic representation of SAMs on a gold substrate: .................................. 19
Figure 1.4: Hale's microcontact printing of liquid ink onto polymer substrate: ................. 21
Figure 1.5: Liquid inks are not as simple to print as SAMs: ............................................... 22
Figure 1.6: Conformal contact is achieved when the stamp conforms to surface asperities of the substrate [19]: ............................................................................................................ 23
Figure 1.7: Petzelka discusses two types of lateral collapse: ............................................. 23
Figure 1.8: The mold created by Petzelka to cast planar PDMS stamps from patterned master wafers: ................................................................................................................................. 24
Figure 1.9: A summary of the traditional microcontact printing process [19]: ..................... 25
Figure 1.10: A planar stamp is wrapped around a print roll to enable roll-to-plate microcontact printing: .......................................................................................................................... 26
Figure 1.11: Roll-to-plate microcontact printing has traditionally been accomplished with planar stamps that are wrapped around a print roll: .................................................................. 27
Figure 1.12: The centrifugal casting machine designed by Petzelka, and a cylindrically cast stamp: ................................................................................................................................. 28
Figure 1.13: The air bushing designed by Petzelka to enable to mounting of cylindrical stamps on metal rolls: ................................................................................................................. 29
Figure 1.14: Petzelka discusses four prominent failure modes of fragile PDMS stamps: ........ 30
Figure 1.15: An illustration of how the various failure modes of PDMS stamps can affect the printed results: .......................................................................................................................... 30
Figure 1.16: An illustration from the U.S. Patent filing of Kendale's planar microcontact printing machine: ................................................................................................................................. 32
Figure 1.17: The roll-to-plate microcontact printing machine developed by Petzelka: ............ 33
Figure 1.18: The roll-to-roll microcontact printing machine developed by Stagnaro: .......... 34
Figure 1.19: The print head developed by Baldesi [38]: .......................................................... 35
Figure 1.20: Sharp et al. present a method of in situ observation of stamp deformation: ..... 35
Figure 1.21: The completed µFLEX machine: ....................................................................... 38
Figure 2.1: Concept visualization of Total Internal Reflection (TIR): ................................. 43
Figure 2.2: Generic scheme for contact visualization using Total Internal Reflection: ......... 44
Figure 2.3: Total Internal Reflection (TIR) implementation for roll-to-plate microcontact flexography [39]: ................................................................................................................... 45
Figure 2.4: Contact image resulting from the TIR sensor shown implemented in Figure 2.3 [39]: 45
Figure 2.5: The precision print roll actuator: ........................................................................ 47
Figure 2.6: Implementation of the glass impression roll system for in-process sensing of stamp contact: ................................................................................................................................. 49
Figure 2.7: A graphical description of the contact length measurement: .............................. 51
Figure 2.8: An image from a TIR-based contact imaging system [39]: .................................... 53
Figure 2.9: Initial test of lighting system: ................................................................................ 56
Figure 2.10: Preliminary contact imaging experiments on microscope. ........................................... 57
Figure 2.11: Preliminary results of a fluorescence-doped stamp in step contact with a glass slide... 58
Figure 2.12: Preliminary results of a fluorescence-doped stamp in step contact with a PET substrate
....................................................................................................................................................... 59
Figure 2.13: A layered, patterned stamp under fluorescing under UV irradiation. ....................... 59
Figure 2.14: A trapped fiber in the contact experiment does well to demonstrate the clear contrast
between contact and no contact ...................................................................................... 60
Figure 2.15: Cross-section of the cast homogenous composite stamp ........................................ 61
Figure 2.16: Cross sectional views of the resulting layered composite stamp............................ 62
Figure 2.17: Graphical functional model of the composite fluorescence contact imaging technique.
....................................................................................................................................................... 64
Figure 2.18: The contact sensing system as implemented .......................................................... 64
Figure 2.19: Configuration of the optical system design showing the topology and parameters for the
optimization.......................................................................................................................... 65
Figure 2.20: Optical system optimization for the best imaging resolution and optical resolution.... 67
Figure 2.21: The adjustable mount for the video camera imaging system for in-situ contact sensing.
....................................................................................................................................................... 70
Figure 2.22: The imaging coordinate convention with respect to the print and impression rolls.... 71
Figure 2.23: Convolution of a contact image with a Sobel kernel for edge finding. .................... 74
Figure 2.24: An improved method of edge-finding for contact length measurement .................... 75
Figure 2.25: Video captures from the integrated contact sensing system showing the macro-scale
contact and balance sensing............................................................................................ 77
Figure 2.26: Still captures from sensing at peak resolution during a force ramp......................... 77
Figure 2.27: Static, long-duration test of the balance sensing signal to characterize noise. ............ 78
Figure 2.28: Static, long-duration test of contact length sensing to characterize noise under a 5
Newton constant force ..................................................................................................... 78
Figure 2.29: Three noise characterization tests of the contact length sensor performed at 3, 5, and 10
Newtonsons .................................................................................................................... 79
Figure 2.30: Normal probability plot for the balance sensing noise test at a constant 5 N test force.
....................................................................................................................................................... 80
Figure 2.31: Normal probability plot for the contact length sensing noise test at a constant 5 N test
force ........................................................................................................................................ 80
Figure 2.32: Histogram of a balance and contact sensing noise test at a constant 5 N test force..... 81
Figure 2.33: Single-sided amplitude spectrum of balance noise test at a constant 5 N test force. .... 81
Figure 2.34: Single-sided amplitude spectrum of contact length measurement noise test at a constant
5 N test force. .................................................................................................................... 82
Figure 2.35: Contact Length controller schematic ................................................................. 83
Figure 2.36: Balance controller schematic ............................................................................... 83
Figure 2.37: Schematic for the combined controller .................................................................... 84
Figure 2.38: Characterization of the balance indication as function of the print head angle....... 85
Figure 2.39: Natural response of balance to a step force input of 5 N at 3.5 s............................ 86
Figure 2.40: Controlled response of balance to a step force input of 5 N at 3.5 s..................... 87
Figure 4.11: A graphical representation of the control software architecture. ........................................ 135
Figure 4.12. The state machine forming the master program in the controller software architecture. ..................................................................................................................................................... 136
Figure 4.13. The summary system schematic for control of the μFLEX machine.......................... 138
Figure 5.1: Deployment of μFLEX East to KFUPM in Saudi Arabia. .................................................. 143
LIST OF TABLES

Table 2.1: Linear Encoder Specifications.............................................................. 47
Table 2.2: Contact Sensor Functional Requirements.......................................... 47
Table 2.3: Glass Impression Roll Specification.................................................. 48
Table 2.3: Inspection System Decision Matrix................................................... 55
Table 2.4: Preliminary Imaging System Experiments.......................................... 55
Table 2.5: Fixed values for optical system optimization..................................... 67
Table 2.6: Summary of optimized optical system parameters............................. 67
Table 2.7: Camera specifications......................................................................... 68
Table 2.8: Lens specifications............................................................................. 68
Table 2.9: Imaging system specifications............................................................ 69
Table 4.1: Web Handling Actuator Electromechanical Specifications.................. 115
Table 4.2: Web Handling Actuator Electromechanical Specifications.................. 117
Table 5.3: Print System Actuator Electromechanical Specifications..................... 118
Table 4.4: Servo Drive Interfaces....................................................................... 120
Table 4.5: Interfaces to the Voice Coil Amplifiers............................................. 122
Table 4.6: Classification of Signals..................................................................... 122
Table 4.7: Evaluation of Electrical Design against Objectives......................... 130
Table 4.8: Evaluation of Control Interface against Objectives.......................... 133
Table 4.9: Evaluation of Control Software against Objectives.......................... 137
Table 4.10: Evaluation of Electrical Design against Objectives......................... 138
CHAPTER

1 INTRODUCTION

This thesis presents advancements in sensing, control design, and machine architecture for advancing microcontact toward high-throughput, continuous manufacturing.

1.1 Microcontact Printing

Microcontact printing (μCP) was developed in the early 90's by Whitesides and Kumar at Harvard University [1]. In this embodiment of the process, polydimethylsiloxane (PDMS) resin is poured over a master template wafer that was patterned using a conventional lithographic process. The cured PDMS stamp is peeled back from the master and inked with alkanethiols. The inked stamp is brought into contact with a gold film substrate, and the alkanethiols transfer to the substrate where contact is made, in a pattern replicate of the master wafer template. These alkanethiols form a self-assembling monolayer (SAM) on the surface of the gold film, which is then used as a resist in a wet etching process. This process was able to reproduce patterns with features as small as 1 μm, and within a year of these results, Whitesides was able to pattern features down to 200 nm in size [2], though with limited quality. The process was further developed by Biebuyck et al. to reliably cast and print geometry with features below 100 nm [3]. A review of microcontact printing achievements and limitations is available [4], [5]. A general version of the μCP process is demonstrated in Figure 1.1.

![Figure 1.1: Traditional plate-to-plate microcontact printing process: (a) A master template is formed with conventional lithographic techniques. Typically, this is formed as a pattern of SU8 photoresist on a silicon wafer. (b) PDMS resin is cast poured onto the master template. Once cured, it is peeled from the template and shown](image-url)
to have reproduced the template’s features. (c) The PDMS stamp is inked with alkanethiols, and brought into contact momentarily with a gold-coated wafer substrate. These molecules diffuse onto the gold surface and self-assemble into monolayer. (d) The SAM acts as a protective mask for when the substrate is etched, leaving just the desired pattern of gold remaining.

1.1.1 Configurations for Microcontact Printing

The microcontact printing (μCP) process can generally be categorized into three categories to describe the configuration and motion of the substrate and stamp. The three configurations, presented in Figure 1.2. Plate-to-Plate (P2P), depicted in (A), was the first invented and moves the stamp linearly into contact with a stationary substrate. Roll-to-Plate (R2P), depicted in (B), utilizes a roll-mounted stamp to roll against a translating substrate. Roll-to-Roll (R2R), depicted in (C), places a rolling stamp in contact with a counter-rotating substrate.

1.1.2 Inks

The purpose of microcontact printing is to reproduce a master pattern on a substrate. A patterned stamp is used to deposit ink onto the substrate where contact is made. Because the printing relies on ink transfer from the stamp to the substrate, the process is highly dependent characteristics of the stamp, the ink, and the substrate. Compatibility between all three materials is crucial for successful printing.

Molecular Inks
Microcontact printing is most commonly performed with self-assembling monolayer (SAM) inks. A self-assembling monolayer is an organized assembly of molecules that form on a surface via adsorption. These single-molecule-thick layers occur when the organic molecules contain a functional head group that has a particular affinity for the target surface. These head groups cause the molecules to self-organize and anchor themselves in a single monolayer structured domain on the surface. The head group has an attached molecular chain that forms a tail, with a functional group at the end. These tails also neatly self-organize, protruding from the surface, and the functional groups at their ends can be changed to vary the interfacial properties of the monolayer. The organization of such a layer is depicted in Figure 1.3.

Figure 1.3: Simplistic representation of SAMs on a gold substrate. Typically, alkanethiols are used in microcontact printing, due to the molecule’s head group (2) showing a strong affinity for gold substrates (1). The tails (3) are functionalized for a variety of purposes, but most commonly, they are able to protect the gold substrate from an etching bath, resulting in a selectively etched patterned surface.

Alkanethiols are specific molecule commonly used to form SAMs. When brought into contact with gold substrates, alkanethiols self-organize into a protective monolayer that can be used to protect the gold from wet etchants. Typically, a PDMS stamp is wetted with a solution of alkanethiols in ethanol or other solvent. This stamp is allowed to dry before being brought into contact with the substrate, during which time the alkanethiols transfer via a diffusion process. This means that, in most cases, the alkanethiols are deposited exactly and only where contact is made between the stamp and the substrate. Once the alkanethiols are on the gold surface, they self-assemble into a monolayer within minutes [6].

The alkanethiols have been shown to quickly transfer to the substrate, with good pattern reproduction achieved with a stamp contact time of only 1 ms [7]. This is one of the benefits of using
SAMs in microcontact printing, as the short requisite contact time allows for high speed printing. As well, alkanethiols are a molecular ink that transfers via diffusion; there are no fluid dynamics effects that need to be considered. Finally, as alkanethiols diffuse through PDMS, a saturated stamp may allow for multiple prints before having to be re-inked [8]. For these reasons, alkanethiols have become commonly used in the process of microcontact printing on gold substrates.

There are a variety of other molecules that form SAMs on specific substrates. Geissler et al. demonstrate eicosanethiols have a similar affinity to alkanethiols for gold, silver, copper, and palladium surfaces [9]. This was used to print metal nanowires on a 1 μm pitch. Lopez and Craighead manufacture surface-relief gratings on a 300 nm pitch via microcontact printing of octadecanethiols onto gold [10]. Delamarche et al. print hexadecanethiols onto copper films in order to achieve a selective etchant mask for TFT LCD gate layers [11]. Jeon and Nuzzo selectively deposit copper onto various substrates using chemical vapor deposition with printed alkylsiloxanes as the SAM mask [12]. These molecules were shown to assemble on substrates of aluminum, silicon, titanium nitride, and their oxides. As well, glasses, indium tin oxide (ITO), and plasma-modified polymide substrates are patterned with the same process. Octadecyltrichlorosilane is shown to assemble on ITO coated glass, which was used in a process to make OLEDs [13]. Hexadecanephosphonic acid [9] and alkanephosphonic [14], [15] acids are shown to form SAMs on aluminum and aluminum oxide surfaces. This is significant because it might allow for the printing of SAMs onto aluminized PET film substrate in the roll-to-roll microcontact process, rather than having to use alkanethiols on expensive gold film substrate. This aluminum-coated film is made via the physical vapor deposition process, and is commonly used in a variety of industries.

More information on SAMs and their use in microcontact printing can be found in the review paper [16].

**Liquid Inks**

Microcontact printing is also be used to print liquid inks. In the field of printed electronics, conductive substrates with printed SAM masks are selectively etched to form the desired conductive traces. Instead, conductive liquid inks are directly printed onto non-conductive substrates in the
desired trace pattern as shown in Figure 1.4. In the printed electronics industry, PET films have emerged as a common substrates because of their low cost, high clarity, and ease of handling. The use of liquid inks allows for numerous other materials to be used as substrates in the microcontact printing process. Kaufmann and Ravoo provide a review of the use of polymer inks in microcontact printing, as well as a review of the use polymer substrates in microcontact printing [17].

Figure 1.4: Hale’s microcontact printing of liquid ink onto polymer substrate [18]. A PDMS stamp was used to transfer Cabot CSD-66 silver nanoparticle ink to a cyclic olefin copolymer substrate. The lines that form the hexagons are approximately 5 µm in width. Such a pattern is discussed in literature for its properties as a conductive grid with a high percentage of optical transmission, potentially useful in photovoltaic cells.

Owing to the fluid dynamics involved, the process of printing liquid inks with PDMS stamps is neither as well understood nor as robust as the SAM printing process. There are many more factors that come into play, such as the surface energies of the stamp and the substrate, the composition of the ink, the inking technique, the geometry of the features, etc. The variables and sensitivities of the liquid ink transfer process are studied in Hale’s thesis work [18]. Figure 1.5 depicts some of the results from Hale’s work demonstrating the use of liquid inks. Their use is often troubled by clumping as seen in the images. With a robust model for ink transfer at the micron scale, the direct printing of conductive patterns on polymer substrates could be scaled up into a high-rate manufacturing process.
1.1.3 Stamp

Typically, the stamps used in the microcontact printing process are cast out of polydimethylsiloxane, a silicon-based organic polymer. Commercially available Dow Corning Sylgard 184 PDMS is a thermoset silicone elastomer that is formed from the mixing of a base and a curing agent. The pre-cured fluid is poured onto a master pattern and is able to closely conform to its geometry. Typically, the masters are made from silicon wafers patterned with the negative of the desired geometry in a conventional lithography process. Drawing a vacuum on this casting helps to degas the liquid and improve results in casting smaller features. As this liquid cures into a solid, the cross-linking process does not cause any significant shrinkage or distortion. These characteristics enable the high fidelity replication of complex geometry with sub-micron features.

PDMS is also a good material for stamps because of its ability to make complete contact with substrates with surface asperities. Because SAMs only transfer from the stamp to the substrate where contact is made, complete contact is necessary for reliable feature replication. Petrzelka refers to the ability of a stamp to completely conform to a surface, even over small asperities, as conformal contact.
Figure 1.6 diagrams this phenomenon. The characteristic of PDMS that makes it good for conformal contact is its high ratio of surface energy to elastic modulus. This ratio is defined as the material radius of curvature [20] which, for PDMS, is on the order of 10 nm. The significant surface energy of the PDMS allows the stamp is able to conform around asperities on this scale, enabling PDMS stamps to make conformal contact with substrates that have a surface roughness of less than 10 nm.

Figure 1.6: Conformal contact is achieved when the stamp conforms to surface asperities of the substrate [19]

Though PDMS has a lot of characteristics that make it a good material to use as a stamp, it also has a variety of traits that are problematic. The high ratio of surface energy to elastic modulus can cause elastic collapse, where features spontaneously adhere to each other as shown in Figure 1.7. This effect is pronounced in features closely spaced or with large aspect ratios. PDMS is a soft elastomer, making it very sensitive to contact stresses and allowing it to easily deform. Finally, PDMS is prone to swelling when exposed to organic solvents [21]. This limits material compatibility to select inks and can cause large area deformations that decrease absolute accuracy.

Figure 1.7: Petrzelka discusses two types of lateral collapse, where the high surface energy of the PDMS stamp causes neighboring features to stick to each other [19]

Flat Stamps
Microcontact printing has traditionally been a plate-to-plate process. In this method, the PDMS stamp is cast from a planar, featured silicon wafer as is seen in Figure 1.8. This plate stamp is then inked and brought into contact with a flat substrate, transferring the ink to that surface as shown in Figure 1.9. Though it has been shown to be able to reproduce patterns with great fidelity even at feature sizes of less than 100nm, this plate-to-plate process is inherently limited and does not allow for printing areas larger than the master wafer. In order to allow microcontact printing to scale to large areas and high rates, a continuous process must be developed to replace this existing method of batch processing.

![Diagram of the mold created by Petzelka to cast planar PDMS stamps from patterned master wafers.](image)

Figure 1.8: The mold created by Petzelka to cast planar PDMS stamps from patterned master wafers [19]. These stamps were used in a plate-to-plate printing setup. As well, some of the stamps formed this way were wrapped around a print roll for roll-to-plate microcontact printing.
Wrapped Stamps

In order to bring microcontact printing to a roll-to-roll basis, the first challenge is to transform the tooling from flat to round. Xia et al. made the first steps in transferring to a round tool by simply wrapping a flat wafer-casted PDMS stamp around a hand-held roller as shown in Figure 1.10 [22]. Inking this roller with SAMs and rolling it over a flat wafer substrate yielded good results, showing that microcontact printing could be successfully achieved on a roll-to-plate basis. Though this was a necessary step on the way to continuous manufacturing, it is requisite to replace the rigid plate substrate with a thin flexible web in order to make the full transition to a continuous roll-to-roll process.
Figure 1.10: A planar stamp is wrapped around a print roll to enable roll-to-plate microcontact printing. Often, the stamp is held in place simply by its large surface energy. For more permanent and precise adhesion, the use of cyanoacrylate glue has been considered, and prior art has also shown PDMS stamps to be plasma bonded to glass cylinders, as in [23].

Rogers et al. proposed a process in which a flat PDMS stamp is plasma-bonded to a glass cylinder and printed on a flexible substrate [23], [24]. The Rogers group then worked on porting microcontact stamp-making techniques to a flexographic printing setting by investigating the fabrication of large area stamps [25]. Flat 12" by 12" PDMS stamps were cast with a mylar backing on a patterned surface, and demonstrated to be able to print features down to 1 μm. These stamps were proposed for printing on flexographic presses with flexible substrates at high speeds. The marriage of microcontact printing and flexography was referred to as microflexography. However, this printing technique was never tested.

Roll-to-plate and roll-to-roll microcontact printing processes require a cylindrical stamp for the print roll. For this purpose, nearly every machine in the literature uses a flat-casted stamp that is then wrapped around a cylinder [22], [23], [25]–[27]. Typically, these stamps are cast from patterned silicon wafers and then cut down into a rectangle before being mounted on a roll, so as to give a clean and prismatic stamp profile. However, wafer sizes are limited, so this process will not be able to scale. There are methods for casting larger area microcontact printing stamps [25], but these result in low absolute accuracy and have not been fully developed. In addition, any method that involves the
wrapping of a flat-casted stamp around a cylinder will result in residual stress and persistent pattern
deformation. Though a stamp can be cut to proper size for wrapping, there will always be a
discontinuity at the seam, where the ends of the stamp meet. Such as seam is shown in Figure 1.11.
This seam will result in a significant once-per-revolution disturbance that might preclude any reliable
printing of micron-sized features. Finally, the stamp accuracy can only be as good as the mounting
process. None of the mounting processes in the literature will be sufficiently accurate for mounting of
large stamps without causing any pattern distortions or thickness variations.

Figure 1.11: Roll-to-plate microcontact printing has traditionally been accomplished with planar stamps that are
wrapped around a print roll. However, this technique will invariably present a gap or seam where the two ends
of the wrapped stamp meet (orange). Such a seam results in a once-per-revolution impulse disturbance to the
system, often orders of magnitude greater than the height of the stamp features.

**Cylindrical Stamps**

One of the key enabling technologies necessary to achieve precision roll-to-roll microcontact
printing is the ability to cast a continuous cylindrical stamp and accurately mount it onto a roll. To
address this challenge, Petrzelka developed a centrifugal casting machine that allowed for the casting
of continuous cylindrical stamps [19]. These stamps are cast on the inside of a rotating cylinder onto
a layer of photoresist that has been patterned by a direct-write laser. These cylindrical stamps have no
seam and no feature distortion. The equipment required for and the result of this casting process are
both illustrated in Figure 1.12.
Figure 1.12: The centrifugal casting machine designed by Petzelka, and a cylindrically cast stamp [19]. This machine works by using a laser to pattern a thin layer of photoresist on the inside of a rotating drum. PDMS resin is then poured into the spinning drum, and the centrifugal force causes the resin to evenly spread throughout the interior surface of the drum. Once the resin is cured, the cylinder is stopped and the stamp is removed. Note the seamless nature of this stamp, and the ability it affords for continuous printing.

Because the PDMS is so sticky and difficult to slide onto a roll, a special bushing was developed to provide an air cushion for the stamp to slide on over the surface of the roll. When the stamp is in place, the air supply is cut off and the stamp collapses onto the roll as the fluid film dissipates. The bushing is removed from the roll, leaving just the cylindrical stamp mounted in a stress-free state, but fixed in place by the large work of adhesion. A demonstration of this mounting technique is displayed in Figure 1.13.
Figure 1.13: The air bushing designed by Petrzelka to enable the mounting of cylindrical stamps on metal rolls [19]. Because of the high surface energy of PDMS, it is too sticky to slide over a metal roll without assistance. This device forms a thin air film cushion between the stamp and the roll, allowing the stamp to be easily slid into place. When the air supply is turned off, the air film collapses and the stamp contracts onto the surface of the roll evenly.

1.1.4 Precision Printing

It is possible to obtain satisfactory patterns from microcontact printing with solely low-cost materials and techniques. However, in order to scale microcontact printing into a large-area high-rate manufacturing process, a reliable and repeatable process must be developed. The machine used for the purpose will likely have to have some precision designed and controllable elements in order to ensure consistent quality printing results.

Stamp Defects

The success of the microcontact printing process is contingent on the complete and conformal contact of the stamp with the substrate. This requires a great enough print pressure to ensure that there are no gaps between the stamp and the substrate. However, too great of a print pressure will lead to stamp defects that can significantly affect the integrity of the transferred pattern. Examples of defects introduced by excessive print pressure include roof collapse, where the roof of the stamp between features bulges outward to make contact with the substrate, and feature buckling, wherein features with large aspect ratios buckle under load. These examples are illustrated in Figure 1.14. Other potential printing defects include sidewall collapse, wherein the sidewalls of the features bulge significantly, and lateral collapse, wherein closely packed features stick to each other due to the large
surface energy of PDMS. Figure 1.15 demonstrates how these modes of stamp deformation can impact the produced product.

Figure 1.14: Petrzelka discusses four prominent failure modes of fragile PDMS stamps: (a) bulging features and sidewall collapse (b) roof collapse in sparsely patterned areas (c) buckling of features (d) lateral collapse due to the high surface energy of PDMS [19]

There have been many papers on the stability of PDMS stamp features [28], [29]. Sharp et al. investigate the theory behind these printing defects and formed models that help to guide the stamp design process [30]. Still, because of the high surface energy and low stiffness of PDMS, microcontact printing stamps often have very narrow process windows for complete conformal contact.

Figure 1.15: An illustration of how the various failure modes of PDMS stamps can affect the printed results: (a) a stamp in conformal contact without any significant defects (b) a high-fidelity replication of the intended pattern (c) a stamp showing three significant failure modes: (i) air trapping (ii) lateral collapse (iii) roof collapse (d) The printed result from the poor stamp contact is significantly different than the master pattern

In order to increase the robustness of the process to these failure modes, various materials stiffer than standard PDMS have been used to form the stamp. Schmid and Michel demonstrated the use of a special formulation of hard PDMS that was about four times stiffer than the regular formation, but at the expense of being more brittle [31]. A UV curable hard PDMS formulation by Rogers allowed for quicker curing times and alleviated thermal shrinkage issues that result from the usual thermal cure process for regular PDMS [32].
The original microcontact printing process by Whitesides experimented with using standard photolithographic plate material, but these were imprecise in recreating fine features and only able to pattern features down to 200 μm [1]. Finally, the potential for using block polymer elastomers as microcontact printing stamps was investigated by Trimbach et al [33]. These stiff thermoplastics are formed using a hot-embossing process that requires high temperatures and pressures, but can handle 10-15 times the load of traditional PDMS stamps before structural collapse occurs. These stiffer stamps are more robust to structural failure, but they have not been widely adopted in microcontact printing because their high stiffness also results in a decreased ability to achieve conformal contact.

1.1.5 Printing Systems

Rather than sacrifice the conformal properties of standard formulation PDMS for a less defect-prone stamp material, precision printing machines have been designed to actuate standard PDMS stamps in such a way that conformal contact is achieved without causing any feature collapse or defects. These machines, especially in the manufacturing setting, must allow for the precise control of contact pressure in the print region.

Kendale developed an automated plate-to-plate printing machine, a schematic of which is drawn in Figure 1.16, that used precision actuation of a hard-backed stamp to print onto silicon wafers [34]. By controlling the displacement and special orientation of the stamp plane, it is possible to control the deformation of the stamp features. Similarly, Burgin et al. built a contact aligner that enabled the careful control of the forces exerted on the substrate during the printing process [35]. This printing machine enabled the printing of sub-micron features and suggested that a similar design would work even for larger scale plate-to-plate machines.
Figure 1.16: An illustration from the U.S. Patent filing of Kendale’s planar microcontact printing machine [36], [37]. This machine precisely controls the roll, pitch, and height of the stamp to enable precise plate-to-plate printing. Though this form of displacement control might work for smaller wafers, it cannot be scaled up to a large area or continuous process.

Petrzelka built a precision roll-to-plate microcontact printing machine, depicted in Figure 1.17, that enabled control of either the displacement or force boundary conditions on the stamp [36]. This printing process is quite different from plate-to-plate printing, as there is only a narrow region of stamp-substrate contact at any given point of time. This contact propagates as the stamp is rolled over the substrate. The Petrzelka machine showed that the precise control over the contact forces was the key to roll-based microcontact printing, and that in-situ inspection of the print region could be a robust form of real-time process control. This precision roll-to-plate printing machine validated the potential for successful roll-to-roll printing and served as the inspiration for this thesis.
Figure 1.17: The roll-to-plate microcontact printing machine developed by Petzelka [19]. This machine utilized parallel kinematic flexure stages to give control over the height and tilt of the print roll. A linear positioning stage below the print roll was designed to carry a wafer or glass microscope slide substrate. As well, an optical prism could be mounted on the linear positioning stage, allowing for real-time in-situ visualization of the contact region between the round stamp and flat substrate.

To investigate the feasibility of roll-to-roll microcontact printing, Stagnaro developed a web-handling machine for the continuous printing of alkanethiols on gold foil [26]. This pilot-scale machine was possibly the first to combine the material system and printing methods of microcontact printing with the roll-based processing techniques used in the manufacturing industry. It demonstrated the successful printing of etch-resistant SAM patterns with 10 μm features at speeds of up to 400 feet per minute. These results show the potential for high-speed, roll-based microcontact printing. However, the machine was limited in its ability to control force at the contact region. The print force was indirectly controlled by manually adjusting micrometer heads, which compressed a compliant layer of foam on the impression roll against the print head. This gave little ability to control the contact between the stamp and the substrate, which would prevent this machine from being able to print more intricate and fragile patterns. As well, the use of a planar cast stamp limited the repeatability of the printing, as the mounting process was very dependent on the operator skill [27].
Overall, the Stagnaro machine, depicted in Figure 1.18, showed promise for roll-to-roll microcontact printing, but also demonstrated the need for a more precisely controllable print head.

![The roll-to-roll microcontact printing machine developed by Stagnaro.](image)

Figure 1.18: The roll-to-roll microcontact printing machine developed by Stagnaro. This machine achieved successful pattern transfer at web speeds of up to 400 feet per minute, but also demonstrated the need for a precision print head and a continuous stamp.

Baldesi continued work on this project and made a precision positionable print head for Stagnaro's roll-to-roll microcontact printing machine [38]. This print head was designed to have actuation in five axes, allowing for the precise setting of the print head location relative to the impression cylinder. However, the positioning was achieved through the manual actuation of micrometer heads. This design, shown in Figure 1.19, was an improvement over the original print head and allowed for the stage to be set in the proper location at the beginning of each print run. However, Baldesi concluded that automated actuators and a closed-loop controllable print head would be necessary for any further development of the process.
Figure 1.19: The print head developed by Baldesi [38]. The print roll is supported by parallel flexure stages with micrometer positioning. This gave manual control over five degrees of freedom, but it was determined that an active closed-loop controllable print head would be necessary for future roll-to-roll microcontact printing machines.

1.1.6 Sensing and Metrology

In the course of their work investigating the failure modes of PDMS stamps, Sharp et al. present methods for observing the stamp and the contact pattern during using an inverted microscope shown in Figure 1.20 [30]. This laid the groundwork for directly observing stamp behavior in situ.

Figure 1.20: Sharp et al. present a method of in situ observation of stamp deformation. The system utilizes an inverted microscope to view the contact. The stamp is placed pattern-side down and loaded through a glass sphere to permit coaxial illumination. Redrawn with permission from Effect of Stamp Deformation on the
The idea for imaging the stamp at the point of contact is employed by Petznelka to evaluate different methods for controlling the print head in a roll-to-plate configuration. Furthermore, the work suggests that direct sensing and control of the contact may be a viable method for scalable process control \[39\].

### 1.1.7 Summary

Process feasibility is proven for all three configurations of the stamp and substrate though plate-to-plate is the most mature having seen the first implementation. A system design for each machine is presented as well. The PDMS printing tool is presented along with some of its inherent advantages and challenges in use with microcontact printing. The importance of contact and its impact on the end product is emphasized through the different investigations.

### 1.2 Scaling

To scale the work, a configuration and method for process control is laid out with a roadmap for development.

#### 1.2.1 Scalable Configuration

Three possible configurations for the microcontact printing process are presented in Section 1.1.1. Using a roll-to-roll format allows for continuous processing and thus offers the best opportunity for scaling to large-area, high-throughput manufacturing. Plate-to-plate and roll-to-plate are fundamentally limited in the size of the article that can be produced. Developments in the toolmaking technique allows for the fabrication of seamless, continuous stamps. Coupling the two reveals a viable framework for implementation.

New, larger equipment must be built to enable the roll-to-roll format. As well, tools and sensors that are compatible with the new format must be constructed.
1.2.2 Process Control

Scaling the process, however, does not solely entail possessing the ability to produce over a large area. Equally important is the quality of the process. Implementing robust process control allows for higher product quality.

In his work, Stagnaro documents a lower limit to feature size before quality plummets. Specifically he relates the issue to the stamp making poor contact with the substrate when too much pressure is applied. He concludes that the fixed position of the print roller, combined with inherent imprecision in the stamp and mechanical assembly, create incidents of high and low print pressure [26].

Baldesi addresses the issue in part with precision, adjustable positioning of the print assembly [38] but lacks real-time control of the process to fully address the problem. Petzelka has the insight, based on modeling and experiments, that the stamp contact, as a function of the print pressure, is the true determiner of quality [39].

Petzelka designs and builds a roll-to-plate machine for controlling contact directly with feedback rather than blindly force. Furthermore, Petzelka demonstrated, once calibrated using contact observation, the process could be performed open-loop with force control with a 50 mm wide stamp. Using this contact controlled machine, Hale is able to demonstrate printing with inks beyond the thiols used previously with the microcontact printing process.

Thus, a roll-to-roll configuration with contact-based process control becomes the path to large-scale microcontact printing.

1.3 Contributions of the Thesis

This work advances continuous microcontact printing by providing scalable solutions for in-situ contact sensing, system design, and system control and integration. It integrates the work of Nietner [40], who has developed models and methods for patterning cylindrical stamps using direct-write laser lithography, and the work of Libert [41], who developed a precision print head system with two controllable degrees of freedom.

In this thesis methods are presented for contact sensing, applicable in a roll-to-roll configuration and robust to including substrate, allow open- and closed-loop contact control to be
investigated in larger-scale roll-to-roll implementation. These new methods leverage new fluorescent stamp constructions, specially designed optics, and image processing algorithms to sense the stamp contact in real-time.

This work further considers methods for transporting the web on the machine and outlines the selection of the resulting configuration. An examination design of the system for integrating the sensing, web handling, and printing in their mechanical embodiments demonstrates the scalability and adaptability of the machine.

Finally, this work demonstrates the integration of the components from an electrical and software control standpoint to provide a framework for the current and future iterations that is modular and highly expandable.

The sum of the work was the construction of a machine for continuous microcontact printing at MIT. This machine, shown in Figure 1.21, is μFLEX.

![Figure 1.21: The completed μFLEX machine.](image-url)
CHAPTER 2  
SENSING CONTACT

The actual process of microcontact flexographic printing occurs only when the image carrier is in intimate contact with the substrate material. It is during this time where material is transferred and patterned according to the design of the stamp. This chapter presents the design and development of an instrument for sensing contact in microcontact flexography (μCF).

2.1 Contact Sensing for Process Control

Petrzelka's work highlights the importance of contact fidelity in attaining high print quality [39]. His work concludes that constant force control on the stamp is sufficient to maintain good contact between the stamp and the substrate in roll-to-plate μCP with a 50mm stamp. In-situ contact sensing was used to confirm this hypothesis.

Thus the role of contact sensing in roll-to-roll μCP is potentially two-fold. The first role is to investigate the performance of force control for regulating contact as stamp widths grow to the continuous form of μCP. If it is found that the open loop force control is insufficient for regulating contact, the sensor shall provide a means for closing the loop around the stamp contact.

2.2 Prior Art in Contact Sensing

2.2.1 Contact Sensing in Research and Industry

Visualizing conformal contact is a problem that spans disparate fields from biometrics, through transportation, to biology. Often, special methods are required for sensing contact beyond direct observation in order to robustly discern regions of contact from regions just out of contact despite their relatively close geometric distances.
Early solutions for contact sensing were developed for fingerprinting methods [42], [43]. These methods use the principles of Total Internal Reflection (TIR) to highlight regions of contact against those of no contact. This general principle was later adopted on a larger scale by the rubber tire industry for studying the contact patch with the road surface [44]. Recent developments in biometric imaging have advanced past the TIR methods to include polarization-based detection methods [45]. Using polarization allows the camera to image past the actual contact surface to look at the underlying, three dimensional structure of the fingerprint itself. This gives more data and allows for a more accurate comparison of biometric data.

Advanced forms of contact sensing are also used in biology for contact microscopy. TIR again finds wide application on this small length scale though often in more exotic form. Total Internal Reflection Fluorescence (TIRF) microscopy has recently emerged as a method for high contrast imaging of cells in contact with a barrier [46]–[48]. The fluorescent technique highlights only those cells in contact with the UV illuminated, transparent barrier to help study specific mechanisms invisible with other forms of microscopy.

The phenomenon of total internal reflection, which lies at the core of so many of these technologies, occurs at the transition between two media of differing indices of refraction. Depicted in Figure 2.1 (A) shows the incident ray passing through the transition with purely refraction whereas (B) depicts an “internal reflection” at the boundary.
Figure 2.1: Concept visualization of Total Internal Reflection (TIR). (A) depicts regular refractive transmission of the incident ray and (B) depicts the total internal reflection of the incident ray.

In regular refractive optics, the path of a single ray through such a material transition is governed by Snell’s law (2.1) where $\theta_1$ is the angle of the incident ray, $\theta_2$ is the angle of the resultant ray, $n_1$ and $n_2$ are the refractive indices of the origin and destination materials respectively.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

(2.1)

The beam path will transition from refraction to reflection at some critical angle of incidence $\theta_c$ defined by (2.2) below. The indices of refraction $n_1$ and $n_2$ are again defined as before. It is important to note, however, the constraint on the relative magnitude between $n_1$ and $n_2$; in order for TIR to occur, $n_2 < n_1$ which is to say TIR will only occur going from a medium of higher index of refraction into a medium of lower index of refraction.

$$\sin \theta_c = \frac{n_2}{n_1}$$

(2.2)

Applying TIR for imaging conformal contact is actually examining two different interfaces in parallel. If it is assumed that the imaging medium is glass, the object is of transparent silicone and the imaging takes place in regular atmosphere, the contact sensing problem can be reduced to recognizing
the regions of glass-silicone interaction and glass-air interaction. If the three materials all have different indices of refraction, there will be two critical angles, one corresponding to each of the two types of material interaction. Performing illumination and detection at an angle that exceeds one \( \theta_c \) but not the other will produce a binary map of contact. In cross-section, this scheme may be implemented as seen in Figure 2.2.

![Diagram of TIR setup](image)

**Figure 2.2**: Generic scheme for contact visualization using Total Internal Reflection. Here the air-glass interface exceeds the critical angle, whereas the test article-glass interface falls below its critical angle.

Implemented properly, TIR will show high contrast bright and dark regions on an image detector that can be geometrically correlated back to the original contact pattern.

### 2.2.2 Contact Sensing for Soft Lithography

The common method of imaging conformal contact through TIR is used by Petzelka [39] to sense stamp contact in microcontact printing. Figure 2.3 shows the implementation of this technique on a roll-to-plate machine for evaluating new control schemes for \( \mu \)CF. Figure 2.4 shows the resulting image of the contact captured from the machine.
This TIR technique was implemented to study the contact between a sample stamp mounted to the roll and the glass surface of the ground prism used to form the TIR system itself. The system functioned superbly well for the roll-to-plate studies but would not be sufficient for operating in the continuous, roll-to-roll, implementation especially when viewed through a polymer substrate.

Moving to a roll-to-roll configuration presents two challenges. First, the geometries of rolls are not as nearly conducive to the geometries required for TIR as those found in a prism. Second, the roll-
to-roll implementation requires a plastic substrate web that introduces another set of interfaces that prevents TIR.

Novel methods have been developed for use in nanoimprint lithography to evaluate the process quality. One such method uses fluorescent microscopy in conjunction with a fluorescent labeled polymer to accomplish the sensing task [49]. Another method employs capacitance sensing for in situ monitoring of the molding process [50].

2.3 Actuating Contact

Of course sensing contact for control is meaningless without an appropriate actuator which may influence the contact. Such a role is fulfilled by the precision print head assembly. Its design and construction are detailed in Libert's work [41].

The print head, shown in Figure 2.5, comprises a print roll (1) to which the stamp is mounted. The print roll is mounted to two, low friction air bearings mounted in pillow blocks (2). These pillow block assemblies are, in turn, mounted to another set of air bearings supported by rails (3) to provide both translation and rotation as indicated. Each side of the carriage is actuated by a voice coil (4) that imparts a controlled force. The two voice coils impart the two degree of freedom: translation (y) and print head angle (ψ).
Figure 2.5: The precision print roll actuator. This assembly applies the print force to the stamp. The system comprises the print roll (1), air bearings (2), linear carriages (3), and voice coil actuators (4). Also shown are the two degrees of freedom in the print head: translation (y) and print head angle (ψ).

Affixed to each of the carriages is a high resolution, high bandwidth, optical encoder for measuring the linear displacement of each of the carriages. Specified in Table 2.1, these encoders are used to calculate the print head translation (y) and print head angle (ψ).

Table 2.1: Linear Encoder Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Renishaw</td>
</tr>
<tr>
<td>Model Number</td>
<td>T1001</td>
</tr>
<tr>
<td>Resolution</td>
<td>20 nm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Max Speed</td>
<td>0.648 m/s</td>
</tr>
</tbody>
</table>

2.4 Developing Sensing for Continuous μCP Using Fluorescent Stamps

Advancing μCF to roll-to-roll implementation requires developing a contact sensing system that can be used in roll-based production which includes substrates. The sensing system, providing information directly about the contact process, can be used for direct feedback control of the printing process.

2.4.1 Establishment of Functional Requirements

The new contact sensing system would have to address the functional requirements shown in Table 2.2, below.

Table 2.2: Contact Sensor Functional Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll-Basis</td>
<td>Roll-to-roll architecture</td>
<td>High</td>
</tr>
<tr>
<td>Substrate</td>
<td>Operate with PET substrate in place</td>
<td>High</td>
</tr>
<tr>
<td>Inked</td>
<td>Operate with inked stamp</td>
<td>Moderate</td>
</tr>
<tr>
<td>High-Speed</td>
<td>Operate at high substrate web speeds</td>
<td>Low</td>
</tr>
</tbody>
</table>
The requirements for the sensing system combine both operating conditions requirements as well as requirements for the information which the sensor is to provide. The following is a more in-depth discussion of each of the points of required functionality:

**Roll-Basis:** The sensing system must operate within the framework of a roll-to-roll architecture. This is a high-priority requirement as it is central to the development of the μCF process. As in flexography, the contact must be against a second, impression surface. In the previous roll-to-plate implementation of μCF, the impression surface was the face of a polished glass prism. The decision was made to create an analog to this contact condition in the roll-to-roll implementation. Thus the concept of a glass impression roller was conceived.

The glass impression roller allows for direct observation of the rolling contact and the polished circumferential surface of the roller injects minimal contact disturbance. The impression roll is unpowered and is turned by the capstan force of the wrapped substrate web. Table 2.3 presents the manufacturing specifications for the glass roll.1

<table>
<thead>
<tr>
<th>Table 2.3: Glass Impression Roll Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimension</strong></td>
</tr>
<tr>
<td>--------------------------------</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Glass SQ1</td>
</tr>
<tr>
<td>Index of Refraction (λ ≈ 500nm)</td>
</tr>
<tr>
<td>Surface Roughness (RMS)</td>
</tr>
</tbody>
</table>

Shown in Figure 2.6 is the configuration of the stamp roller and impression roller in the machine arranged with a generic sensing path. The impression roll is supported by an array of six radial, porous-media, air bearings2 that allow for contact-free, low-friction rotation of the cylinder,

---

1 Supplied by Hellma Optik GmbH, Müllheim, BW-DE
2 New Way Air Bearings, Aston, PA-US
and two axial thrust bearings for lateral support. The figure shows the clear line of sight through the impression roll to the contact region. In the figure (B) shows the arrangement of these air bearings around the roll and (C) shows the implementation on the machine.

Figure 2.6: Implementation of the glass impression roll system for in-process sensing of stamp contact. (A) displays the concept for including the glass impression roll. (B) demonstrates the air-bearing support for the impression assembly. (C) depicts the practical implementation of the proposed mount for the glass roll impression system.

Substrate: Roll-to-roll implementation for μCF naturally includes processing a substrate web. The sensing technique, to be useful for production feedback, must be robust to operating with film substrate in the sensing path between the stamp and the impression roll. The initial fabrication tasks of the μFLEX machine will be restricted to using PET, which is transparent to visible light. This makes the satisfaction of the substrate requirement more realizable in the near term.
Inked: The sensing system will eventually have to operate effectively in the presence of inks or other functional fluids used in production process. For the initial development of the sensor, this is only given a moderate priority as the variety in the coatings that could be potentially used with the process is too wide to find a universal solution. The space is narrowed by restricting the process to utilize only a handful of coatings including Thiols or UV-Cure printing inks. Finally, the requirement is slightly relaxed because the initial tests of the system will not include ink transfer but only study of the rolling contact.

High-Speed: The sensor should have appropriate bandwidth for capturing the dynamics of the moving substrate web. This, for example, sets the frame-rate requirement of an optical imaging system. In this implementation of the sensor and machine, the substrate web is transported at speed relatively slower than what is common in other forms of roll-to-roll processing. In previous work [39], web substrate speeds didn’t exceed $1 \frac{\text{mm}}{s}$ with a contact sampling frequency of $10 \text{ Hz}$. This is in stark contrast to commercial systems that transport the substrate webs at up to $30 \frac{\text{m}}{s}$.

Contact Output: The primary output of the sensor is the measure of the quality of the contact between the stamp and substrate against the impression roll. Sensing the quality of contact is of the highest importance to the application of the sensor as it this measure around which the control loops are closed to achieve the high resolution output. The contact parameter stands as the singular, absolute measure of the ink transfer process. Figure 2.7 illustrates how the contact length measurement arises from the interaction of the impression roll and the print roll.
Balance Output: As a corollary to the contact measurement itself, an additional parameter for the gross measure of evenness across the width of the stamp. This parameter is used to provide the initial operating point. Taken together with the output for the measure of contact from the sensor, the two degrees of freedom in the print roll positioning system. The contact balance measurement must be stabilized before the an accurate measurement of contact is sensed.

Feature Metrology: The sensor has the capability for returning accurate dimensional data regarding contact of discrete features. This functionality is given relatively low priority for this iteration of the contact sensor. The print actuation system only has two degrees of freedom thus being able to feedback data on specific points of contact is not at this stage useful. Future methods of actuation may include many more degrees of freedom and thus be able to use the information from a finely calibrated, integrated metrology system.

System Modification: Implementing the imaging system must be done without modifying existing hardware and workflows. This requirement was given low priority. Though the sensing system should
not require substantial changes to the already proven architecture, e.g. the existing stamp-manufacturing processes, there is substantial opportunity for altering the processes or influencing the concurrent component design for the machine.

### 2.4.2 Concept Generation and Selection

To address the new sensing challenge, five concepts are evaluated against the aforementioned functional requirements to make a selection for preliminary testing. The concepts are presented and evaluated in the following and a summary Table 2.4 concludes the section.

The concepts were generated to use an array of detectors sensitive to the visible spectrum of electromagnetic radiation. Such sensors are commonly line or area scan video cameras with CCD or CMOS photodetector arrays. The sensing values used for control are not immediately revealed in the raw images. To automate the task, the camera is connected to a computer with image processing algorithms tailored to the images obtained by the sensing technique which only then yield the parameters for contact and balance as specified in the requirements.

**Front Illumination:** This simple form of imaging uses broadband, diffuse, white light to illuminate the region of contact along the axis of the camera. The sensing physics allow for roll-to-roll implementation of this technique and the inclusion of a transparent substrate web. The orientation and condition of the lighting does not enhance or highlight the regions of stamp contact. Without particularly enhanced contrast at the contact, the signal-to-noise ratio (SNR) is not particularly high. This inhibits the implementation of robust, computational image processing algorithms for real-time automation of the sensing tasks. Therefore, the simple front illumination scheme is inappropriate for application to the contact sensing task.

**Total Internal Reflection (TIR):** As presented above, TIR as a technique for contact sensing and measurement in μCF has been implemented in previous work. Unlike front illumination techniques, TIR highlights and enhances the regions of stamp contact and is thus highly applicable to automated techniques of sensor data processing. Prior implementations were not inclusive of designs compatible
with roll-to-roll architecture though the sensing physics would not prevent such. As previously shown, a TIR method requires that the contact of interest form an interface that includes the conformal object of interest and the primary optical element of the sensing system. If the substrate web is introduced into this sensing system, this condition is violated and the sensing system fails. Thus, a TIR technique was deemed inappropriate for long-term implementation in μCF. Figure 2.8 shows an image from a TIR contact sensor [39]

Figure 2.8: An image from a TIR-based contact imaging system. [39]

**Polarized Illumination & Imaging:** Whereas TIR-based techniques require precise geometric conditions to be placed on the illumination and imaging angles to locate contact, a polarization-based approach “encodes” the actual rays themselves with an oriented polarization. When some of the rays are reflected at the stamp-impression contact interface, the polarization will be shifted. These rays are selectively imaged onto the camera sensor with a second polarizing filter. This technique has distinct advantages over TIR of requiring neither highly controlled geometries nor direct contact between the stamp and the impression surface. As with the suggested TIR technique, introducing the substrate web led to problems with the sensor. A PET substrate, comprised of long chain hydrocarbon polymers, will randomly reorient incident polarized light thus destroying any contact data encoded therein. Deemed inappropriate for immediate application to the μCF process in development at MIT, it is
important to note an appropriate alteration to the substrate composition is sufficient to allow for this implementation.

**Backlight & Brightfield:** A backlit technique places the object of interest between a light source and the imaging system. Rather than relying on pure reflections, it operates using the occlusion and transmission of the light source through the sample. Such a technique is effective for highlighting the bounds of contact in the transparent impression-substrate-stamp system. Inserting a proper light source to provide this illumination is problematic considering that the stamp must be mounted to a frictionless steel backing roller.

**Darkfield:** Illumination in darkfield can provide similarly high-contrast edge imaging as backlit techniques without requiring the light source to be placed in direct line with the camera and behind the contact region. In darkfield, light is introduced from the sides of the contact interface and scattered, rather than transmitted or reflected as in previously presented cases. This technique is sensitive to including the substrate web but not to the point of failure.

**Integrated Fluorescent Backlight:** A technique integrating a passive light source into the stamp itself leverages the unique advantages of a backlit imaging system while eliminating many of the issues concerning the mechanical and electrical integration of a light source behind the rotating stamp. Fluorescent particles integrated into the stamp are excited by radiation outside the sensitivity of the optical imaging system. When excited, the particles reemit diffuse light in the visible spectrum that serves as a diffuse backlight. Furthermore, the introduction of the excitation illumination can be along a number of differing geometries including all of the aforementioned. Thus, given its flexibility, satisfaction of the functional requirements, and integration with the existing design, this technique was selected as the candidate for further development.

Table 2.4 summarizes the discussed imaging techniques compared with the functional requirements of Table 2.2. As seen in the table integrated fluorescent backlighting is superior to the other methods for initial study in μCF implementation.
Table 2.4: Inspection System Decision Matrix

<table>
<thead>
<tr>
<th>Method</th>
<th>Roll-Basis</th>
<th>Substrate</th>
<th>Inked</th>
<th>Contact</th>
<th>Balance</th>
<th>Metrology</th>
<th>Modification</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Illumination</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>Total Internal Reflection</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Polarized Illumination and Imaging</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>2</td>
</tr>
<tr>
<td>Brightfield Backlight &amp;</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Darkfield Integrated Fluorescent</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>3</td>
</tr>
<tr>
<td>Integrated Fluorescent Backlight</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

2.4.3 Proof of Concept Testing

The fluorescent illumination concept was vetted for full-scale implementation in a series of small-scale bench tests to evaluate each of the proposed capabilities, to validate assumptions put forth in the initial consideration, and to inform the design of the full-scale system. The proof-of-concept experiments herein presented are summarized below in Table 2.5. Image results, with accompanying discussion, follow. Conducted in parallel to the imaging experiments, new stamp manufacturing techniques were developed. These efforts are summarized in section 2.4.4, and covered in detail in Nietner [40].

Table 2.5: Preliminary Imaging System Experiments

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Result Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Test of illumination</td>
<td>Figure 2.9</td>
</tr>
<tr>
<td>2</td>
<td>Fully fluorescent with step test</td>
<td>Figure 2.11</td>
</tr>
<tr>
<td>3</td>
<td>Fully fluorescent with PET substrate</td>
<td>Figure 2.12</td>
</tr>
<tr>
<td>4</td>
<td>Layered fluorescent with print features</td>
<td>Figure 2.13</td>
</tr>
</tbody>
</table>
The first experiment carried was simply to examine the interaction of the fluorescent particles within the silicone matrix of the stamp. The result is shown in Figure 2.9 and demonstrates effective suspension of the particles in the silicone matrix of the stamp. Furthermore, the experiment demonstrates the illumination from said particles when irradiated with UV light.

![Figure 2.9: Initial test of lighting system showing (A) a brightfield micrograph showing the suspended fluorescent particles in the silicone stamp matrix. The same field of view is shown in (B) in darkfield, fluorescent illumination showing the particles reemitting in the visible range.](image)

To simulate the contact conditions to be implemented on the full-scale sensor, the experimental setup shown in Figure 2.10. The setup comprises the fluorescent-PDMS composite stamp, a glass cover slide, and optionally, a sample of the PET web substrate. These components find analogy to the stamp, impression roll, and substrate web respectively. As well, the microscope objective is depicted as well standing in for the imaging camera and lens.

The second experiment carried out was to establish the expected contrast gains at a boundary of contact. A step of about 40 μm was created in a flat cast stamp to examine this case. The stepped stamp is brought in even contact with a glass cover slip to simulate contact with the impression assembly. The results presented in Figure 2.11 show (A) the corner of the step in purely backlight lighting scheme. The area of contact is visible where the image is bounded with the dashed cyan line. In the brightfield image, the contact is visible where the image is slightly darkened. The region of
contact is much more pronounced in (B) in the region of high intensity, again highlighted by the dashed cyan boundary. This experiment shows that the proposed imaging technique enhances the contrast of the contact boundary over what is seen in using existing brightfield techniques.

![Diagram of contact imaging experiments](image)

**Figure 2.10:** Preliminary contact imaging experiments on microscope. Setup shows (A) pure contact on glass and (B) contact imaging with PET substrate web in situ.

The third experiment extends the findings to examine the imaging results from the introduction of the PET substrate web. In Figure 2.11 the contact is again bounded in blue. The same step of about 40 \( \mu \text{m} \) is again shown. The introduction of the substrate does diminish the quality of the signal slightly as seen by the slightly “murkier” image. The contact is still both clearly visible and the edge substantially highlighted by the illumination technique. The experiment concludes the illumination and imaging technique is able to resolve enhanced contact information even with the introduction of the substrate web.

The previous experiments were conducted with experimental stamp samples produced with fluorescent particles dispersed throughout. The fourth and final proof of concept experiment was to introduce the feasibility of a layered composite stamp. Detail is given in section 2.4.4 as to the motivation for experimenting with such a stamp construction. Furthermore, the experimental sample was produced with features similar to those to be printed as a final verification of the method. Again, the PET substrate web was included in the test setup to simulate operating conditions.

Depicted in Figure 2.13, the results of the test show excellent contrast between the horizontal lines in contact and the surrounding areas of no contact. This result demonstrated the feasibility of...
working with a layered composite fluorescent stamp, rather than with a homogenous fluorescent stamp. Further, the experiment demonstrated feasibility of using the sensing method with patterns for printing.

Figure 2.11: Preliminary results of a fluorescence-doped stamp in step contact with a glass slide. An image captured in brightfield (A) shows the contact area in the blue bounded region. Likewise, (B) shows an image captured with the fluorescent illumination technique.

The proof of concept tests all demonstrated very high likelihood of successful full-scale implementation of the imaging technique. An open question remained regarding the situation where the impression surface and the stamp were in very close proximity but still out of contact. Would the substantial contrast difference that was observed in the step and line tests still appear despite the close air gap? This question was addressed by happenstance a dust particle was trapped between the stamp and the PET substrate web. Figure 2.14 shows the result micrograph and a schematic of the assumed situation. Important to note is the reappearance of the step contrast change between the area of contact and the area of no contact despite the very close geometric proximity of the two surfaces.
Figure 2.12: Preliminary results of a fluorescence-doped stamp in step contact with a PET substrate sample and a glass slide. The image shows the contact regions, highlighted in blue, are emphasized in the fluorescent imaging technique even with the presence of PET.

Figure 2.13: A layered, patterned stamp under fluorescing under UV irradiation. The lines of contact are highlighted in the horizontal direction.

Taken in summary, these experiments all proved the concept of the proposed integrated fluorescent backlighting as a valid method for visualizing stamp-substrate intimate contact in microcontact printing.
Figure 2.14: A trapped fiber in the contact experiment does well to demonstrate the clear contrast between contact and no contact despite close physical separation. A diagram to the right illustrates a cross-sectional view of the constituency comprising the situation.

2.4.4 Tool Fabrication

This section briefly presents the novel process for making stamps developed at MIT for tools in microcontact flexography. Of specific concern is how the addition of fluorescent particles will influence that process. (For a more complete consideration of the process development, see Nietner [40].)

The MIT process was developed to produce seamless, cylindrical stamps [39], [51] from polydimethylsiloxane (PDMS) silicone. The technique uses a centrifugal process to achieve excellent geometry control.

For initial testing, the composite fluorescent stamps result from a suspension of consumer grade fluorescent dye. To make the homogenous composite stamp, the particles are simply suspended in the uncured PDMS and cast in the centrifuge to cure. However, the dynamics of the centrifugal casting process caused the particles to migrate to the stamp surface, distorting the printing topology of the stamp. These effects are shown in Figure 2.15.
Figure 2.15: Cross-section of the cast homogenous composite stamp showing the topology distortion at the feature level caused by the intrusion of the fluorescent particles.

The introduction of a layered composite stamp construction remedies this situation by building a barrier to impede the migration of the fluorescent particles. A transparent PDMS layer is first cast to create the fine geometries required for printing. The transparent PDMS has excellent optical properties in transmission and is backed by a homogenous PDMS-fluorescent composite. The results of this new construction under (A) brightfield illumination and (B) UV irradiation are shown in Figure 2.16.

With their excellent geometry reproduction and outstanding results in preliminary experimentation, a layered composite construction was selected for the full-scale implementation of the contact imaging system.
 Deploying Fluorescent Contact Imaging

Following on the heels of a successful series of preliminary experiments, this section examines a full-scale design and implementation of a fluorescent contact imaging system. The section gives a more in-depth consideration of the sensing physics, the theoretical and practical designs for the system, sensor data processing and algorithm development, sensor characterization, and application to closed-loop control.

2.5.1 System Model

A schematic model of the imaging system is presented as Figure 2.17 with illustrative ray paths to demonstrate the functionality of the system. The model shows the three optical media with which the rays interact. The stamp is a layered composite construction with a fluorescent upper portion and a pure PDMS lower, feature carrying half. The rays numbered one through four indicate the incoming UV ($\lambda = 405\text{nm}$) rays to excite the fluorescence in the stamp. The rays are confined to the impression roll through total internal reflection. The green rays indicate the visible light from the excited fluorophores propagating toward the camera sensor.
Once entrained in the impression roll, there are four options for the path any single ray can take based on the criteria of total internal reflection for the glass-air, glass-PDMS, and PDMS-air interfaces. Considering equation (2.2), $n_{air} \approx 1.0, n_{S1} = 1.46, n_{PDMS} = 1.4$ [52] these conditions are bounded in the following way. The condition for the ray to depart the glass solely at the PDMS interface is $43^\circ < \theta < 73^\circ$ and to be entrained in the clear PDMS when $46^\circ < \theta$.

These criteria are illustrated graphically by the four numbered rays in the Figure 2.17. The first ray (1) shows reflection off of the glass-air boundary back into the impression roller. The second ray (2) meets the criteria to exit the glass impression and is entrained by total internal reflection within one of the features in the stamp. The third ray (3) is refracted through the interface and does not encounter the sidewalls of the lower, transparent layer of the PDMS stamp.

The rays that are transmitted through the pure PDMS impinge the fluorescent layer and excite the fluorophores which in turn emit in the visible spectrum. This phenomenon is represented by the green glow in the figure. It is significant to note the illuminated area on the fluorescent layer is wider than the corresponding feature resulting in some "gain" factor to the imaging system. This gain geometry is usually beyond the depth of field of the imaging system but still is seen as a source and will blur the edges the true geometry.
The preceding section described the model of the functionality for the sensing system to create the image of the contact. The image must then be collected on the camera sensor. Additional optics in a lens assembly are required to focus the image onto the camera sensor. Figure 2.18 shows the relative arrangement of the lens/camera system, the impression roll as an optical element, and the image source at the point of contact.

The question then becomes how to select a lens and camera that would be appropriate. There are actually two imaging tasks at hand. One is to image the entire width of the stamp, approximately 50mm, to sense the large area contact parameters including the side-to-side balance of the contact and the average length of the contact. The physical reference for the contact length is shown in Figure 2.7. The system should also have the ability to show individual stamp features as they come into contact.
similar to the TIR image in Figure 2.8. The first task sets the requirement on the maximum field of view for the system in order to see the entire width of the stamp in one image. The second places requirements on the minimum feature size the camera can resolve.

The field of view is determined by the size of the image sensor in the camera and the magnification of the optical system. The relationship between the sensor size and the projected field of view where the system is focused is related by the magnification by the following (2.3) where \( A_s \) is the actual area of the sensor, \( A_p \) is the projected area of the sensor at the point of focus, and \( M > 1 \) is the magnification of the lens system. With the current tool making techniques for \( \mu CP \) at MIT, the width is 50mm.

\[
A_p = \frac{1}{M} A_s
\]  

The other imaging objective, to view individual features under high magnification, is limited not only by the magnification of the imaging lens system, but also the fundamental optical resolution. These two limits can be taken together to form the design equations for optical system. Figure 2.19 shows the design variables and the geometric arrangement of the components of the imaging system.

![Figure 2.19: Configuration of the optical system design showing the topology and parameters for the optimization. The view is shown top-down.](image)
The magnification of the imaging system, $M$, is determined from the object distance, $d_o$, and the focal length of the imaging lens, $f$, according to eqn (2.4) below.

$$M = \frac{f}{d_o - f} \quad (2.4)$$

The magnification is used to correlate the distance between the pixels in the camera, $L_p$, to the minimum distance between two points on the stamp, $L_R$, the imaging resolution of the system. The correlation between $L_R$ and $L_p$ by $M$ is shown in (2.5). Combining (2.4) and (2.5) yields (2.6), the design equation around the resolution limit.

$$M = \frac{f}{d_o - f} \quad (2.5)$$

$$L_R = L_p \left( \frac{d_o - f}{f} \right) \quad (2.6)$$

Magnification is determined but also limited by optical resolution, the minimum separation angle at which two points are distinguishable from one another. This angle, $\theta$, is dependent on the wavelength of the light, $\lambda$, and the diameter of the aperture through which they are observed, $D$, according to (2.7). From this, a resolvable distance between the two objects, $L_R$, at an observation distance, $d_o$, is found with (2.8).

$$\theta = 1.22 \frac{\lambda}{D} \quad (2.7)$$

$$L_R = 2d_o \sin \left( 1.22 \frac{\lambda}{D} \right) \quad (2.8)$$

Either the optical resolution or the sensing resolution will limit the resolution of the total system at some set of operating parameters. The design objective is to minimize the overall $L_R$ so system resolves the smallest possible feature. The optimization is performed around the two parameters of the lens, $f$ and $D$. The other values are fixed according to Table 2.6, below.
Table 2.6: Fixed values for optical system optimization.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>500 nm</td>
<td>Common approximation for broadband visible light</td>
</tr>
<tr>
<td>$d_o$</td>
<td>250 mm</td>
<td>Minimum safe mounting distance on machine</td>
</tr>
<tr>
<td>$L_p$</td>
<td>5, 10 $\mu$m</td>
<td>State of the art vision cameras [53]</td>
</tr>
</tbody>
</table>

With both the design equations and the all of the variables accounted for, the maximum for the zoom is found at the optimization of the variables. Resulting plots of the two governing equations are shown below as Figure 2.20. The best achievable resolution is at the intersection of the two curves. The results of the optimization are also presented in Table 2.7.

![Figure 2.20: Optical system optimization for the best imaging resolution and optical resolution. The optimal resolution of 7.7$\mu$m is achieved with a pixel pitch of 5$\mu$m at a focal length of 99 mm and an aperture diameter of 19.8 mm.](image)

Table 2.7: Summary of optimized optical system parameters.

<table>
<thead>
<tr>
<th>Pixel Pitch</th>
<th>Optimized Parameter</th>
<th>Optimized Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Imaging Resolution Limit @ 5 $\mu$m Pixel Pitch</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Imaging Resolution Limit @ 10 $\mu$m Pixel Pitch</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Optical Resolution Limit</td>
<td>10</td>
</tr>
</tbody>
</table>

67
2.5.3 Implementation

The optimization performed above is for the ideal case and does not necessarily represent components that are available. The optimization exercise helped to bound the component search.

The camera was selected with a near 5μm pixel pitch. From previous work [39], a lower bound on the control loop frequency for the contact control was set at 10 Hz. The camera was selected to have a frame rate amenable to meeting this specification. A camera with a Gigabit Ethernet interface was selected to interface easily with the control system, detailed in section 4. Table 2.8 summarizes the camera specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Basler GmbH</td>
</tr>
<tr>
<td>Model Number</td>
<td>acA1300-60gc</td>
</tr>
<tr>
<td>Sensor Type</td>
<td>CMOS</td>
</tr>
<tr>
<td>Pixels</td>
<td>1280 x 1024</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>5.3μm</td>
</tr>
<tr>
<td>Sensor Size</td>
<td>6.78 x 5.43 mm</td>
</tr>
<tr>
<td>Interface</td>
<td>GigE</td>
</tr>
</tbody>
</table>

Selection of an appropriate lens system was similarly driven by the results of the optimization study. A manual zoom lens, with adjustable focus, was selected. This allows for one camera to be adjusted for viewing the entire width of the stamp for the large-scale contact measurement or at the peak resolution for viewing the distinct features. The lens does have a minimum working distance of 280mm which is slightly longer than the 250mm used in the optimization. The specification of the lens is given in Table 2.9.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Computar</td>
</tr>
</tbody>
</table>
Model Number: MLH-10X
Zoom Ratio: 10:1
Focal Length: 13-130mm
Aperture: F5.6-F32
Aperture Diameter at full Zoom: 23-4.1mm

With the particular pairing of the presented lens and camera, the overall system performance was calculated. These results are presented as Table 2.10.

**Table 2.10: Imaging system specifications.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized Resolution</td>
<td>9.3μm</td>
</tr>
<tr>
<td>Maximum Magnification</td>
<td>0.57</td>
</tr>
<tr>
<td>Minimum Field of View</td>
<td>12 x 9.5mm</td>
</tr>
<tr>
<td>Maximum Field of View</td>
<td>139 x 111mm</td>
</tr>
<tr>
<td>Minimum Magnification</td>
<td>0.048</td>
</tr>
</tbody>
</table>

The camera and lens were attached to an adjustable mount for positioning it properly in the optical path. The mount has a simple linear plane bearing stage for gross alignment across the stamp and a precision stage for vertical alignment with the impression roll. This assembly is presented in Figure 2.21 in (A) schematic and (B) as implemented on the machine.
Figure 2.21: The adjustable mount for the video camera imaging system for in-situ contact sensing. (A) shows the schematic of the system highlighting the axes of motion. (B) depicts the implementation of the camera mount in place on the machine.

2.5.4 Algorithm Development

Acquiring an acceptable image showing the regions of contact on the stamp is only half of the battle. Automated processing of the images to extract the actual contact information is necessary for the schemes utility in sensing.

As discussed in section 2.4.1, the sensor yields two streams of information about the stamp contact: balance data and contact length data. These data are generally coupled to one another thus the measurements are not entirely independent. This fact can be exploited to simplify each individual sensing algorithm especially in the case where control is closed around each parameter individually. Specifically, the contact length measurement algorithm is drastically simplified when it is assumed that
the contact is already in proper balance as will be discussed in the following. Figure 2.22 presents the coordinate convention used in this section.

![Figure 2.22: The imaging coordinate convention with respect to the print and impression rolls used in the ensuing presentation of the imaging algorithms.](image)

**Balance Sensing**

The balance sensing algorithm is intended to detect angular misalignments between the print head and the impression roll as they manifest as uneven pressure across the width of the stamp. This sort of large-scale sensing requires the camera to have the entire width of contact in the field of view. In the case of imbalanced contact, assuming the stamp is periodically patterned across its width, the image of contact will be biased to the side of the stamp under greater contact pressure. From an imaging standpoint, this amounts to a distribution of intensities that are not centered about the middle of the stamp. Therefore, a centroid locating approach is a fast and appropriate basis for the algorithm. Furthermore, as the print head is only actuated in one rotational axis, only the centroid in the $x$ direction must be calculated. An effective way to find the centroid of an image is the calculation of the image moment [54], [55].

The moment, $M_{pq}$, of an intensity field, such as an image, is calculated according to eqn (2.9) where $I(x, y)$ is the intensity at the point $(x, y)$ in 2D space.
In a discrete, sampled signal, such as an image captured using a camera, the calculation of the image moment is done according to (2.10).

\[
M_{ij} = \sum_{x} \sum_{y} x^i y^j I(x, y)
\]  

(2.10)

From the expression of the moment, the centroid, \(\bar{x}\), is found by evaluating \(M_{00}\) and \(M_{10}\) where

\[
\bar{x} = \frac{M_{10}}{M_{00}}
\]  

(2.11)

As the centroid of the image deviates from the centerline of the field of view, appropriate control action is applied to servo the angle of the print head with respect to the impression roller to bring the image centroid back to the field of view centerline. If aligned properly, this will correspond to even contact pressure across the width of the stamp.

**Sensing Contact Length**

After the balance has been corrected by the print head force controller, the contact sensing begins. Whereas the balance sensing operated on the large scale structure of the image, the contact sensing is tasked with the slightly more difficult job of locating the boundaries of where the stamp enters and leaves contact with the substrate and impression roll. These boundaries are often indicated by a sharp transition in image intensity. Due to the gain factor occurrence previously mentioned in section 2.5.1, the edges of the contact may not be as distinct as in an ideal case.

Edge finding is most often accomplished by computationally inspecting the gradient of the original image. High values of the gradient indicate a rapid change in intensity from one pixel to the next. Often these images are sampled and thus discrete operations are used to approximate the gradient.
A common, fast method for approximating the image gradient convolves the source image with the Sobel kernel [56]–[58]. As shown below, different kernels are required to estimate the gradient of the image \( A \), in \( x \), \( G_x \), and in \( y \), \( G_y \), calculated according to eqn (2.12) and eqn (2.13). The total gradient, \( G \), is calculated according to (2.14).

\[
G_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} \ast A \tag{2.12}
\]

\[
G_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \ast A \tag{2.13}
\]

\[
G = \sqrt{G_x^2 + G_y^2} \tag{2.14}
\]

Figure 2.23 demonstrates the application of this gradient estimation technique to the original image \( A \). The total gradient is shown in (B) and exclusively the \( x \) direction estimated gradient is shown in (C). A strong indication of the edge is seen in (B) but taking the total gradient actually adds noise back into the image (C). Leveraging the previous knowledge that the balance controller is providing consistent contact in \( x \) and assuming proper mounting of the camera, it is an acceptable assumption that the edge of the contact will be primarily indicated in the \( x \) direction gradient.

The Sobel method is designed to be able to detect edges in any orientation. As the orientation of the edges of the contact region are already known, additional measures are taken to enforce this knowledge onto the image processing. An additional kernel was derived to consider the likelihood of the edge occurring at any particular point where the magnitude of the gradient is high. This kernel (2.15) operates on \( G_x \) to yield \( B \), a result which considers the behavior of the eight nearest pixels.

\[
B = \begin{bmatrix} 0 & -1 & 0 \\ 2 & 3 & 2 \\ 0 & -1 & 0 \end{bmatrix} \ast G_x \tag{2.15}
\]
Figure 2.23: Convolution of a contact image with a Sobel kernel for edge finding. (A) is the source image. (B) is the estimate of the gradient in the x direction. (C) is the estimate of the total gradient throughout the image.

If the adjacent pixels along the x direction also have high gradients, then the overall likelihood that a high gradient at the point of interest is on the edge. If however, the pixels in the y direction should also have high gradient, then the point is less likely to indicate the edge of the contact.

The result of applying this additional convolution is shown in Figure 2.24. (A) is the representation of $G_x$, (B) is the result of the additional convolution, $B$, and (C) shows the detected upper and lower lines of contact. The final placement of these lines is done by finding the maximum
and minimum values for every column in $B$, which are the locations most likely to correspond to the edges of contact. Each point is then used to best fit the line by least squares.

Figure 2.24: An improved method of edge-finding for contact length measurement. A secondary convolution of $G_x(A)$ adds consideration for how the edge should appear by looking at neighboring pixels (B). With the higher fidelity from this additional step, the yellow lines of contact can be placed with increased confidence (C).

An advantage to the gradient-based method is its relative robustness to varying lighting conditions. Simple summation of area or thresholding to find edges requires an arbitrary intensity to be selected as the indication of contact. With changing conditions in lighting, these intensity set points may likewise vary making repeatability of the sensor problematic.
The addition of the second convolution helps to incorporate the a priori knowledge regarding the orientation and appearance of the contact lines. Adding this extra step helps to abate some of the problem with detecting along a blurred edge.

2.5.5 Sensor Testing

Qualitative Verification

Testing of sensor for balance and contact validation was achieved with ramp tests about both to check repeatability and accuracy. Tests under static tests were also conducted to characterize the noise in the signal. The test was conducted under constant force over the course of five minutes. The histograms shows the random distribution of the noise.

Following initial verification, the sensor was placed through its various modes of sensing. First was the macro-scale sensing of contact on the stamp. The field of view was established to capture the entire width of the stamp. Figure 2.25 shows a video capture from the balancing operation under these conditions. In (A) the intensity is biased to the right which generates a corresponding displacement in the image centroid. The balance controller is the activated (B) and the intensity is evenly distributed across the width of the stamp returning the image centroid to the center of the field of view.
Next, the imaging system was set up to its peak resolution to image some of the individual features on the stamp. Figure 2.26 shows two captures from this imaging condition. Under balance control, the force was ramped taking the stamp from a state of good contact (A) to full collapse (B).

![Figure 2.26: Still captures from sensing at peak resolution during a force ramp. The images show results from good contact (A) and full collapse of the stamp features (B).](image)

**Quantitative Characterization**

The two sensing parameters, contact and balance, were independently characterized to understand how the aspects of contact couple the machine and the stamp.

Video is an inherently noisy signal [59], [60], thus noise in the contact and balance signals is not unexpected. To characterize the noise and evaluate the resolution of the sensor, static, long-duration tests were performed.

Figure 2.27 shows a sample of the two-minute test of the balance sensing, under constant force conditions, for a five Newton print force using the print head system developed by Libert [41]. The noise is apparent in the signal, and there is deterministic behavior of slow decay that is visible in the signal. This decrease may be caused by the stamp actually creeping viscoelastically under uneven, but constant force, which is a phenomenon well established for PDMS [61].
Figure 2.27: Static, long-duration test of the balance sensing signal to characterize noise. A test force of 5 Newtons is applied.

Figure 2.28 shows a similar static test performed on the contact length sensor. The noise is again noted on the signal in this example case for a five Newton constant force. In this case, the signal does not display the deterministic behavior at the same scale as before but still shows a downward trend. Again, this may be attributed to the viscoelastic properties of the PDMS.

Figure 2.28: Static, long-duration test of contact length sensing to characterize noise under a 5 Newton constant force.
The noise tests for both sensing systems were performed at nominal, steady-state forces of three, five, and ten Newtons. Figure 2.29 displays the three tests of the contact length measurement system together. As well, the figure shows the different steady-state contact lengths that correspond to the three test forces.

![Graph showing contact length measurements](image)

Figure 2.29: Three noise characterization tests of the contact length sensor performed at 3, 5, and 10 Newtons.

To examine the nature of the noise, normal plots were prepared for the balance measurement, shown in Figure 2.30, and for the contact length measurement, shown in Figure 2.31. The near linearity of each of the plots indicates normal noise distribution in both cases. This is reflected, as well, in the histogram of the noise data presented in Figure 2.32.
Figure 2.30: Normal probability plot for the balance sensing noise test at a constant 5 N test force.

Figure 2.31: Normal probability plot for the contact length sensing noise test at a constant 5 N test force.
The frequency content of the noise is just as important to the dynamics of the system. Plots of the power spectral densities, calculated using a Fast Fourier Transform, are presented as Figure 2.33 and Figure 2.34 for the balance measurement noise and the contact length measurement noise, respectively.

Figure 2.32: Histogram of a balance and contact sensing noise test at a constant 5 N test force.

Figure 2.33: Single-sided amplitude spectrum of balance noise test at a constant 5 N test force.
The sampling frequency of the imaging system was $10 \text{ Hz}$ during the tests. To capture the behavior, the data recording system, operated at $50 \text{ Hz}$ in observance of the Nyquist criterion. The spectra illustrate the same general shape in the noise between the two measurements. Large peaks near $0 \text{ Hz}$ indicate significant low frequency content. This can be attributed to the same viscoelastic creep previously discussed. The spectra indicate that a low-pass filter may be able to effectively suppress noise. The limited sampling frequency of the system, however, places noise content very close to the

### 2.6 Sensing for Control

Ultimately, the sensor is designed to explore the scaling of different process control methods. This section considers how the sensor, stamp, and print roll motion are connected. Further consideration is given to integrating control around each parameter.

#### 2.6.1 Methods for Control

Libert develops methods for implementing control around the balance and contact sensing [41]. These controllers implement two independent control loops for contact, shown in Figure 2.35, and for balance, shown in Figure 2.36.
An error signal is generated from the reference of the controller and the measured contact length from the sensor. The controller calculates a force to compensate for the error which is then evenly added to any force preload on the two voice coil channels and sent to the respective voice coil controllers.

![Contact Length controller schematic](image)

**Figure 2.35:** Contact Length controller schematic.

The balance controller, shown in Figure 2.36, functions similarly in generating an error signal and a control action. In this case the control effort is added to each voice coil channel in opposite directions to impart a net torque on the system without changing the total force.

![Balance controller schematic](image)

**Figure 2.36:** Balance controller schematic.

Combining the two controllers is merely a liner combination of their action as shown in Figure 2.37.
Libert showed that the balance and contact systems can be treated as two decoupled second-order systems. Each is controlled by a tuned PI controller, whose bandwidth is for now limited by the camera sample rate.

### 2.6.2 Balance Sensing and Control

Balance was first investigated as it relates to the angle of the print head. The results in Figure 2.38 show the balance indication as a function of the print head angle over three runs of identical conditions. The print head angle adjustment was achieved through sweeping the force offset between the two actuators but maintaining a constant total force of 5N. The print head angles are calculated geometrically from the linear encoders on either side of the print head. These sensors are discussed more in section 2.3.
Figure 2.38: Characterization of the balance indication as function of the print head angle.

This result shows the repeatability of the balance measurement across a series of trials demonstrated by the overlap of the curves. Furthermore, the result shows a nearly linear correlation with the measured print head angle and the balance indication around the zero point which helps to correlated the dimensionless balance indication to a physical quantity in the region of interest. This is helpful for the design of an appropriate controller. The curve shows increasingly nonlinear behavior as the contact region reaches the extremes of its balance but is not expected to cause substantial issue as the sensor is not intended for operation outside of the linear region.

In order to evaluate the need for a controller around contact, the behavior of the contact balance and the print head angle were investigated when the system encounters a step in the total force command without any sort of compensation. Figure 2.39 shows this response to a force step of five Newtons imparted at 3.5 s.
Both the balance and the print head angle begin at zero. At the step, the dynamics in each appear and are especially pronounced in print head angle. Both signals then settle at new values, notably offset from zero. This demonstrates the failure of constant force control to maintain appropriate contact, but also shows a low frequency mechanical filtering effect from the viscoelastic stamp material. The data for the print head angle is produced using the high resolution, high bandwidth, linear optical encoders. This generates a much higher fidelity signal than the balance sensor and better shows the transients in the motion of the print head.

Implementing a controller around the balance signal, and subjecting this new system to the same disturbance, yields the response in Figure 2.40, again showing the print head angle and the balance indication. Again, both signals begin at 0 but in this case, the controller rejects the disturbance and drives balance, and consequently print head angle, back to zero. This demonstrates the successful application of a controller around the balance measurement.
2.6.3 Contact Length Sensing and Control

With the balance control enabled, a test was performed to relate the calibrated contact sensing to the input print force. Again, the test is performed over multiple trials to reveal information about the repeatability of the instrument. These results are included as Figure 2.41.

Figure 2.40: Controlled response of balance to a step force input of 5 N at 3.5 s.
Figure 2.41: Characterization of the contact length measurement as a function of the input print force.

Again, the overlap of the two runs indicate the repeatability of the instrument. The experiment shows a largely linear correlation between the contact length and the applied force. Print force from one to nine Newtons were selected for a typical print force range. One can imagine at very high forces, the contact length saturates as the stamp reaches its maximum deformation and at very low forces, contact length approaches zero.

Both the balance and contact sensing results above display very characteristic hysteresis loops, highlighted in Figure 2.42. These show sensitivity of the stamp to changes in the direction of loading. The high ratio of surface energy to elastic modulus, characteristic of PDMS stamps, contributes significant work of adhesion along the stamp contact [39], [62], [63]. From an energy standpoint, the additional work of adhesion accounts for the difference in strain energy that presents as hysteresis in the experiments.
Figure 2.42: Hysteresis loops highlighted in the contact length testing (A) and in the testing for balance sensing (B). The paths show the load-unload direction through each loop.

The hysteresis that the sensor revealed has important ramifications for designing an appropriate controller. For example, deadband or other non-linearities could result. However, with direct contact sensing, these limitations can be overcome.

2.6.4 Application to Closed-Loop Contact Control

Whereas the previous sections have shown the two sensing system operating independently. In the proposed case for closed-loop control in the microcontact patterning process, these two sensing systems need to work in concert. To evaluate this co-operation, the combined control was tested under another step disturbance, this time to the contact control set point to simulate a sudden change in contact condition in the stamp or in the printing process. The test was performed with the balance controller disabled, shown in Figure 2.43, and with the balance controller enabled, shown in Figure 2.44.
Figure 2.43: Response to step disturbance in contact length reference for testing a combined balance/contact controller. This test performed with the balance controller disabled.
Figure 2.44: Response to step disturbance in contact length reference for testing a combined balance/contact controller. This test performed with the balance controller enabled.

The test with the balance controller disabled shows the transients as the contact length rises to 1.75 mm from 1.5 mm. At the end of the 15 second sample, the contact length settles to its new value. At the step disturbance, the stamp balance, having started at zero falls, with some transients, to about -0.055 indicated balance but does not recover to a well-balanced, zero indicated, condition.

With the balance controller enabled, there are fewer apparent transients as the contact length rises to 1.75 mm but it does not appear to settle nearly as well to its new value. The stamp balance, on the other hand, returns well to its zero reference after falling at the step. Taken together, this test shows improvement in balance at the expense of contact noise.

The combined controller was applied to a moving, rolling stamp under the following three conditions: force only control, contact only control, and the full controller.

Figure 2.45 shows the response of rolling contact, along the balance and contact length parameters, using only the constant force control. There is substantial fluctuation in both the contact and balance.
Figure 2.45: Rolling contact without control. One revolution of the print roll without any active control.

Figure 2.46 shows the same one revolution of the stamp with an active contact length control about the setpoint. The contact is controlled much better in this case but the balance remains fluctuating.

![Graph showing contact length and balance control](image)

Figure 2.46: Rolling contact with contact length control. One revolution of the print roll with active control of the contact only.

Finally, Figure 2.47 shows the system response to one revolution of the print roll with control of the contact length and contact balance activated. In this case, slightly improved performance is seen on the balance response but this comes at the cost of diminished performance of the contact length controller. In the combined controller, the speed of the rollers is substantially limited by the bandwidth of the controller.
2.7 Conclusions and Future Work in Contact Sensing

2.7.1 Proof of New Sensing Concept

This chapter demonstrated the proven functionality of a sensing system specifically conceived to address the need for in-situ monitoring of conformal contact between stamp, substrate web, and impression roll in a continuous microcontact printing process. The development of image processing algorithms specifically for sensing contact also proved successful.

2.7.2 Sensing for Process Control

In addition to proving its functionality in the role of sensing, the new technique was also demonstrated as part of a control loop closed around the actual contact between the stamp, substrate web, and impression roll. Furthermore, this new closed-loop control was shown to offer substantive improvements in maintaining quality contact during the operation of the process.
2.7.3 Future Work on Contact Imaging Physics

The accuracy of the sensing is in part impeded by the blurry edges formed at the boundary of contact. This is a direct consequence of the process relying on layered composite stamps. If the stamp manufacturing process can be further advanced to where a homogenous, fluorescent composite stamp is realized, the image gain of the layered construction could be effectively eliminated.

2.7.4 Future Work on the Optical System

Future development on the optical system could increase the resolution substantially. The biggest limit in the resolution is simply the large working distance enforced by the solid impression roll. If said roll could be made as a thin-walled construction, the working distance could be substantially decreased and the resolution of the imaging system drastically improved. There is a limit to how thin the impression roll can be. It must be stiff enough to resist the force of printing without substantial deformation.

2.7.5 Future Work on the Image Processing Algorithms

The implementation of the secondary kernel for edge recognition is really only just an initial implementation. It's more representative of the concept that a secondary operation, considering what is known about the pattern beforehand can yield improvements to the sensing system. It is not presently clear how extensible this second kernel method is to other patterns beyond what is proved here. As well, the balance sensing

2.7.6 Application to Closed-Loop Control

To aid in accomplishing closed-loop control, the most significant development should be to increase the bandwidth of the sensor. Presently, the bottleneck to the bandwidth is the frame capture rate of the camera that is directly related to the light gathering. To improve the bandwidth, this limitation must be overcome.
2.7.7 Conclusion

The Fluorescent Contact Imaging technique is promising as a sensing technique for microcontact patterning involving transparent substrates. The key property the technique leverages is the single frame sensing: from one video frame, image processing algorithms extracted the contact length measurements and the provided balance sensing for control.

There may be even more, yet unexplored, information waiting to be revealed from each frame. As an early indication of this, consider Figure 2.48. Note the birefringence pattern to the right of the boundaries of contact. This pattern is well known from interferometry. This hints that it might be possible to obtain information about the state of the stamp in the regions very close to contact.

Figure 2.48: Tantalizing evidence that there may be even more data to extract from each frame of the fluorescent contact sensing technique.
CHAPTER

3

A MACHINE FOR CONTINUOUS μCP

The equipment for solving the problems previously addressed was simply not available off the shelf. This required the development of specialized hardware to implement roll-to-roll (R2R) microcontact printing (μCP). A survey of state of the art in machine design and capability for commercially available flexographic presses and lab-scale soft-lithography machines was made to determine how much of this capability could be purchased rather than developed in-house. The resulting machine is a combination of both off-the-shelf web handling components and unique print region hardware. This chapter details this novel machine, referred to as the μFLEX machine.

3.1 Commercially Available Equipment

In this section, we will consider how commercial printing equipment is designed and controlled and how such machines could be further adapted for Continuous μCP.

3.1.1 Commercial Printing Press Construction

The simplest arrangement of the printing system is a linear placement of modular printing systems each containing its own inking system, anilox roller, image carrier and impression system. Figure 3.1 below shows a particular “inline” machine constructed as described and installed at Clemson University. This particular machine was used in producing the samples for the aforementioned plate imaging study. [64]
Because of its modularity the inline machine architecture is straightforward to construct. Furthermore, modules are easily removed, added, or replaced with other inline processes, such as gravure. If an inline press is arranged vertically in order to reduce the machine footprint in the facility, a “stack press” is the resulting architecture. These distinct advantages can come at the cost of the alignment, often called “registration,” in subsequent production steps. This arises simply from the transport of the substrate web from imperfectly aligned rolls.

Usually, each of the modules on a machine, such as those shown in Figure 3.1, represent the printing of a single color. As the substrate web travels from station to station, the different colors are added creating a full color image at the end. In the case of continuous \( \mu \)CP, the modular stations would not represent different colors but rather different patterning, inspection, chemical processes, etc.
The second major architecture for multi-process flexography seeks to address the registration problem by drastically reducing the number of transfer rollers the web sees in during printing. Figure 3.2 illustrates a central impression-type press. The individual print units (4) are placed radially around a single, large impression roll (3). The registration on this type of machine is superb due to the fact that the substrate does not transfer from transfer roller to transfer roller.

![Diagram of a central impression-type press](image)

**Fig. 1-22** Eight-color central impression cylinder flexographic printing press, reel to reel operation (W&H)

Figure 3.2. An eight-color central impression cylinder flexographic printing press.[65]

### 3.1.2 Control of Commercial Printing Presses

Regardless of the arrangement of the press elements, control of the machine is founded on the appearance of the printed product. This control is often in the form of one or many experienced press operators visually inspecting the printed media and making adjustments to the press. On smaller machines, such adjustments are applied manually through hand wheels whereas larger machines are adjusted electronically on large control consoles like that shown in Figure 3.3.
Some advanced machines are using vision systems and other computerized measurement systems to take continuous color measurements during the process and automatically adjust the individual color printing stations. Micromanufacturing by roll-to-roll means requires more advanced automated forms of inspection as the operator cannot easily see the produced patterns as in the case of print media production.

### 3.2 Roll-to-Roll Micro-fabrication

The size, throughput, and cost of commercial flexographic presses often make them inappropriate for lab-scale research. Furthermore, commercially available machines do not usually have the flexibility in design to meet the needs of a highly-experimental research environment. Thus, there exists a body of work for implementing micromanufacturing, both roll-to-roll and otherwise, for the research community. Machines for high-rate micromanufacturing research are seen both in laboratory implementation and, more recently, on the commercial market.
3.2.1 Machines for the Laboratory

Roll-to-roll nanoimprint lithography has seen a number of implementations in roll-to-roll of appreciable scale in academic research facilities around the world. One of the larger of these implementations is shown in Figure 3.4. The Nano Emboss 100 is installed in the Center for Hierarchical Manufacturing at the University of Massachusetts Amherst. This machine comprises an unwind station (1), a gravure coater (2), the UV-cure nanoimprint station (3), a station for advanced inspection and metrology (4), and a rewind stand (5). These stations are arranged inline. Each of these stations is modular and mounted to a stand enclosing the control electronics. Furthermore, the components are cantilevered from a breadboard backplane to allow rolls to be moved and for the rapid installation of additional components. The operator station is fixed at the unwind end of the machine, as seen at the left side of the figure.

Figure 3.4. A large-scale implementation of a roll-based machine for nanoimprint lithography installed at the Center for Hierarchical Manufacturing at the University of Massachusetts in Amherst, MA-US.
Depicted in Figure 3.5, is the design and construction of a hybrid gravure/flexography machine also based on a modular design [67]. The machine has the capability to operate the print stations in either gravure (direct or transfer) or flexographic configurations. Compared to the University of Massachusetts machine, the biggest difference is the addition of multiple, inline printing processes. Similar to the University of Massachusetts machine, however, is the modular construction of each of the modules as well as the open frame design of the cantilevered rolls. The location of the operator station is neither specified nor depicted.

Figure 3.5. This three process printing system for electronic fabrication was designed and built at the Korea Institute of Machinery and Material at the University of Science and Technology, Daejeon-SK [68].
3.2.2 Commercial Machines

Recently, some of the first roll-to-roll machines for microfabrication have become commercially available. The EV Group of St. Florian am Inn, Oberösterreich-AT has released the machine shown in Figure 3.6 for nanoimprint lithography. Like the two custom lab machines, the EVG machine uses an open-frame architecture. The machine is modular around the unwind, imprint, and rewind stations. As a commercial machine, it does not have the breadboard backplane for remounting rolls and instruments.

![The EV Group 750](image)

Figure 3.6. The EV Group 750 is one of the first production nanoimprint machines for high-throughput R2R microfabrication.

3.3 The μFLEX Machine

The goal of designing the particular realization of the μFLEX concept sought to draw the best practices from machines in industry and in other research laboratories. Specifically, the roller
arrangement, roller support, frame construction, operator position, and vibration abatement were considered in drafting the final design.

At the outset, a hybrid configuration stacking the three roll-configurations were initially considered. Presented in Figure 3.7, they are (A) a four-roll, (B) an eight-roll, and finally (C) a six-roll configuration. Common to all topologies are the components that comprise configuration (B), the wind and unwind rolls, the impression roll, and the print roll. Excepting the inking system, this configuration represent the minimum requirement for flexographic machine.

![Diagram of process roller topologies](https://via.placeholder.com/150)

Figure 3.7. The proposed process roller topologies for the μFLEX machine: (A) a four-roll configuration with no accessory rollers, (B) an eight-roll configuration with steering and tension sensing, and (C) a six-roll configuration with two idler rollers.
The first considered implementation for the μFLEX machine was the eight-roll configuration. Beyond the four-roll configuration, this eight-roll configuration adds two steering rolls for guiding the web into the print and impression rollers and to guide the web onto the rewind roller. The steering configuration was selected based on guidelines from industry practice.[69] The configuration also includes two tension sensing rolls immediately upstream and downstream from the print and imprint rolls to interrogate the tension state of the web immediately before and after printing.

The final implementation of the system was simplified down to six-rolls. The steering was removed given the low operation speed and the short web spans in the process. The tension rollers were exchanged for two idler rollers to maintain a constant web wrap angle around the impression cylinder to compensate for the constantly changing sizes of the wind and unwind rolls as the material is process. These modifications led to the final configuration shown above in Figure 3.7.

Beyond the simple arrangement of the rollers in the system, the other high-level classification of the machines is with respect to the mechanical mounting of the components themselves. Generally there are two categories of machine based on this designation: open-frame machines and simply-supported machines. These two roll support schemes are presented graphically in Figure 3.8. Often simply supported components are recommended for larger roll processing machines as a result of needing long rollers to support wide substrates [69].
Figure 3.8. Here are presented the two schemes for supporting the process rollers in the machine: (A) a simply-supported roller, as found in closed-frame machines, and (B) a cantilevered roller, as found in open-frame machines.

As seen previously in the review of existing equipment, large-scale flexographic production machines tend towards simply supported rollers while the purpose-built microfabrication machines tend toward open-frame design. Machines operating with wide web substrates, at high speeds, and/or high tension tend toward simply supported designs for its increased stiffness. The open-frame, cantilevered design is well suited for lower speed and tension operating points seen with the narrow webs. Furthermore, the open-frame design allows for barrier free access to the web path from the operators’ position.

The implementation ultimately selected for the μFLEX machine combines cantilevered handling rolls with simply supported print and impression rolls. The Figure 3.9 shows this combination in the mechanical drawings for the machine. The hybrid open-frame design allows for good access to the substrate web path for manually manipulating the material and placing specific instrumentation. The high precision impression and print rollers were simply supported, though still in the cantilevered framework. The system was assembled on a breadboard backplane, as seen on the UMass and KIMM machines.
The final six-roll design comprising two idler rolls for web guidance. The schematic shows both the implemented roll topology and the open-frame architecture with the breadboard backplane. The wind, unwind, and idler rollers are all cantilevered off of the backplane whereas the print and impression rollers are simply supported.

The backplane is mounted to a custom T-Slot, extruded, aluminum\(^3\) structural frame. This framing strategy was selected to give high rigidity to the backplane, especially in the high load regions surrounding the wind and unwind rollers. The t-slot design allows for rapid assembly of the frame as well as the capability for mounting additional components. The frame extends vertically above the backplane to allow the future addition of components such as additional terminal boxes, control cabinets, or dust control.

Figure 3.10 shows the completed installation with a 1.75m tall operator. The roll equipment, mounted to the backplane and frame, is placed on a heavy steel machine stand. The frame is supported on elastic feet to help abate vibration transmission to the printing region. This stand also supports the electrical cabinet, control computer, and operator control station.

\(^3\) Products of the 80/20 Corporation, Columbia City, IN-US
The installation is designed to give the operator good viewing of the process as well as good access to the machine while in operation. An important extension of this is design and placement of the main operator control station. Consisting of a computer monitor, mouse and keyboard, connected
to the main control computer, and a panel of hardware buttons, the station is fixed to an adjustable
mount\(^4\) for varying height and position. Elevation (C) shows the flexibility in accessing the operator
station while maintaining visual and tactile proximity to the different areas of the machine. This, of
course, aids in efficient operation of the equipment but also promotes safe operation by offering readily
accessible emergency stop locations, one on the operator station and one mounted directly to the
machine as noted.

3.4 Conclusion

Figure 3.11 presents photographs of the finished µFLEX machine in operation. The piece of
equipment successfully combines features of roll-to-roll production machines both on production-
scale machines and those suited for lab and experimental work.

\(^4\) Ergomart TRS7000, Ergomart, Dallas TX-US
Figure 3.11. This figure shows the completed installation of the μFLEX machine at the Massachusetts Institute of Technology, Cambridge MA-US.
CHAPTER

4 A DESIGN FOR CONTROL

This chapter presents the implementation of the control system for the μFLEX machine to scale the microcontact printing (μCP) process. The chapter begins by outlining the overall objectives for the control system. A discussion of the combine mechanical and electrical, or electromechanical, components considers the actuation of the machine and the goals of the control. The electrical methods for connecting power and control to the electromechanics follows. The methods for interfacing the electrical systems to a control system are then presented followed by the control system itself. Finally, a brief discussion on user interface proceeds the conclusion to the chapter.

4.1 Control Objectives

This section presents the high-level goals for the implementation of the control system to advance the machine and the μCP process toward scalability.

4.1.1 Development of the Objectives

Similar to Chapter 3, the objectives for control were inspired by control as implemented on industrial and laboratory-based equipment.

Industrial Equipment

The motivations for building most industrial control systems often include safety, reliability over long operational lifetimes, ease of maintenance, ease of operation, and easy integration with the rest of the factory or process. These conditions, among others, establish the notable characteristics of an industrial control system: established construction methods across the industry, codified safety protocols, rapidly replicable, and construction from off-the-shelf components.
The style for constructing the cabinets that house the electrical connections and hardware are very common across organizations. Time in industry shows this is the application of some written and many unwritten rules and conventions for construction. Despite the different manufacturers, the similarity in construction makes it easy for an experienced technician to understand the machine just from observation.

As the equipment is installed in industrial space it is tightly regulated by electrical standards. In the United States, these standards are of the National Electric Code (NEC) produced by the NFPA. The code exists for the safety of all those who interact with the machines and it dictates everything from fuse sizing and configuration to the emergency stop devices in place on the machine.

In the case of many pieces of installed equipment, CNC machining centers, canning machines, or printing presses, the controls are designed to be replicable. This often is a function of the original equipment manufacturer (OEM) offering a line of stock, or semi-custom machines or automation solutions.

Finally, the vast majority of the control systems installed in industry are constructed from the integration of many off-the-shelf components. Very rarely does one encounter one-off custom components. This aids in achieving reliability, the manufacturers perform rigorous testing to prove their products ready for the field, and assists maintenance, if a component does fail, a replacement is obtained quickly.

Laboratory-Based Equipment

Machines in the lab different substantially from industrial equipment. Often they are custom-built by a student who may not be familiar with all of the conventions of industry, they are built for a shorter lifespan, usually to last until the competition of a thesis, and service may not be a top consideration. They are often built to higher tolerances, greater precision, and with much more room for fast alteration as an investigation progresses. These conditions define the traits of control implementation in laboratory equipment: rapid reconfiguration, transparency, purpose-specific construction.
4.1.2 Presentation of the Objectives

The objectives for designing and implementing are presented with a brief explanation in Table 4.1, below.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>The system is safe for prolonged operation in a lab environment, around students, without direct supervision.</td>
</tr>
<tr>
<td>Modularity</td>
<td>The system is built from exchangeable subassemblies of distinct functions.</td>
</tr>
<tr>
<td>Adaptability</td>
<td>The configuration of the system can be changed quickly and easily to accommodate new modules or experiments.</td>
</tr>
<tr>
<td>Accessibility</td>
<td>The construction of the system is understandable to others in the field.</td>
</tr>
<tr>
<td>Availability</td>
<td>The number of custom components in minimized.</td>
</tr>
</tbody>
</table>

4.1.3 Scalability and Control

The control system needn't be a passive result of the scaling of the process. On the contrary, the control system, properly designed, can act as an aid in the scaling of the process. Developing a process from bench to commercial pilot requires continual experimentation and refinement at each stage. Through a well-conceived control architecture, this may be accelerated by eliminating a requirement for new equipment at each stage of the process. The objectives taken together, reflect this philosophy.

4.2 The Electromechanics of µFLEX

In the implementation of µFLEX as a machine for continuous µCP presented in Chapter 3, there are two points of physical interaction with the web. The first is the web handling subsystem which imparts motion to the substrate web and provides the tension for handling the web. The second is the printing subsystem which controls the contact between the stamp and the substrate web for the conducting microcontact printing.

4.2.1 Web Handling
The web handling system controls the behavior of the substrate web as it travels from the unwind roll, through the print region, and is collected on the rewind roll. The substrate is supplied on reels wound onto cardboard cores. A chuck fits inside of the cardboard core and engages the core to provide torque, through the entire reel, ultimately to the web. This configuration of substrate, reel, and drive chuck is diagrammed in Figure 4.1.

![Image of web handling system components](image)

Figure 4.1. The substrate web (1), reel (2), and chuck (3) used for manipulating the substrate through the machine.

The combination of the chuck and reeled substrate are driven by a motor connected by a gearbox to the chuck. The assembly of these components and their situation on the completed machine are shown below in Figure 4.2. The gearbox is necessary to match the operating speed of the motor to the web speeds required by the process. To achieve the substrate web speeds up to 0.5 m/s, a gearbox with a reduction of 32:1 was selected. The motor also includes a 10,000 count encoder for

---

5 Double E Company, LLC, MA-US
6 SVL-202, Automation Direct, GA-US
7 PLE60-32, Neugart GmbH, BW-DE
measuring the position and speed of the motor and chuck during operation. The specifications for the motor are presented in the following Table 4.2.

![Image of motor and chuck assembly](image)

**Figure 4.2.** The chuck (1), gearbox (2), and motor (3) assembly comprising the web handling system.

The motor is connected to a servo driver which comprises various power electronics to switch the incoming power lines in order to drive the AC motor. Furthermore, the drive contains high-speed encoder counters coupled to embedded closed loop controllers for precise control of position, speed and torque of the motor and thus the chuck and substrate reel.

In operation, it is desirable to control both the tension in the substrate web and the travel speed of the same. One motor is used to control directly each of these parameters. The unwind roll is controlled to a constant torque to provide the resistive force imparting the tension on the web. In the meantime, the rewind chuck is controlled by speed to determine the travel speed of the substrate web though the machine.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Type</td>
<td>Brushless, AC, NdFeB Permanent Magnet</td>
</tr>
<tr>
<td>Motor Power</td>
<td>200 W</td>
</tr>
<tr>
<td>Rated Torque</td>
<td>0.64 N-m; 20.5 N-m with gearbox</td>
</tr>
<tr>
<td>Max Torque</td>
<td>1.9 N-m; 61.2 N-m with gearbox</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>3000 rpm; 93.8 rpm with gearbox</td>
</tr>
<tr>
<td>Max Speed</td>
<td>5000 rpm; 156 rpm with gearbox</td>
</tr>
<tr>
<td>Rotor Inertia</td>
<td>$0.18 \times 10^{-4}$ kg·m²</td>
</tr>
<tr>
<td>Mechanical Time Con.</td>
<td>0.9 ms</td>
</tr>
</tbody>
</table>

Table 4.2: Web Handling Actuator Electromechanical Specifications
Motor Constant 0.39 $N\cdot m/A$ or $V\cdot s/rad$
Armature Resistance 7.5 $\Omega$
Armature Inductance 24 $mH$
Encoder Resolution 10,000 counts/rev

The unwind and rewind chucks assemblies are identical in mechanical construction. Thus the function of each can easily be altered solely in software.

4.2.2 Print Head Actuation

The printing subsystem is designed to manipulate the PDMS stamp with the patterned features to perform the $\mu$CP tasks. A detailed explanation of the development, design, and implementation for the printing hardware is given in Libert’s work [41]. In summary, the print head is a device with two degrees of freedom driven by two voice coil (Lorentz force) actuators. A diagram of the print head is presented in Figure 4.3. The actuators can be considered conceptually as force-current transducers. The specifications for these actuators is given as Table 4.3.

![Print Head Subsystem Diagram](image)

Figure 4.3. A diagram of the print head subsystem. The system comprises (1) a print roll for mounting the stamp, (2) linear guides, (3) voice coil actuators, to yield force control in (4) two degrees of freedom.

Table 4.3: Print System Actuator Electromechanical Specifications

---

8 NCC05-18-060-2X, H2W Technologies Inc., CA-US
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Constant</td>
<td>29.56 N/A</td>
</tr>
<tr>
<td>Coil Resistance</td>
<td>11.40 Ω</td>
</tr>
<tr>
<td>Coil Inductance</td>
<td>3.95 mH</td>
</tr>
<tr>
<td>Electrical Time Constant</td>
<td>0.35 ms</td>
</tr>
</tbody>
</table>

As stated, the voice coil actuators can be considered simply as current to force transducers. Thus for controlling the force at the print stage, merely a current amplifier is required. The μFLEX machine uses two linear amplifiers. Linear amplifiers convert a reference control voltage into a current in the voice coil without any switching electronics. Selecting a switching amplifier introduces the risk of introducing current, and thus force ripple, into the very sensitive stamp contact. To do so risks collapsing the features. Furthermore, the linear amplifier does not rely on analog to digital conversion and thus eliminates quantization noise as well.

4.3 Electrical System Design

This section outlines the electrical portion of the control system beginning with the interfaces to the electromechanical systems presented in Section 4.3, through the high voltage circuit design, and to the design of the electrical cabinet. The section concludes with a reflection of the scalability of the design.

4.3.1 Application of Design Objectives

The electrical design comprises a number of distinct principles in order to embody the overall design objectives. The electrical portion of the control system is implemented with NEC and UL compliance, modular and self-contained low-level control, and built with standard construction techniques using commercially available equipment.

Though not specifically called out during each subsystem description, the system was designed and built in compliance with proper safety code [70], [71].

---

9 LCAM 5/15, H2W Technologies LLC., CA-US
10 Compliance with UL 508A-2001
4.3.2 Defining the Electrical Interfaces

This section covers the inputs and outputs required to interface with the electromechanical hardware introduced above.

Motor Drives

The drives\(^\text{11}\) have embedded, closed-loop controllers to command the speed and position of the motor. The drives are commercial components and have a variety of methods for setting commands including a variety of industrial serial protocols. As deployed on the \(\mu\)FLEX machine, the interface is through physical channels for each of the values of interest. This increases the reliability and transparency of the process; it allows for direct visibility and timing of discrete signals corresponding each to a unique action or parameter of the drive. Recognizing that the machine is deployed first in a research lab with students rather than industrial control technicians, this method makes operation of the drives much more accessible.

Table 4.4 describes each of these interfaces and how it’s used in controlling the web speed. There are two types of signals used in the interface: analog and digital. Analog signals can take any arbitrary value from 0-10VDC and digital signals are either low at 0VDC or high at 24VDC.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Type</th>
<th>Direction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_REF</td>
<td>Analog</td>
<td>Input</td>
<td>Reference voltage for speed control</td>
</tr>
<tr>
<td>T_REF</td>
<td>Analog</td>
<td>Input</td>
<td>Reference voltage for torque control</td>
</tr>
<tr>
<td>Digital</td>
<td>Input</td>
<td></td>
<td>Enables power to the motor and activates control</td>
</tr>
<tr>
<td>Digital</td>
<td>Input</td>
<td></td>
<td>Selects between the jog and speed/torque modes</td>
</tr>
<tr>
<td>Digital</td>
<td>Input</td>
<td></td>
<td>Jogs the motor forward</td>
</tr>
<tr>
<td>Digital</td>
<td>Input</td>
<td></td>
<td>Jogs the motor in reverse</td>
</tr>
<tr>
<td>Digital</td>
<td>Output</td>
<td></td>
<td>Signals an alarm and drive has faulted</td>
</tr>
</tbody>
</table>

Discussion of the how the input signals are used

\(^\text{11}\) SVA-2040, Sure Servo, GA-US
V_REF & T_REF: A 0-10VDC reference signal commands the speed and torque of the motor between 0 and a preset maximum. The reference signal is input to a 10-bit analog to digital converter (ADC). The maximum value does not have to be the maximum rated speed or torque for the motor. At low speeds and torques, the effective resolution of the voltage conversion is increased by lowering the preset maximum.

Enable: When high, this line allows the drive to command the motor. It is important to note, however, this does not necessarily disconnect power from the motor.

Mode Select: When this input is low, the drive obeys the voltage reference commands for either speed or torque. When the input is high, the drive obeys the jog commands and locks the position of the motor when it is not actively being jogged.

Jog Forward/Jog Reverse: Moves the motors and chucks at a preprogrammed speed while the input is high. Does not obey the torque control. This mode is used primarily for position the chucks when feeding new material into the machine. As it does not use torque control, it is an inappropriate mode for actually printing. Used improperly, it can break the substrate web in the machine by over-tensioning it.

Alarm: This channel outputs 24VDC when everything is operating normally on the drive. If one of the drives should fail, this signal will fall and signal the control system to stop until the alarm can be resolved. Furthermore, if the connections to the drive should fail, or the drive is off, this signal will still fall low to indicate the drive is not in an operable condition.

Voice Coil Amplifiers

The voice coil amplifiers are designed with internal controllers to precisely match the output current to the command reference voltage. As they are fundamentally analog devices, they amplifiers do not have options for serial communication. Again, direct interfacing is used with all of the benefits
introduced previously. The interface comprises both analog (0-10VDC) and digital (0 or 24VDC) signals. Table 4.5 introduces the interface to the current amplifiers used for driving the voice coils.

Table 4.5: Interfaces to the Voice Coil Amplifiers

<table>
<thead>
<tr>
<th>Signal</th>
<th>Type</th>
<th>Direction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIGNAL</td>
<td>Analog</td>
<td>Input</td>
<td>Reference voltage for current output</td>
</tr>
<tr>
<td>Enable</td>
<td>Digital</td>
<td>Input</td>
<td>Couples the controller to the output</td>
</tr>
<tr>
<td>Fault</td>
<td>Digital</td>
<td>Output</td>
<td>Signals the amplifier has shut off</td>
</tr>
</tbody>
</table>

**Reference Voltage:** The reference voltage determines the current output of the amplifier. The gain factor can vary based on user calibration. In the μFLEX machine, the gain is set to 210 mA/V.

**Enable:** Activates the amplifier to the controller when pulled high.

**Fault:** The amplifier signals to the controller that it is out of operation due to a fault when this signal is pulled low.

### 4.3.3 Input/Output and Low Voltage Design

**Consideration of the Signaling Need**

The signal specifications above demonstrate the variety of sources needed to drive all of the devices. The system requires both digital and analog inputs and outputs (IO) at different speeds and resolutions. Signals from the linear encoders are high-speed (30 MHz) digital whereas the digital signals controlling the drive state, are much lower frequency, on the order of single Hertz. Thus a tired solution is employed to handle the different classes of signal. Three broad categories capture the signaling needs: low-speed digital, high-speed digital, and precision analog. Table 4.6 shows the categorization of the signals into these three categories noting that there are two servo drives, one for each of the chucks, and two voice coil amplifiers, one for each of the voice coils on the print stage.

Table 4.6: Classification of Signals

<table>
<thead>
<tr>
<th>Type of Signal</th>
<th>Source</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enable (2x)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Apart from the motion axes, the low-speed digital IO also handles a number of other functions of basic machine operation such as watching the air pressure sensor for abnormal conditions, reading button status on the HMI, illuminating indicator lamps, among other things. These are very standard operations for industrial control hardware and thus the low-speed IO is appropriate for handling these task as well.

Modularity is also important to the IO design strategy so that more inputs and outputs of any type can be rapidly added as the requirements of the machine change.

Presentation of the IO System

Relatively low-speed, highly expandable IO systems are truly the domain of industrial automation hardware. In a given production process, there may be thousands of signals all monitored at less the kilohertz speeds. An industrial field IO\textsuperscript{12} is selected for handling the low-speed digital signals. The system, shown in is comprised of an interface module to connect to the controller, and a series of bases with screw terminals for connecting the wires, and modules, which plug into the bases, and provide the function such as digital output.

\textsuperscript{12} Terminator I/O, Automation Direct Inc., GA-US
To handle the signals for the high-speed digital IO and the high-precision analog IO, a modular data acquisition system\textsuperscript{13} is deployed. This system, depicted in Figure 4.5 shows the base and the interchangeable interface modules. Unlike the industrial field IO, this system is designed for precision data acquisition and has more appropriate specifications for handling the analog and high-speed signals on the machine.

\textsuperscript{13} C-Series DAQ, National Instruments Corporation, TX-US
For building the μFLEX machine, a digital to analog converter, with 16-bit resolution, is used. For handling the high frequency data, a module for handling digital inputs up to 10 MHz is employed.

Using this tiered strategy matches the different types of signals to appropriate hardware to yield good flexibility and high performance.

4.3.4 Power Design

The machine is fed with 5-Wire, 208 VAC 3 Phase Wye electrical power at 60 Hz configured L-L-L-N-G (line-line-line-neutral-ground). A complete explanation and description can be found in any number of resources on commercial electrification. Essentially, this connection allows taps for 208 VAC power to the servo drives (as the manufacturer specifies) and 120 VAC connection
for the other equipment in the machine. The 120 VAC source is identical to a common wall socket in the United States.

The main power is fused at 15 A inside the main disconnect and feed to a distribution block. All of the electrical power on the machine comes through this single feed to provide for a single point of connection in installation and a single point of disconnect for lock-out safety. Figure 4.6 depicts the installed disconnect with the power and fuse rating labeled as per code.

Figure 4.6. The main disconnect to the machine.

The configuration of the motor circuits was guided primarily by the manufacturer but are replicated here for completeness. Shown in Figure 4.7, the circuit consists of (1) a circuit breaker to isolate the entire motor subsystem, (2) a motor starter detailed below, (3) fuses to limit current to the control circuits inside the motor driver (4), and the final connections to the motor itself (5).
Figure 4.7. The configuration of one of the two motor power circuits. Shown are (1) a circuit breaker to isolate the entire motor subsystem, (2) a motor starter detailed below, (3) fuses to limit current to the control circuits inside the motor driver (4), and the final connections to the motor itself (5).

The motor starter comprises three elements: a manual disconnect which can be used as a lock-out point to prevent the motor from moving even though the drive is enabled, a thermal relay that protects the motor from continuous overloading, and a contactor which requires a signal from the field IO to finally admit power to the motor.

Apart from the servo drives, the rest of the devices, including the voice coil amplifiers, operate on low voltage, 24VDC. Power is distributed in two branches: one for all signals that could cause the machine to move (the motion power) and one for all of the control electronics. In an emergency stop, all power to the motion branch is cut while the control power persists. Figure 4.8 shows the front panel of the machine with one of the three emergency stop locations, the emergency stop reset and the indicators for control power and motive power. The machine is in the stopped configuration so the reset button (red) is illuminated and the motion power indicator (blue) is extinguished.
4.3.5 Implementing the Design

All of the components are enclosed in a rated enclosure, shown in Figure 4.9 for isolation from operators and the environment in accordance with code. Following common industry practice, the components are mounted to DIN rail. The gray, rectangular components in the picture are wire duct for easily containing and routing wires. The components, which fill the cabinet, are all commercially available.
Figure 4.9. The interior of the completed control cabinet. The image shows the mounting of all of the components and the wire ducting in gray.

Figure... shows the two levels of organization in laying out the panel. The first level (A) was to isolate the lower power to the left of the panel while keeping the high power circuits to the right for safety and to help abate electromagnetic noise in the precision components. The second level of organization (B) was by function. By keeping related components close together and wire runs short, the likelihood of noise problems is further diminished.
Figure 4.10. The schematic layout of the panel depicting the two levels of component organization. (A) shows the division by power requirements. (B) shows the organization by function.

4.3.6 Summary

Section 4.3 examined the implementation of the electrical hardware for control of the μFLEX machine using NEC and UL compliant techniques, self-contained servo drives and current amplifiers for motion control, industry standard methods for construction, and assembly from commercial components. These factors align the electrical design with the overall objectives for scalable control of the process. Table 4.7 summarizes which of the objectives are supported by each principle.

<table>
<thead>
<tr>
<th>Table 4.7: Evaluation of Electrical Design against Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Principle</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>1. Power Distribution</td>
</tr>
<tr>
<td>2. Industrial IO</td>
</tr>
<tr>
<td>3. C-Series Precision IO</td>
</tr>
<tr>
<td>4. Coil Amplifiers</td>
</tr>
<tr>
<td>5. Servo Drives</td>
</tr>
</tbody>
</table>
4.4 Software—Electrical Interface

With all of the control signals terminated to either the field IO or the C-series DAQ, this section outlines the distribution of commands from the controller to each of the points in the IO subsystem.

4.4.1 Control Network

In recent years, there has been a growing trend toward using TCP/IP over Ethernet as the foundation of industrial control networks [74], [75]. There has been concern regarding the latency and non-determinism surrounding Ethernet protocol when used for control. Researchers have shown that in the appropriate contexts, Ethernet performs well enough to be used for control [76], [77]. The 10-30 Hz bandwidth of the μFLEX machine fits within this operating envelope.

Ethernet based control is attractive from many different viewpoints with respect to scaling. Fundamentally, its most attractive qualities are its ease and speed of original deployment and subsequent expansion. As ultimately used on the μFLEX machine, the Ethernet network is compatible both with the field IO and the cDAQ hardware. Adding additional sensing or actuation capacity becomes as simple as adding an additional Ethernet connection.

The vision system is also gigabit Ethernet based for a number of similar considerations considering ease of use. Furthermore, the high bandwidth allowed over gigabit Ethernet is useful for image capturing. In implementing the contact sensor, this is reflected by the GigE camera upon which the system is built.
4.4.2 Protocol

The network architecture merely describes how the nodes are interconnected but does not go as far as to describe what information is exchanged on the network. It was crucial to specify a protocol that was compatible with an Ethernet network and was not restricted to a specific controller or field IO. A survey of the state of the art raised the OLE for Process Control (OPC) as a likely candidate to fill this role. Furthermore, research shows the flexibility across a variety of controllers and IO devices as well as its relative transparency in use. An OPC server\(^{16}\) provided the communication to the field IO with the capability to extend to large number of types of devices (including the Arduino). OPC can be integrated with existing automation systems as well.

The interface to the cDAQ had to be handled outside of the OPC framework by National Instruments’ DAQmx software. Though not as flexible as the OPC protocol, DAQmx is still accessible by different types of controllers.

4.4.3 Controller

A high performance, multi-core PC was used as the controller. Whereas high-frequency, high-bandwidth, real-time control solutions generally reject PC-based control, the application on the \(\mu\)FLEX machine allows for it. A PC, over other types of controllers, including industrial PLCs or embedded microcontrollers, provides a very familiar work environment to the researcher.

The multi-core PC allows for the integrating processor intensive tasks, such as machine vision, into the workflow. From one machine, the researcher designing new experiments or implementing new software has access to all of the resources of the system from a single point. In the case of the \(\mu\)FLEX machine, all of the vision processing for the contact sensor was performed within the same framework as the machine control.

The PC can run loops reliably up to 1 kHz but not much faster as the Windows operating system is not designed for real-time operation. The latency in the Ethernet network further suppresses the frequency to around 100 Hz. Using the self-contained servo drives and current controllers shifts

\(^{16}\) KEPServer EX, Kepware Technologies, ME-US
the high frequency load off of the control PC. If there is a point where high-frequency, real-time control is required, it is possible to use an Ethernet-attached FPGA, compatible with the same C-Series modules as before. Taken in summary, these conditions promote the use of a PC as controller while offering alternatives if the limitations of the PC are reached.

### 4.4.4 Scalability

Combining PC-based control with an OPC protocol on an industrial Ethernet network is advantageous for scaling. Already considered is the addition of a networked FPGA for real-time control, which demonstrates the flexibility of the system in adding capability. Likewise, if new instrumentation or more field IO is required, addition is straightforward with off-the-shelf components.

This flexibility is not restricted to a single machine, however. Multiple machines of similar control architecture can be attached to the network and operated together. As the interfaces are also compatible with existing, industrial control designs, the µFLEX machine could theoretically be deployed straight into a modern commercial facility. By having this common interface with industrial control, there is a direct pipeline from development at the bench-scale to deployment to industry.

Table 4.8 evaluates the interface decisions against the design objectives.

<table>
<thead>
<tr>
<th>Design Principle</th>
<th>Safety</th>
<th>Modularity</th>
<th>Adaptability</th>
<th>Accessibility</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethernet Network</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>OPC-UA Protocol</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC-Based Controller</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

### 4.5 Control Software Design
4.5.1 Application of Design Objectives

The software design for the control system faced unique challenges. For scalability concerns, the software had to be applicable for rapid alteration during experimentation and early pilot but still have relevance for early production.

4.5.2 Platform

The PC-based controller is introduced in section 4.4.3. Industry provides many solutions for using a PC for control. Notable among these is TwinCAT\(^{17}\) and LabVIEW\(^{18}\). LabVIEW is widely used in engineering education in the United States promoting familiarity for programming among the researchers and is a block programming language helping to promote accessibility. LabVIEW comes equipped with many built in function for communicating with the OPC interface, handling the data to and from the cDAQ, and has functions for vision processing to integrate the contact imaging.

The software platform is not restrictive; the implementation of the interface around OPC and DAQmx offers libraries for C, C++, and Java development among others.

4.5.3 Architecture

The LabVIEW design for operating the machine is, like the machine itself, is modular based on a common architecture. The concept, generally, is for individual software controllers and processing modules, which are high-level and easy to modify, to fit into a more complex master program to handle the low-level operations. This architecture is presented graphically in Figure 4.11. The software modules can contain the controllers for the force control, algorithms for vision processing for contact sensing, etc.

\(^{17}\) Beckhoff Automation GmbH, NW-DE

\(^{18}\) National Instruments Corporation, TX-US
The master program handles software tasks like timing, sending values to the field IO, and assigning processors to different tasks. The master program also handles the machine monitoring functions looking for faults from the drives and emergency stop functions. Using the master program places ultimate control authority with one entity which can help to alleviate unintended machine movement. The master program itself can receive high-level commands via OPC as well allowing for interaction or control by an existing control system which could be found in industry.

The master program is built using a state machine to determine what mode the machine is in. Each "state" represents a set of conditions that were required to enter, a specified behavior of the machine, and a set of conditions which must be satisfied in order to move to a different state. Figure 4.12 shows the state machine in graphical form. With a description of the states to follow.
1) **Start-Up Check:** the machine enters this state as soon as power is applied. In this state no motion is enabled and no power is applied to the motors. The program checks to make sure there are no faults and prompts the operator to confirm powering on the machine. With the operator's confirmation, the state advances to state 2.

2) **Manual Mode:** This state is intended for allowing the used to manually position the web and used, for example, when loading new material on the machine. This state is entered either after startup or when exiting the automatic mode. In the manual mode, power is applied and motion is enabled only on the servo drives. The jog mode for both drives is selected and the operator has direct control of the roll jogs from the operator panel. This state is exited when the operator selects the automatic mode or selects to shutdown the machine.
3) **Automatic Mode**: This state is designed for use in producing product. This mode is entered from the manual mode at the discretion of the operator. In the automatic mode, power is applied and motion enabled on the servo drives and the voice coil amplifiers. The software modules for print force control, vision processing, etc. are operating during this state and control the machine through the master program. This state is exited upon activation of the manual mode or on machine shutdown.

4) **Shutdown**: This state is designed to gracefully prepare the machine for power off. This state is entered from either the automatic mode or manual mode state. The state stops, disables, and depowers all motion, stops the controllers, and closes the controller. This is the terminal state of the machine.

5) **E-Stop/Fault**: This state is designed to handle the event of an emergency stop or fault from one of the devices. This state is entered automatically when a fault or emergency stop is triggered. It stops and disables all motion and removes all motive power. Diagnostics are run and the source of the fault or emergency stop is displayed to the operator. The state advances to the automatic mode, though with motion disabled, when the fault has been cleared.

### 4.5.4 Summary

Building the software in LabVIEW around a master state-driven program with independent, modular software for control supported the overall design objectives according to Table 4.9, below.

**Table 4.9: Evaluation of Control Software against Objectives**

<table>
<thead>
<tr>
<th>Design Principle</th>
<th>Safety</th>
<th>Modularity</th>
<th>Adaptability</th>
<th>Accessibility</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>LabVIEW</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Implementation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Master Program</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Software Modules</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

### 4.6 Conclusion
Figure 4.13 summarizes the control system for the μFLEX machine and shows the different hierarchies of the control construction. It shows the propagation of control from the PC-based to controller, through the OPC and DAQmx interfaces, across the industrial Ethernet network, arriving at the field IO and cDAQ, transmittal to the drives and amplifiers to finally arrive at the electromechanical components.

![Control System Schematic for μFLEX Machine](image)

Figure 4.13. The summary system schematic for control of the μFLEX machine.

The control system was designed and built to satisfy the design objectives. Table 4.10 presents the satisfaction of said objectives at every scale of implementation.

<table>
<thead>
<tr>
<th>Table 4.10: Evaluation of Electrical Design against Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Principle</strong></td>
</tr>
<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>NEC &amp; UL Compliant Servo Drive System</td>
</tr>
<tr>
<td>Voice Coil Amplifiers</td>
</tr>
<tr>
<td>Standard Construction</td>
</tr>
</tbody>
</table>

138
Commercial Components

<table>
<thead>
<tr>
<th>Ethernet</th>
<th>Network</th>
<th>OPC-UA</th>
<th>Protocol</th>
<th>PC-Based</th>
<th>Controller</th>
<th>LabVIEW</th>
</tr>
</thead>
</table>

Implementation

<table>
<thead>
<tr>
<th>Master Program</th>
<th>Design</th>
<th>Software</th>
<th>Modules</th>
</tr>
</thead>
</table>

The purpose for enforcing these objectives was to build a control system that supports and enhances the scaling of the \( \mu \)CP to industry. As shown, the control for the \( \mu \)FLEX machine accomplishes this goal. An important result of the design is the inherent modularity. The simplicity of adding actuation or sensing capability just by attaching an Ethernet cable and adding a software module has advantages in research where the requirements for machines and experiments frequently change.

The modulatory extends beyond the \textit{intra}-machine level to \textit{inter}-machine operations. Entire versions of a \( \mu \)FLEX machine can be constructed and configured independently then connected by Ethernet to share process information, even control parameters and access to IO. For scaling the process, this is advantageous. If the researcher is able to use nearly identical hardware to where the process was proved in pilot testing, rather than having to begin from scratch with a new machine, the path to commercialization becomes much shorter and cheaper.
5.1 Contributions

This work provides possible solutions to technical issues keeping roll-to-roll microcontact printing from large-scale commercialization. Namely, the work addresses sensing for the deposition process by in-situ automated observation and sensing of contact. Additionally, the work presents a roadmap for control hardware and software implementation scalable with the machine from research through early phase pilot. Finally, the work presents µFLEX, a case of implementing the integrated sensing and control hardware and software in a machine for further research and development of the continuous µCP process.

In conjunction with Adam Libert’s work on designing and controlling the precision print head [41], the µFLEX machine stands as true system to push the scale of continuous microcontact printing forward through the exploration of continuous contact control, long-run testing of novel tools based on Larissa Nietner’s work [40], and new systems yet to come.

5.1.1 Sensing for Contact Control

This work demonstrates a new method for sensing the actual contact between the image carrying stamp and the substrate. Implementing Fluorescence Contact Sensing allowed for the closed-loop control of the stamp contact around two parameters: contact balance and contact length. The work also presents algorithms developed for the task of automated contact inspection and sensing.

5.1.2 Scalable Machines for Continuous Microcontact Printing Research and Production
The work examines a control implementation in the μFLEX machine scalable from laboratory process research through to early production pilots. Modularity and flexibility are designed into the control system at different scales to facilitate this objective.

5.2 A Case Study in Deployment

To assist the efforts of the collaboration with the King Fahd University of Petroleum and Minerals, the μFLEX system faced its first big test: replication. Where it is one matter to construct a machine in one’s own lab where mistakes can be easily corrected, it is an entirely different matter to let a contract on a machine to be used so far away from her creators.

Nonetheless, bids were solicited and drawings approved and released on μFLEX East, a machine specialized not on printing like her big sister, but designed to face the challenges of web transport and handling experimentation. The machine was ready for testing at the contractor\(^{19}\) in November 2013, shipped December 2013 and commissioned onsite January 9\(^{th}\), 2014. Figure 4.1 depicts the identical electrical designs in similar electrical panels on μFLEX East (A) and μFLEX at MIT (B). Prior to shipping (D), the machine was inspected, loaded with control software, and tested at the manufacturer (D) before final installation in Saudi Arabia (E).

\(^{19}\) Double E Company LLC., MA-US
Figure 4.1: Deployment of μFLEX East to KFUPM in Saudi Arabia. The electrical design of the new μFLEX East (A) is identical to μFLEX (B). The machine was built and tested in Massachuestts (C) before shipment (D). The machine was installed in January 2014 at the KFUPM laboratories (E).
5.3 Future Work

5.3.1 Sensing for Contact-Based Control

Future work in developing the sensing technology should involve a reexamination of the impression roll for opportunities to decrease the distance between the stamp and the sensor imaging system. To do so offers an extraordinary opportunity to increase the resolving power of the sensor for much finer metrology at the stamp feature level.

Additionally, the algorithms driving the data processing should be examined for optimization to the sensing task to improve the outputs of the sensor.

Finally, the technique needs to be evaluating for robustness in true printing cases for better evaluation of applicability to production.

5.3.2 Control for Continuous Microcontact Printing

Future work with regard to the control architecture could consider other fields or modular machines where such an architecture could be advantageous. As well, it is worth considering the situation of this approach within the broader landscape of flexible automation and advanced manufacturing control including the emerging Industry 4.0 (Industrie 4.0).

5.4 Outlook

The future for large-scale implementation of continuous microcontact printing looks favorable. Immediate applications can be seen in printed electronics. Application to the general glass of surface modification solutions broaden its appeal to industries ranging from water treatment to aerospace. The advancements presented here, along with the present and future work on the μFLEX system and elsewhere, propel μCP even closer to such application.
REFERENCES


[66] “GOSS Sunday Press.”


