Design and Prototype - A Manufacturing System for the Soft Lithography Technique

By

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B.Eng., Electrical Engineering
National University of Singapore, 2005

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Manufacturing

at the

Massachusetts Institute of Technology
August 2006

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Design and Implementation of a Micro Contact Printing Machine

By

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ABSTRACT

Ever since 1998 when the term “soft lithography” was first created, soft lithography techniques have drawn close attention of the academia and the industry. Micro contact printing is by far the most widely used soft lithography technique in the industry. The objective of this research project is to design and prototype a micro contact printing machine which could achieve high scalability, feature resolution and production rate. It should also fulfill quality requirements, in terms of minimizing the tool deformation and air trapping during printing. A reel-to-reel design with wipers to create linear propagation during stamping was used in the final design. The final prototype was made of three stations, the printing station, the inking station and the rotary system, which switches the stamps between printing and inking station. The other important design novelty is that the PDMS stamp has been fixed and the Au coated PET was actually applied to the stamp to get printed. The design minimizes the deformation on the stamp and also eases the linear propagation of the printing interface. The reel-to-reel design can be easily scaled up for mass production with large volume. The prototype was tested and the printing samples were made.

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TITLE: PROFESSOR OF MECHANICAL ENGINEERING
ACKNOWLEDGEMENTS

There is an old saying in China which says that whenever you drink some water, think about the source of it. Now, I’m drinking the “water”, which is the completion of the Master study in such a great institution like MIT, I have to think about all the sources.

I would like to thank my parents. They provided all the supports that possible, physically, mentally, spiritually. Being part of a great institution like MIT was only a dream of the greatest kind but they helped me make it into a reality. Thank you, dad and mum.

I would like to thank Professor David E. Hardt for his guidance, patience, support and generosity in imparting his valuable knowledge over the course of my graduate degree. Whenever there was any academic problem, or even other problems, he was there ready to provide help more than you need. He is a true gentleman. I am indeed honored to have worked under his mentorship. Thank you, for being a great guru and a flawless gentleman invoking my most sincere awe.

My gratitude has to go to Xiao Ni for her unselfish and complete support throughout the whole year. Without it, I could hardly imagine where I could end right now.

Thank Hyung-Jun, from whom I have learned so much, for his kind and encouragement help all the time.

Thank everyone in MIT LMP lab, Grant, Kunal, Munhee, Sam especially. You guys make me feel like home.

Finally, my Lord, once again you have shown your mercy and love on me. Thank you, Father.
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1.1. An Introduction to Soft Lithography

Soft Lithography comprises a set of techniques that uses soft materials to enable replication and pattern transfer on a wide range of dimensional scales, ranging from nanometers to centimeters. These techniques follow a non-photolithographic strategy for pattern transfer based on self-assembly\(^1\) of molecular layers and replica molding for carrying out micro and nanofabrication.

Most Soft Lithography techniques have been recently developed and have attracted significant attention from both academia and industry because of their tremendous potential to support or even replace conventional means of micro manufacturing. The low capital costs and potential for high volume manufacturing with a variety of materials are significant attractions as well. The control over surface chemistry, required for some

\(^1\) Self-assembly is the spontaneous aggregation and organization of subunits (molecules or meso-scale objects) into a stable, well defined structure via non covalent interactions. The information that guides the assembly is coded in the properties (e.g. topologies, shapes, and surface functionalities) of the subunits; the individual subunits will reach the final structure simply by equilibrating to the lowest energy form. Because the final self assembled structures are close to or at thermodynamic equilibrium, they tend to form spontaneously and to reject defects.
applications in medicine, is possible if using soft lithography. Other potential applications of soft lithography in the near future could include simple optical devices such as polarizers, filters, wire grids, and surface acoustic wave (SAW) devices (Zhao et al. 1996). Longer term goals include working toward optical data storage systems, flat panel displays, and quantum devices.

1.2. The Soft Lithography Taxonomy

Several different techniques are known collectively as soft lithography. Holistically, every soft lithography technique formally consists of three steps:

(1) Fabrication of a topographically patterned master, for example on a silicon wafer, using a conventional process like photolithography.

(2) Molding this master with a functional organic material (usually Polydimethyl siloxane or PDMS) to generate a patterned template.

(3) Generating a replica of the original template in a functional material or a 1:1 projection of the pattern on a surface by applying the stamp.
The techniques which are collectively known as Soft Lithography techniques are:

(A) Near Field Optical Lithography

A transparent PDMS mask with relief on its surface is placed in conformal contact with a layer of photo resist. Light, from a source, passing through the stamp is modulated in the near-field. If the relief on the surface of the stamp shifts the phase of light by an odd multiple of $\pi$, a null in the intensity is produced. Features with dimensions between 40 and 100 nm are produced in photo resist at each phase edge.

(B) Micro-contact Printing($\mu$CP)

A thin layer composed of an alkanethiol and ethanol, called “ink” is spread on a patterned PDMS stamp. The stamp is then brought into conformal contact with the
substrate, which can range from coinage metals to oxide layers. The thiol ink is transferred to the substrate where it forms a self-assembled monolayer, or SAM\textsuperscript{2}, that can act as a resist against etching. Features on the substrate are revealed after etch treatment. Features as small as 300 nm have been made in this way[2]. This process will be discussed in detail in Chapter 2.

![Figure 1-2 Schematic procedures for $\mu$CP of hexadecanethiol (HDT) on the surface of gold: printing on a planar surface with a planar stamp [2]](image)

(C) Replica Molding

A PDMS stamp is cast against a conventionally patterned master. Polyurethane (typically) is then molded against the secondary PDMS master. In this way, multiple copies can be made without damaging the original master. Xia et al. [3]demonstrated replica molding against elastomeric PDMS molds with resolution $<$10 nm.
Figure 1-3 Schematic illustration of procedure for replica molding (REM) [4]

(D) Micromolding in Capillaries (MIMIC).

Continuous channels are formed when a PDMS stamp is brought into conformal contact with a solid substrate.[5] Capillary action fills the channels with a polymer precursor. The polymer is cured and the stamp is removed. MIMIC is able to generate features down to 1 μm in size.
**Figure 1-4** Schematic illustration of procedure for micro molding in capillaries (MIMIC) [4]

**E) Microtransfer Molding (µTM)**

A PDMS stamp is filled with a prepolymer or ceramic precursor and placed on a substrate. The material is cured and the stamp is removed. The technique generates features as small as 250 nm and is able to generate multilayer systems [6]

![Diagram of Microtransfer Molding](image)

**Figure 1-5** Schematic illustration of procedure for micro transfer molding (µTM) [4]

**F) Solvent-assisted Microcontact Molding (SAMIM).**

SAMIM (Figure 1-6) forms relief features by spreading a small amount of solvent on a surface of a substrate such that the solvent can dissolve a thin layer of the substrate without affecting the PDMS mold. [7] After dissolving or swelling of a layer of the substrate by the solvent, the resulting fluid or gel is molded against the relief structures
in the mold. SAMIM is similar to embossing in terms of operational principle, but it is different in that SAMIM uses a solvent instead of heat to soften a thin layer of substrate. Moreover, an elastomeric PDMS mold rather than a rigid master is used to imprint patterns on the surface of substrates. [4]

Figure 1-6 Schematic illustration of procedure for solvent-assisted micromolding (SAMIM) [4]

1.3. Overview of the thesis

This thesis is based on a 10-week internship in a high-tech startup specialized in soft-lithography techniques. The objective of this project is to design and prototype a printing and inking system to simulate micro contact printing. It is highly desired that the design be implemented into the mass production at large scale. This project is a group project with three members, namely Hyung-Jun Kim, Karan Chauhan and myself. Hyung-Jun focused on the design and implementation of the printing station. Karan’s part has great focus on
the system automation. And I took charge of the inking station and rotary table/Z-machine system.

The first chapter of thesis is the introduction to the soft-lithography technology, firstly developed in George Whitesides’ group at Harvard. [4]. Chapter 2 is a literature review on the replica molding. The manufacturing considerations are covered in Chapter 3. In this chapter, several critical factors, which is also important design metrics, like the inking time, printing time, ink concentration etc, are discussed. Chapter 4 lists several concepts proposed before finalizing on the reel-to-reel design. It also discusses mass production considerations and scalability of the finalized design. It also proposes some alternative designs. Chapter 1, 2 and 4 are shared among the team, Hyung-Jun Kim, Karan Chauhan and myself. Chapter 5 elaborates in details the design and implementation of the inking station. In chapter 6, the design novelties, future improvement and alternative designs have been discussed. Chapter 7 summarized the whole thesis.
CHAPTER

2 Replica Molding

2.1 Introduction to Replica Molding

Replica molding duplicates the information for example, the shape, the morphology, and the structure, present in a master. It is a procedure that accommodates a wider range of materials than does photolithography. It also allows duplication of three-dimensional topologies in a single step. It has been used for the mass production of surface relief structures such as diffraction gratings holograms, compact disks (CDs) and micro tools. Replica molding with an appropriate material (usually in the form of a polymer precursor) enables highly complex structures in the master to be faithfully duplicated into multiple copies with nanometer resolution in a reliable, simple, and inexpensive way. The fidelity of replica molding is determined by van der Waals interactions, wetting, and kinetic factors such as filling of the mold. These physical interactions should allow more accurate replication of features that are smaller than 100 nm than does photolithography, which is limited by optical diffraction.[4]
PDMS is most widely used as a master with patterned relief on the surface to generate patterns and structures with feature size ranging from 30 nm to 100 µm. PDMS carries the following advantages over other materials as the printing stamps:

- Surface with good chemical stability
- Gas diffuses easily
- Good thermal stability
- Optically transparent
- Durable
- Interfacial properties easily modifiable

In the replica molding process, the features of the Polydimethylsiloxane (PDMS) stamp can be transferred to many thermosetting polymers, such as Polyurethane (PU), Polyethylene terephthalate (PET), Polyethylene naphthalate (PEN) etc. In this research project, PET/PEN will be used.

The replica molding process can be divided into five main steps. The work piece is firstly applied to the PDMS stamps before the excess material is wiped off. Then the stamp is either placed onto the substrate or goes through the curing process directly. The work piece is then peeled off from the stamp, as the final step. We will explore the manufacturing tactics for each step in greater detail.
2.2 Break down of molding steps

2.2.1 Step 1: work piece material filling

In the filling process, it will be difficult to have exactly the right amount of pre-polymer in the PDMS stamps. Excess material may potentially cause the air-trapping in the work piece in the later stage when the stamp is placed on the substrate while material insufficiency will lead to incomplete mold filling as well as non-planar surface. Figure 2-1 shows the different types of material filling errors graphically and Table 2.1 lists the potential issues with each type.

![Figure 2-1 Types of material filling errors](image)

Table 2.1 Material Filling Scenarios and Potential Issues

<table>
<thead>
<tr>
<th>No.</th>
<th>Scenarios</th>
<th>Potential Issues</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Just right amount of material</td>
<td>Difficult to achieve</td>
</tr>
<tr>
<td>2</td>
<td>More than needed</td>
<td>Waste of the material</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Material overflow</td>
</tr>
<tr>
<td>3</td>
<td>Insufficient</td>
<td>Incomplete mold filling</td>
</tr>
</tbody>
</table>
During the filling process, issues like the non-planar surface of the material will also occur. The different scenarios and their associated issues can be found from Table 2.1.

### 2.2.2 Step 2: Wipe-off extra material

There are two possible ways to wipe off the excess of materials. A Nitrogen stream can be used to blow off the extra material. It is fast, clean and generates a planar surface. The only disadvantage is that excess material recycling is difficult using this method. The alternative method is to use a PDMS plate to wipe off away the extra material. The shortcoming of this method is the lower rate. Also, there is danger that during the wipe-off process, the surfaces of the tool might be roughened or damaged. It could potentially cause the non-planar surface for the work piece as well. Figure 2.2 shows the two excess wiping methods with the nitrogen wiping method 1 and PDMS plate sliding method 2.

|   | Insufficient | · Incomplete mold filling  
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<tbody>
<tr>
<td>3</td>
<td></td>
<td>· Unexpected surface shape</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 4 | Non-planar surface/ Non-uniform distribution | · Unexpected surface shape  
|   |              | · Trapped air |

![figure 2.2](image)
2.2.3 Step 3: Substrate placement

There are three ways of placing the substrate.

Method 1: Place the substrate directly down onto the work piece. It will cause waste of material and also air trapping.

Method 2: Fix one end and bring down the other end down slowly with a constant angle.

Method 3: Slide the substrate in at the surface of the mold. The deformation of the mold and non-planar surface of the work piece might be the possible issues with this method.

Figure 2.3 shows the three placement methods.
The work piece in all the three above methods has been fixed and the substrate is moved. As the alternative to all the three methods, the substrate could be fixed. The prepolymer material is then uniformly distributed on the substrate surface. After it, the PDMS mold is placed onto the substrate. In this way, the mold is placed on the fixed substrate.

2.2.4 Step 4 Curing Process

The material used in this process is called the thermosetting polymers or thermosets. During polymerization, the network of the thermosets is completed and the shape of the part is permanently set. The curing reaction is irreversible.

The polymerization process for thermosets generally takes place in two stages. The first occurs at the chemical plant, where the molecules are partially polymerized into linear chains. The second stage occurs at the parts-producing plant, where cross-linking is completed under heat and pressure during molding and shaping of the part.

The advantage of the material and also the process is normally the better mechanical, thermal and chemical properties, electrical resistance, and dimensional stability than what ? thermoplastics?].

There are two methods of curing using either heat UV radiation. In this research, heat curing was more deeply explored. The heat transfer process includes both convection and conduction, but convection was be neglected in this case. Conduction takes place among a
hot plate, the substrate, the PDMS mold and the work piece. The Figure 2.4 shows the heat transfer process.

**Figure 2-4 Illustration of Heating Transfer Processes**

There are several design considerations for the heating curing process:

- Heat up the oven at the fastest possible rate to get optimal production rate
- Increase the oven temperature gradually and evenly to avoid the non-uniform heating
- Avoid overheating, as the polymers may burn up or downgrade

In order to achieve faster curing and better quality, the oven should be kept at a constant temperature to avoid repeated heating and cooling cycle.
2.2.5 Step 5 De-molding processes

As the final step, the de-molding process can also be the most critical. There are many factors associated with the de-molding rate and difficulty.

- **Aspect ratio.** Aspect ratio is defined as distance between two features divided by the feature height. It will greatly decide the difficulty to peel off the mold. The greater the aspect ratio the harder it is to peel off the work piece and the easier to damage the work piece.

- **Mold/Work Piece Channel complexity.** The more complex the structure of the mold/work piece, the more difficult it is to peel off is and the more likely defects would be caused in the process.

Other factors, like the heat conductivity of the work piece and the heating/cooling system can also affect the quality and rate of the de-molding process.

2.3 Manufacturing issues for Replica Molding

Key manufacturing issues include the rate, quality, cost, flexibility and the scalability of a process.

2.3.1 Manufacturing rate
The production rate is the major concern for the manufacturing using replica molding technique. There are many factors that can affect the molding rate, among which gel time and de-molding time, which is the materials intrinsic properties, is the most critical and decisive.

Other factors including the material filling rate, process flow rate and the number of molds and productions line.

The material filling rate is decided by the prepolymer viscosity. Pre-heating treatment can dramatically reduce the material viscosity, which leads to the reduction of filling time. The design of the manufacturing system itself will decide the process flow time and the scale of production lines

2.3.2 Quality

Quality is another major concern. The defects or low quality of the final products can be due to various causes, namely

- Deformation of the tools
- Trapped air in the product
- Mold not fully filled with Polyurethane
- Deformation to both tool and products during de-molding

The elastomeric character of PDMS is the origin of some of the most serious technical problems.
First, gravity, adhesion and capillary forces exert stress on the elastomeric features and cause them to deform and generate defects in the pattern that is formed. If the aspect ratio of the relief features is too large, the PDMS microstructures fall under their own weight or collapse owing to the forces typical of inking or printing of the stamp. It has been shown that aspect ratios of the relief structures on PDMS surfaces had to be between about 0.2 and 2 in order to obtain defect-free stamps. [4]

Second, when the aspect ratios are too low, the relief structures are not able to withstand the compressive forces typical of printing and the adhesion between the stamp and the substrate; these interactions result in sagging. This deformation excludes soft lithography for use with patterns in which features are widely separated, unless nonfunctional "posts" can be introduced into the designs to support the non-contact regions.

Third, achieving accurate registration without distorting the multilayer fabrication process is substantially more difficult with a flexible elastomer than with a rigid material.

There are several other disadvantages that may limit the performance of PDMS for certain types of applications. For example, PDMS shrinks by a factor of about 1% upon curing, and PDMS can be readily swelled by non-polar solvents such as toluene and hexane.

The elastomeric character of PDMS is also the origin of some of the most serious technical problems. The PDMS stamps can have the paring, sagging and shrinking problems as Figure 2.5 shows.
Figure 2-5 several types of PDMS stamp deformations [4]
3 Micro-contact Printing

3.1 Introduction

Micro contact Printing (or $\mu$CP), as it will be frequently referred to in this text) uses the relief patterns on a PDMS stamp to form patterns of self-assembled monolayers (SAMs) of inks on the surface of a substrate through conformal contact. Micro contact printing differs from other printing methods, like inkjet printing or 3-D printing, in the use of self-assembly (especially, the use of SAMs) to form micro patterns and microstructures of various materials.[8]

This chapter provides a literature review of the process including its principles and characteristic features. We also discuss some industrial design efforts to take this technology from the laboratory to commercial production.

3.2 Principles and characteristics of Micro contact Printing

Micro contact printing is a method for patterning Self-Assembled Monolayers (SAMs) on surfaces using elastomeric stamp [9]. The most distinct characteristic of $\mu$CP is its use of self-assembly (especially, the use of SAMs) to form micro patterns on a substrate. [10] SAMs are formed by contact between a topographically patterned elastomeric stamp,
wetted with an ink consisting of molecules that are capable of forming SAMs, and the surface of substrate.

Micron scale SAMs by Micro contact printing can be formed manually in a conventional chemical laboratory and it does not require any photolithographic equipment or a clean room environment. Therefore, the simplicity and economic efficiency for patterning micron scale layer are major benefits of Micro contact printing.

Another Characteristic of MCP is conformability. Because the Micro contact printing uses PDMS stamps, the stamp is able to conform to substrate with little external normal force and at the same time can compensate for the surface roughness of the substrate. This is important in transporting molecular level SAMs.

Self-Assembled Monolayers (SAMs) are layers formed on a solid surface by spontaneous organization of molecules. It has been reported that a polymer inked with an alkanethiol and brought into contact with a gold-coated surface can form a monolayer of these molecules in the areas of contact [12].
The ink used in Micro contact printing to form the SAMs is mainly transported through diffusion at the stamp-substrate interface. Diffusion from the edges of the stamp and vapor transport are the non-contact mechanisms that can also form SAMs (see figure 3.1). When the target feature sizes are smaller than 500 nm, these non-contact transport mechanisms become significant enough to degrade the output quality [14].

The substrates, on which the SAMs are formed, are generally prepared by common physical vapor deposition (PVD) methods, i.e., thermal or electron beam evaporation. Among a wide range of materials used for substrates, gold is the most commonly used as it is easily available as a thin film and easy to pattern by a combination of lithographic tools (photolithography, micromachining) and chemical etchants. In addition, gold is a very inert material, so it does not oxidize at temperatures below its melting point. However, silver [15] and copper [16] have been used as a substrate for forming SAMs through Micro contact printing.
Figure 3-2. Self assembled monolayers. (A) Schematic diagram of an ideal, single-crystalline SAM of alkanethiolates supported on a gold surfaces (B) The variety of structural arrangements found in SAMs prepared by μCP when the stamp is wetted with a 1-10 mM solution and applied to the substrate for 1-10 seconds [17].

3.3 **Micro contact printing Procedure.**

Micro contact Printing can be thought of as a two stage process: Inking and Stamping. Inking consists of wetting with the ink and drying. Ink that forms SAMs is transferred through a solvent such as ethanol, so the solvent needs to be removed after transferring ink to stamp. The wetting step is applying ink solution to a PDMS stamp and the drying step is removing solvent from the PDMS. The solvent can be dried in the air, but a stream of nitrogen gas helps to reduce time for drying. Inking and drying times depend on factors
such as ink concentration, printing area, and printing method. Typically, the inking step takes 30 ~ 60 seconds and drying requires 10 ~ 60 seconds.

The stamping process comprises 3 sub-steps: Initial contact & propagation, full contact, and separation. Achieving full contact through gradual application of the stamp is important in order to minimize air trapping between stamp and substrate. After achieving full contact, contact time is required to transport inks from a stamp to a substrate and form SAMs. The required length of contact time can be different mainly according to ink type, concentration of ink or target thickness of SAMs.

Figure 3-3: Micro contact printing procedure [2].
Table 3.3 summarizes the process, the required time and typical failure modes of Micro contact printing reported through the research so far.

**Table 3.3: Micro contact Printing Process and characteristics**

<table>
<thead>
<tr>
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<th>Non-planar surface/ Non-uniform distribution</th>
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<td>• Unexpected surface shape</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Trapped air</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Non-uniform distribution of material</td>
</tr>
</tbody>
</table>

During the filling process, issues like the non-planar surface of the material will also occur. The different scenarios and their associated issues can be found from Table 2.1.

2.2.2 Step 2: Wipe-off extra material

There are two possible ways to wipe off the excess of materials. A Nitrogen stream can be used to blow off the extra material. It is fast, clean and generates a planar surface. The only disadvantage is that excess material recycling is difficult using this method. The alternative method is to use a PDMS plate to wipe off away the extra material. The shortcoming of this method is the lower rate. Also, there is danger that during the wipe-off process, the surfaces of the tool might be roughened or damaged. It could potentially cause the non-planar surface for the work piece as well. Figure 2.2 shows the two excess wiping methods with the nitrogen wiping method 1 and PDMS plate sliding method 2.
2.2.3 Step 3: Substrate placement

There are three ways of placing the substrate.

Method 1: Place the substrate directly down onto the work piece. It will cause waste of material and also air trapping.

Method 2: Fix one end and bring down the other end down slowly with a constant angle.

Method 3: Slide the substrate in at the surface of the mold. The deformation of the mold and non-planar surface of the work piece might be the possible issues with this method.

Figure 2.3 shows the three placement methods.
The work piece in all the three above methods has been fixed and the substrate is moved. As the alternative to all the three methods, the substrate could be fixed. The prepolymer material is then uniformly distributed on the substrate surface. After it, the PDMS mold is placed onto the substrate. In this way, the mold is placed on the fixed substrate.

2.2.4 Step 4 Curing Process

The material used in this process is called the thermosetting polymers or thermosets. During polymerization, the network of the thermosets is completed and the shape of the part is permanently set. The curing reaction is irreversible.

The polymerization process for thermosets generally takes place in two stages. The first occurs at the chemical plant, where the molecules are partially polymerized into linear
chains. The second stage occurs at the parts-producing plant, where cross-linking is completed under heat and pressure during molding and shaping of the part.

The advantage of the material and also the process is normally the better mechanical, thermal and chemical properties, electrical resistance, and dimensional stability than what thermoplastics?]

There are two methods of curing using either heat UV radiation. In this research, heat curing was more deeply explored. The heat transfer process includes both convection and conduction, but convection was be neglected in this case. Conduction takes place among a hot plate, the substrate, the PDMS mold and the work piece. The Figure 2.4 shows the heat transfer process.

![Figure 2-4 Illustration of Heating Transfer Processes](image)

There are several design considerations for the heating curing process:

- Heat up the oven at the fastest possible rate to get optimal production rate
• Increase the oven temperature gradually and evenly to avoid the non-uniform heating

• Avoid overheating, as the polymers may burn up or downgrade

In order to achieve faster curing and better quality, the oven should be kept at a constant temperature to avoid repeated heating and cooling cycle.

2.2.5 Step 5 De-molding processes

As the final step, the de-molding process can also be the most critical. There are many factors associated with the de-molding rate and difficulty.

• Aspect ratio. Aspect ratio is defined as distance between two features divided by the feature height. It will greatly decide the difficulty to peel off the mold. The greater the aspect ratio the harder it is to peel off the work piece and the easier to damage the work piece.

• Mold/Work Piece Channel complexity. The more complex the structure of the mold/work piece, the more difficult it is to peel off is and the more likely defects would be caused in the process.

Other factors, like the heat conductivity of the work piece and the heating/cooling system can also affect the quality and rate of the de-molding process.
2.3 Manufacturing issues for Replica Molding

Key manufacturing issues include the rate, quality, cost, flexibility and the scalability of a process.

2.3.1 Manufacturing rate

The production rate is the major concern for the manufacturing using replica molding technique. There are many factors that can affect the molding rate, among which gel time and de-molding time, which is the materials intrinsic properties, is the most critical and decisive.

Other factors including the material filling rate, process flow rate and the number of molds and productions line.

The material filling rate is decided by the prepolymer viscosity. Pre-heating treatment can dramatically reduce the material viscosity, which leads to the reduction of filling time. The design of the manufacturing system itself will decide the process flow time and the scale of production lines

2.3.2 Quality

Quality is another major concern. The defects or low quality of the final products can be due to various causes, namely

- Deformation of the tools
- Trapped air in the product
- Mold not fully filled with Polyurethane
- Deformation to both tool and products during de-molding

The elastomeric character of PDMS is the origin of some of the most serious technical problems.

First, gravity, adhesion and capillary forces exert stress on the elastomeric features and cause them to deform and generate defects in the pattern that is formed. If the aspect ratio of the relief features is too large, the PDMS microstructures fall under their own weight or collapse owing to the forces typical of inking or printing of the stamp. It has been shown that aspect ratios of the relief structures on PDMS surfaces had to be between about 0.2 and 2 in order to obtain defect-free stamps. [4]

Second, when the aspect ratios are too low, the relief structures are not able to withstand the compressive forces typical of printing and the adhesion between the stamp and the substrate; these interactions result in sagging. This deformation excludes soft lithography for use with patterns in which features are widely separated, unless nonfunctional "posts" can be introduced into the designs to support the non-contact regions.

Third, achieving accurate registration without distorting the multilayer fabrication process is substantially more difficult with a flexible elastomer than with a rigid material.
There are several other disadvantages that may limit the performance of PDMS for certain types of applications. For example, PDMS shrinks by a factor of about 1% upon curing, and PDMS can be readily swelled by non-polar solvents such as toluene and hexane.

The elastomeric character of PDMS is also the origin of some of the most serious technical problems. The PDMS stamps can have the paring, sagging and shrinking problems as Figure 2.5 shows.

Figure 2-5 several types of PDMS stamp deformations [4]
3 Micro-contact Printing

3.1 Introduction

Micro contact Printing (or $\mu$CP), as it will be frequently referred to in this text) uses the relief patterns on a PDMS stamp to form patterns of self-assembled monolayers (SAMs) of inks on the surface of a substrate through conformal contact. Micro contact printing differs from other printing methods, like inkjet printing or 3-D printing, in the use of self-assembly (especially, the use of SAMs) to form micro patterns and microstructures of various materials.[8]
This chapter provides a literature review of the process including its principles and characteristic features. We also discuss some industrial design efforts to take this technology from the laboratory to commercial production.

3.2 Principles and characteristics of Micro contact Printing

Micro contact printing is a method for patterning Self-Assembled Monolayers (SAMs) on surfaces using elastomeric stamp [9]. The most distinct characteristic of \( \mu CP \) is its use of self-assembly (especially, the use of SAMs) to form micro patterns on a substrate. [10] SAMs are formed by contact between a topographically patterned elastomeric stamp, wetted with an ink consisting of molecules that are capable of forming SAMs, and the surface of substrate.

Micron scale SAMs by Micro contact printing can be formed manually in a conventional chemical laboratory and it does not require any photolithographic equipment or a clean room environment. Therefore, the simplicity and economic efficiency for patterning micron scale layer are major benefits of Micro contact printing.

Another Characteristic of MCP is conformability. Because the Micro contact printing uses PDMS stamps, the stamp is able to conform to substrate with little external normal force and at the same time can compensate for the surface roughness of the substrate. This is important in transporting molecular level SAMs.

Self-Assembled Monolayers (SAMs) are layers formed on a solid surface by spontaneous organization of molecules. It has been reported that a polymer inked with an alkanethiol
and brought into contact with a gold-coated surface can form a monolayer of these molecules in the areas of contact [12].

![Schematic illustration](image)

**Figure 3-1**: Schematic illustration depicting the application of a PDMS stamp containing thiols to a polycrystalline metal film. The mechanisms of mass transport from the stamp to the substrate are also shown [13].

The ink used in Micro contact printing to form the SAMs is mainly transported through diffusion at the stamp-substrate interface. Diffusion from the edges of the stamp and vapor transport are the non-contact mechanisms that can also form SAMs (see figure 3.1). When the target feature sizes are smaller than 500 nm, these non-contact transport mechanisms become significant enough to degrade the output quality [14].

The substrates, on which the SAMs are formed, are generally prepared by common physical vapor deposition (PVD) methods, i.e., thermal or electron beam evaporation. Among a wide range of materials used for substrates, gold is the most commonly used as it is easily available as a thin film and easy to pattern by a combination of lithographic tools.
(photolithography, micromachining) and chemical etchants. In addition, gold is a very inert material, so it does not oxidize at temperatures below its melting point. However, silver [15] and copper [16] have been used as a substrate for forming SAMs through Micro contact printing.

![Diagram of SAMs](image)

**Figure 3-2.** Self assembled monolayers. (A) Schematic diagram of an ideal, single-crystalline SAM of alkanethiolates supported on a gold surfaces (B) The variety of structural arrangements found in SAMs prepared by μCP when the stamp is wetted with a 1-10 mM solution and applied to the substrate for 1-10 seconds [17].

### 3.3 Micro contact printing Procedure.

Micro contact Printing can be thought of as a two stage process: Inking and Stamping. Inking consists of wetting with the ink and drying. Ink that forms SAMs is transferred
through a solvent such as ethanol, so the solvent needs to be removed after transferring ink to stamp. The wetting step is applying ink solution to a PDMS stamp and the drying step is removing solvent from the PDMS. The solvent can be dried in the air, but a stream of nitrogen gas helps to reduce time for drying. Inking and drying times depend on factors such as ink concentration, printing area, and printing method. Typically, the inking step takes 30 ~ 60 seconds and drying requires 10 ~ 60 seconds.

The stamping process comprises 3 sub-steps: Initial contact & propagation, full contact, and separation. Achieving full contact through gradual application of the stamp is important in order to minimize air trapping between stamp and substrate. After achieving full contact, contact time is required to transport inks from a stamp to a substrate and form SAMs. The required length of contact time can be different mainly according to ink type, concentration of ink or target thickness of SAMs.
Figure 3-3: Micro contact printing procedure [2].

Table 3.3 summarizes the process, the required time and typical failure modes of Micro contact printing reported through the research so far.

Table 3.3: Micro contact Printing Process and characteristics

<table>
<thead>
<tr>
<th>Process</th>
<th>Inking</th>
<th>Stamping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step</td>
<td>Immersion</td>
<td>Initial contact and propagation</td>
</tr>
<tr>
<td>Time</td>
<td>30 ~ 60 sec</td>
<td>10 ~ 60 sec</td>
</tr>
<tr>
<td>Failure</td>
<td>Swelling</td>
<td>Distortion</td>
</tr>
</tbody>
</table>

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3.4 Critical Factors for \( \mu \text{CP} \)

The critical factors for high quality printing for a given pattern are explained next.

3.4.1 The Elasticity of the PDMS Stamp

The use of flexible stamps allows micro contact printing to achieve conformal contact for ink transfer. PDMS stamps with low young’s Modulus (1~3 MPa) are widely used because they provide near perfect conformal contact. Young’s modulus is determined by the mixing ratios between the prepolymer precursor and curing agent, and the preparation conditions, such as curing time and temperature.

In the past, the critical dimension of soft lithography was limited by the choice of commercial siloxane with a young’s modulus of 3 MPa as stamp material. This material proved to be too soft to define features smaller than 500 nm. Harder stamp materials had to be developed to allow printing with critical dimensions below 100 nm. An IBM research group demonstrated 80 nm feature size Micro contact printing using a harder stamp with a young’s modulus of 9.7MPa [18]. Therefore, young’s modulus should be carefully determined in accordance with the feature size of the product.
3.4.2 Contact Time of the Stamp with the Substrate

The thickness of the printed SAMs is proportional to contact time (Figure 3-4). Also, the longer the contact time, the lower is the defect rate but the greater the pattern width (Figure 3-5). Generally, it has been shown that contact time is less than 30 seconds, but longer contact time ( >30s ) usually results in an undesired pattern transfer due to vapor transport of thiols from the stamp to the surface in non-contact regions.

Figure 3-4: Relationship between thicknesses printed with 0.2 milli Mole solution of ECT ink [19].
3.4.3 Concentration of the Ink Solution

The relative proportion of thiol and ethanol in the solution affects not only the width of the pattern transferred but also the defect rate as shown in figure below.

Figure 3-6: Quality of Micro contact printed gold structures performed in the case of an ECT contact-inked stamp. Note that defects in patterns are decreased when concentration of ECT gets higher [21].

In addition, concentration and printing time are also inversely related: High concentrations of thiols takes less printing time.

3.4.4 Contact Pressure

The required pressure is based on the pressure that can initiate and control conformal contact. Excessive pressure causes the relief features of the stamp to collapse. In order to
prevented unexpected printing caused by collapse of stamp from excessive force, we need to consider the basic deformation mechanism. Figure 3-7 shows a basic geometry of a stamp that consists of periodic relief line features with height of $h$, feature width of $2w$, and trench width of $2a$. When pressure is applied to the stamp, several deformations occur. These deformations include in-plane lateral expansion, "sagging" of the trench and relief feature from compression by the external stress [22].

Figure 3-7: Illustrations of (a) basic geometry of a PDMS stamp and stamps deformed into contact with substrates under (b) required minimum and (c) excess pressures. [13] showed that the height-to-width ratios, the aspect ratios, of the relief structures on PDMS stamps need to be between about 0.2 and 2 in order to obtain defect-free printing. If the aspect ratio of the PDMS feature is too high, the roof of the feature may come into contact with a substrate under its own weight or under an external pressure. When the aspect ratios are too low, the relief structures are not able to withstand the stamp weight [23].
Specifically, a model for promoting contact between roof and substrates under external stress is suggested by Hui [13] as follows.

\[ V_{\text{max}} = \frac{4\sigma_{\text{min}}}{\pi E^*} (w + a) \cosh^{-1} \left( \frac{w\pi}{2(w + a)} \right) \]

where \( V_{\text{max}} \) is the maximum displacement of the roof by an applied minimum external stress, and the conformability (i.e. the ratio of Young's modulus divided by the work of adhesion (or \( E/w \)) of the material) was found to be a measure of the spontaneous occurrence of conformal contact as well as of spreading collapse [24].

Another driving force that causes the stamp to collapse or driving the conformal contact is the adhesion force. According to the analysis performed by Bietsch and Michel [25] it takes 400 kPa to conform a Sylgard 184 stamp to a surface with 50 nm rms roughness.

However, conformal contact can be achieved under a small force such as the weight of the stamp. Moreover, K. J. Hsia et al. [26] observed collapse of groove regardless of self-weight or normal force. According to their study, interfacial adhesion force is the main driving force of groove collapse, and they developed a parameter, which is a function of feature width, height, surface energy, and Young’s modulus, that determines the adhesion force.
3.4.5 The Choice of Inking Method

Inking can be carried out in three different ways – Immersion inking, Pen-Type inking, and Contact inking.

![Figure 3-8: Three different types of inking for Micro contact printing.](image)

The patterned stamp is consequently inked only via the contact zones where molecules will be needed in step 2. Concentration and immersion time are inversely related: low concentrations of thiols in solution require long immersion times. (A) A liquid inking technique allows impregnation of the entire surface of the patterned stamp with a drop a dilute solution of thiols in ethanol. The possible consequence of this inking method is the interference during printing of thiols on the stamp adjacent to the regions of contact. (B) Inking a stamp by transferring thiols from a liquid reserve of alkanethiols in ethanol through the PDMS allows the stamp to be inked permanently and reused readily, but does not localize this stamp impregnation only where needed (C) Direct inking of the patterned
stamp follows its contact with a flat inker pad previously impregnated by immersion in a dilute solution of thiols. [27].

3.4.6 Propagation methods.

Air bubbles trapped between the stamp and substrate easily occur when large areas are printed. Several methods, such as Micro contact printing under the low pressure environment [28] and forcing air out using flexible backings have been studied, but contact initiation and propagation is simple and generally used method.

The contact propagation can be categorized into three methods: radial contact propagation, linear contact propagation, and rolling contact propagation.

Figure 3-9: Three contact propagation methods (a) Radial contact propagation (b) Linear contact propagation (c) Rolling contact propagation [28].
Radial contact propagation is done by making a stamp convex. The contact initiation starts from the center, and convexity is decreased gradually along with the spreading contact region. Linear contact propagation starts from line instead of point contact. The end of a bent stamp creates line contact initiation and the contact area gradually increases by dropping the stamp gently. A thin bendable layer of metal or polymer can be used for backing the soft stamp. The third contact propagation method is rolling contact, using a cylindrical stamp. In terms of automation, rolling propagation has benefits in that it does not require another mechanism or process for separation of stamps after printing. Moreover, rolling propagation can be simply scaled to mass. However, the deformation of stamp is difficult to predict during cylindrical stamp preparation and subsequent printing.

3.4.7 Temperature

It has been known that forming SAMs at temperatures above 25°C can improve the kinetics of formation and reduce the number of defects in them [29]. Also, the effect of temperature is particularly relevant during the first few minutes of the formation of a SAM when most of the adsorption and reorganization of the SAM is taking place.

3.5 Summary of manufacturing considerations.

Rate, quality, cost, and flexibility of manufacturing process provide a systematic and analytical view not only in evaluation but also in designing the process. Therefore, critical factors related to physics and automation of the process should be considered based on the four factors.
3.5.1 Rate

In designing an automated Micro contact printing process, it is important to decouple the printing and inking processes such that two processes operate independently or individual processing times.

As discussed in chapter 3.2, different inking methods require different inking times, and printing time depends mainly on two factors, concentration of ink solution and target thickness of SAMs. Because micro contact printing is a sequential process involving inking and stamping, the time to complete inking and printing needs to be considered by examining key factors such as inking method and concentration of ink before designing a production line.

3.5.2 Quality

There are a lot of factors that affect printing quality, but the fundamental problems of Micro contact printing relate to the properties of the stamp material. Xia et al [30] proposed three main concerns when Micro contact printing is implemented as one of the micro fabrication process.

1. The shrinkage of PDMS during curing and the swelling of PDMS by a number of nonpolar organic solvents such as toluene and hexane.

2. The elasticity and thermal expansion of PDMS makes it difficult to get high accuracy in registration across a large area.

3. The softness of an elastomer limits the aspect ratio (height of feature / length of feature) of microstructures in PDMS. When the aspect ratio is too high, two posts
can easily stick together (pairing). If the aspect ration is too low, space between two posts will collapse (sagging).

![Diagram showing Pairing and Sagging](image)

**Figure 3-10:** Schematic illustration of possible deformations of microstructures in the surfaces of elastomers [31].

### 3.5.3 Cost

The expected cost of tool, ink solution, change over time should be considered in designing & evaluating Micro contact equipment. Usually, tool cost depends on wear of the tool (PDMS stamp) but wear has not been reported so far, so it is very difficult to predict the total tooling cost. However, we can minimize the tool cost by minimizing the number of tools in the buffer between inking and printing station.

### 3.5.4 Flexibility

In a high volume manufacturing process, flexibility of tooling and tool change - over time are important, so Micro contact printing machine should be designed such that it provides a
fast tool changing mechanism. In addition, if Micro contact printing machine is used for multilayer micro fabrication, the tool changing mechanism should also provide accurate registration capability.

3.6 Industrial design efforts for Micro contact printing

3.6.1 Rolling

![Schematic procedure for conducting μCP with a rolling PDMS stamp](image)

Figure 3-11: Schematic procedure for conducting μCP with a rolling PDMS stamp [32].

Micro contact printing by rolling is one way to form patterned SAMs at a high speed and, therefore, appropriate for mass production. Younan Xia et al demonstrated that a minimum
feature size of ~300nm is achievable using a cylindrical stamp of which diameter is approximately ~ 4 cm. 3 inch gold coated wafer (an area of 50 cm2) was used for a substrate and printed at 2cm/sec. (It take 15 seconds to print 3 inch wafer) A single inking can print 4~5 times of printing without showing any difference in terms of defects in SAMs. The main disadvantage of rolling is that feature on stamp should be deformed to make a cylindrical stamp, which limits the minimum resolution or feature width of pattern.

3.6.2 Wave printing

![Wave printing diagram](image)

Figure 3-12: A vertical Cross-section of the wave printing prototype [33].

1: Stamp-backplane assembly; 2: Substrate; 3: Working gap (≈100μm); 4: Vacuum supply; 5: Pressure supply (≈2kPa); 6: Valves switched to pressure supply, thereby creating the wave. 7, 8: Grooves-plate [15].

The concept of wave printing [33] was proposed in order to minimize the deformation and distortion of patterned SAMs printed by the stamp which has both large and small feature and space in a single stamp. Slender posts (height to width ratio h/w 2.5) can be easily buckled and sagging will occur if the height of posts is relatively small to space between
relief features by a small normal force. In wave printing, a glass backplane as a flexible glass mount is attached to elastomeric stamp to prevent distortion of relief features and this stamp-backplane creates wave by the pressured air mechanism, generating line contact between stamp and backplane. It took twenty minutes for inking, one hour for drying, and 15 seconds for printing as small as 0.75 μm, with h_{post} =2.3 μm. Micro contact wave printing demonstrated single layer capabilities with very low distortions.

3.7 Conclusions

In this chapter, we discussed the process physics and principles behind micro contact printing. The critical factors that determine manufacturability using the process were also discussed besides a few design efforts to automate the process. In the next chapter, we will discuss a manufacturing system that we have designed for commercializing production using micro contact printing. We will also present the design of a prototype to automate the inking and stamping steps.
4 Concept Design and Realization

4.1 Introduction

The objectives of this project included designing a manufacturing system for micro contact printing and prototyping an automated system for inking and stamping that can achieve economically viable process. To achieve these goals, a thorough understanding of the process physics involved in micro contact printing was required besides identifying the critical factors that contribute to output quality and production rate. The final manufacturing system design and the prototype design were derived after several design iterations. The key breakthrough in the design process was achieved on the realization that the target substrate was a flexible sheet of gold coated plastic film which allowed keeping the stamp stationary (to avoid stamp deformation) and apply the substrate onto the stamp while achieving linear propagation (to avoid air bubbles).

This chapter takes the reader through some of the most important design iterations towards the final design. We discuss designs for both the inking and stamping steps. Though some of the designs do not involve the use of a flexible substrate, not only are they are significant milestones in this project but also and can be considered for hard substrates. Finally, we propose a complete manufacturing system for high volume production.
**4.2 The Inking Process**

Three inking methods are explored and discussed in the literature [34].

1. **Wet Inking** - Ink is uniformly applied to the PDMS stamp to cover the entire exposed surface area. This is done by fully submerging the patterned surface of the stamp in an ink tub.

2. **Pen Stamp** - Ink is stored in an ink tank behind the PDMS stamp and diffuses onto the surface of the stamp for stamping. The method derives its name due of its functional similarity to a writing ink pen.

3. **Contact Inking** - Ink is only applied only to the relief features of the stamp. This is achieved by bringing the stamp’s relief feature in contact with a pad soaked with ink.

Table 4.2 gives a functional comparison for each method.

**Table 4.2 Comparison of Three Methods of Inking Stamps for Mcp.**

<table>
<thead>
<tr>
<th></th>
<th>Wet Inking</th>
<th>Pen Stamp</th>
<th>Contact Inking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distortion of stamps</strong></td>
<td>Capillary effects, slight swelling</td>
<td>Strong swelling</td>
<td>No distortion</td>
</tr>
<tr>
<td><strong>Adversary diffusion of the ink (HDT)</strong></td>
<td>Strong</td>
<td>NA</td>
<td>Strongly minimized</td>
</tr>
</tbody>
</table>
Stamp distortion is important to us since a single stamp may have to go through multiple rounds of printing in the industrial production. Even slight distortion would be dramatically reduces the productivity and product quality collectively.

The scalability is also important to us as the goal is to design a machine good for large scale production. For output quality of the printed patterns, it is important that adversary diffusion (due to vapor transport) is minimized. With the factors above and Table 4.2, contact inking was chosen be the most appropriate inking method for this project.

4.2.1 Designs for Inking

Having decided upon contact inking for the reasons outlined in section 4.2, several mechanisms to achieve it were considered. The most important ones are described next.
4.2.1.1. Roll Inking

A hard roller is inked by rolling it over an ink-soaked pad (contact inking) or by having an ink tank inside (Pen Inking). Then the roller rolls over a fresh stamp to transfer the ink. The advantage of this design is that it can generate linear propagation (to the ink) during the inking process to apply the ink uniformly over the stamp. Also the inking time between the roller and the stamp can be well controlled by the forward motion of the roller. Thirdly, it’s convenient to shift between the stamping inking stage and the inking roller inking stage.

However, there are also several challenges with this design.

1. The vertical position of the inking roller determines the applied pressure. Excessively high pressure may deform the stamp while insufficient pressure may lead to insufficient ink transfer or worse, slippage causing some relief features to miss ink application completely.

2. The weight balance of the roller. As the weight of the roller itself is big enough to cause the deformation of the stamp, the weight must be well balanced with the external mechanism.

3. If applying the wet ink to the stamp, it takes longer to dry the ink. After the stamp is inked, it has to wait for another 10-60 seconds before it can be shifted to the printing. This can be the bottleneck for the process.
4.2.1.2. Polygonal Inking

Instead of a cylindrical inking roller, a regular polygonal rolling tool can be used. We consider the case using a hexagonal tool. The design is easily understood with the help of figure 4-1. A major advantage is that the inking and stamping steps are readily integrated.

However, the challenge is that the inking pad and stamp have to be lifted up or down each time the hexagonal tool rotates. As figure 4-1 shows, when the hexagonal tool rotates, the ink pad and the stamping stage have to be moved vertically by $\frac{1}{2}$ of the edge length to allow the pinnacles of the hexagon rolling through. This requires high precision position control system, particularly given that the stamps will have to be changed regularly.

The other disadvantage, which is more critical than merely the mechanical inconvenience, is air trapping. As the hexagon surface rests over the stamps, there will be no linear contact propagation.

Figure 4-1: The basic concept of polygonal inking.
4.2.1.3. The Finalized Inking Design

The final inking design is shown step by step in figure 4-2. This design is based on the inking roller idea and takes into consideration the need for weight balance, pressure adjustment and vertical position control.

Figure 4-2: The finalized inking design. (A) The inking roller runs over an ink pad to collect ink while a stream of Nitrogen gas dries the ink solution. (B) The inked roller transfers the dried ink onto a fresh PDMS stamp (C) The inked stamp is transferred onto the stamping station and is replaced by a new stamp.
The inking roller is supported by two arms and an arm connector that is driven by a lead screw actuator. The roller is rigidly fixed to a steel shaft that is connected to the arms. The roller is supported on either end by timing belt pulleys which run on a urethane timing belt track. This ensures smooth and slip free motion. The ink pad is set up under the rails. The junction between the roller shaft and the arms is slotted to allow free vertical motion of the roller.

A nitrogen stream will be applied to the roller to dry the ink while the roller moves on the rails. The ink will then be almost dry before being transferred to the stamp. With this dry inking design, the actual drying and inking time to the stamp will be dramatically shortened and yet the quality will be assured.

A fresh stamp will be positioned on the other side of the inking stage. After ink has been collected from the ink pad and dried by the nitrogen stream, the roller will start transferring the ink onto the stamp. After the inking completed, the newly inked stamp will be transferred to the stamping station through two sequential transfer mechanisms- transfer of the stamp from the inking station to the stamping station and transfer of the stamp onto the stamping stage for stamping.

With this design, the two challenges to the previous roller design have been overcome. The weight of the roller will be supported by the rail together with the frame system. The vertical position can be adjusted along the slots on the two roller arms. More importantly, with the dry inking design, the inking and dry time for the PDMS stamp will be shortened, which will greatly improve the production rate.
At the same time, the advantages of the roller design remains. The linear propagation effect will reduce the air trapping during inking and automating the shift between the inking pad and stamps is straightforward.

4.3 The Stamping Process

In our design a flexible sheet of PET is used as the substrate, which is applied onto a stationary PDMS stamp, and this played a dominant role in finalizing the design for the stamping process. However, several designs for stamping with hard substrates were also considered, which helped us in arriving at the finalized design. Regardless, the following are the key considerations for achieving good stamping outcome:

1. The ability to bring the stamp and the substrate in contact at an appropriate contact pressure.
2. Spreading of the substrate onto the stamp or vice versa in a way such that there is no air trapping.
3. The ability to peel off with force just enough to overcome the adhesion force.

Excessive force might damage the printed features due to excess strain induced.

4.3.1 Designs for Stamping

In this section, we will discuss the most important stamping designs which led us to the final design. We shall first describe a couple of designs for hard substrates and then present the final design applicable to flexible substrates.
4.3.1.1. Roll Stamping

![Diagram of Roll Stamping](image)

Figure 4-3: Roll Stamping. The motor Mx moves the roll forward and the motor My can control the vertical position of the roll and hence the contact pressure either actively or in open loop.

In this design a hard roller wrapped with a PDMS stamp with the desired patterns is run over an ink pad. The ink solution is dried with a stream of nitrogen and transferred onto a fresh PDMS stamp. While the process is extremely simple and involves only a horizontal motion, it has the following drawbacks:

1. Wrapping of the stamp over a roller can cause deformation of the features on the stamp (figure 4-4). It can be easily shown that the strain in the stamp will be a function of the diameter of the roll. This will severely affect the resolution achievable with this process.

2. The vertical position of the roller will have to be very accurately controlled in real time to achieve the right contact pressure.
3. Any slippage due to mismatch between the angular and linear motions would be detrimental to output quality.

4. It would have been hard to control the contact time.

Figure 4-4: Elastic strain induced in the stamp with Roll Stamping. The strain is $[1 - \sin(\beta)/\beta]$. So, as contact length becomes large, we have greater strain which would severely distort the stamp given the high feature-size/resolution ratio. However, if the radius of the roll is large, the angle can still be small.

4.3.1.2. Polygonal Stamping

An improved variation to roll stamping, polygonal stamping overcomes the stamp deformation due to wrapping of the stamp on a roller. Each face of the polygonal tool is
covered by a PDMS stamp (but not rigidly attached). The tool can rotate about a hinge (the instantaneous edge of the polygonal tool in contact with the substrate. See figure 4.-5) and applies the stamp onto the substrate. Linear propagation is achieved without wrapping the stamp onto a cylindrical roller and thus stamp deformation is avoided. The design is explained step by step through figure 4.-7.

This edge held 'hinged' while the center of body rotates about it
Sufficiently rough material AND some external forces needed.

Figure 4-5: The basic concept of polygonal stamping.
Figure 4-6: The stamping tool proposed for Polygonal Stamping.

Figure 4-7: The hinge effect of the polygonal stamping tool.

In this design, it is important that the PDMS stamps are not attached to the faces of the tool as then no linear propagation can be achieved when the stamp is applied to the
substrate. If they are indeed made to hang freely between the two fixed edges, some deformation of the stamp (near the second edge) might take place while the stamp face is parallel to the ground.

4.3.1.3. Pseudo Roll Stamping

The design derives it name from its similarity in concept to roll stamping. The stamp is applied to the substrate through a mechanism that resembles roll stamping with a roll of infinite diameter (which gives almost no deformation). The process is explained through Figure 4-8.
Inking roller

Nitrogen blowers

B.

C.
The stamp will be kept at near zero tension
The process discussed does not address any contact pressure adjustment means. In roll stamping this can be achieved by balancing the weight of the roller with counter-weights. In this design, this can be achieved by either using a thicker stamp or through a uniform stream of air.

4.3.1.4. The Finalized Stamping Design

We developed a reel to reel stamping design that gives linear propagation for substrate application as well as peeling off. The design utilizes the fact that the substrate (gold coated PEN film) is flexible and can be applied onto the PDMS stamp. The substrate application is achieved through two foam covered wipers whose motion in the vertical plane is controlled through two separate XY-Positioners. Referring to figure 4-9, the use of foam cover on the
wiper core prevents any excessive pressure to be transmitted onto the stamp-substrate interface. This allowed us, for the sake of this prototype, to use a fully open loop based vertical position control system.

Figure 4-9: Two foam covered cylindrical wipers apply the gold coated PEN sheet onto the PDMS stamp.

The process is explained, step by step, through figure 4-10.

The two wipers move down to touch the stamping stage while the pay-off reel supplies the fresh substrate.
One wiper moves towards the pay-off-reel, applying the substrate onto the stamp in the process. The other wiper and the take-up reel are held fixed so as not to allow any substrate movement.

Both the wipers are held fixed for a period of time long enough to enable ink transfer between the stamp and the substrate.

The take-up reel begins to collect the stamped substrate.
The second wiper moves towards the first wiper while the take up reel collects. This is the peel off step.

Both wipers begin to move upwards, away from the stamping stage. The take-up reel collects the substrate.

Both the wipers begin to move back to their original position.
Stamping cycle is complete. The used stamp is transferred onto the inking station and is quickly replaced by a freshly inked stamp.

Figure 4-10: A step by step illustration of the stamping design developed. [35]

4.4 A Manufacturing System for High Volume Production

For micro contact printing to succeed commercially, it is very important that the process be capable of producing products at production rates that cost less than the existing pattern transfer techniques. The most important goal while designing a manufacturing system for micro contact printing is to achieve the highest possible quality at a rate that is ideally limited only by the chemistry of the process.

An integrated design of the inking and stamping processes above can be considered as the miniature model of the high-volume production machine without the etching step. We will show later that inking station can be integrated with the stamping station so that the production throughput from the inking-stamping steps depends only on the ink transfer time in the stamping station. After being stamped, the substrate would be etched in an etch-bath as shown in figure 4-11. Because etching time is considerably larger than the inking or stamping times, the length of the substrate inside the etch-tub can be as long as necessary to keep up with the stamping process. The process resembles hot rolling in the way the individual processing times are decoupled.
Another version of the manufacturing system showing higher level detail is shown in figure 4-12. Here, ink is applied to the stamp by applying an ink pad onto the stamp and leaving it for an appropriate period of time. A stamp with an ink pad residing on its top can still move on the conveyor. This decouples the stamping time and inking time from the production rate. The decoupling of the etching time from the production rate has already been discussed.
Figure 4-12: Another version of the manufacturing system. Note that here, the inking step is shown is different than the one ultimately used. Note also that the number of stamps on the belt between the 4 stations can be adjusted based on the time for inking, printing, removing etc.

4.5 Conclusions

In this chapter, we described development of our design to achieve inking and stamping. We also discussed how the three steps for micro contact printing – inking, stamping and etching can be integrated for high volume production such that the production rate depends
only on the chemistry of stamping. We hope that scientific advancements with a better process optimization or discovery of new materials could reduce this time further.
5 Design and Implementation of the Inking Station

In this chapter the design of an inking station is developed. This station is meant to integrate with the printing system detailed in chapter 4. The overall system is first described and then the details of the inking station are given.

5.1 Design overview

There are two major stations for our process system: the inking station and the printing station. The two stations can be run separately, yet synchronized together during manufacturing.

At the inking station, the dry ink solution is rolled onto the PDMS stamps. The inking time and drying time of the stamp after inking vary with different ink concentrations.

At the stamping stage, the PDMS stamp will be fixed on the printing stage once inked and the PET/PEN substrate will roll over the stamp to get the features transferred.

5.1.1 Inking

The ink solution is applied in a liquid state onto a hard glass roller and is made to dry in a Nitrogen rich environment. The roller with dried ink on its surface is then rolled onto the
PDMS stamp and ink is uniformly transferred onto to the relief features. The inked stamp is then transferred from the “inking station” to the “stamping station”.

5.1.2. The inked PDMS stamp is held fixed while a continuous sheet of gold coated PET/PEN wrapped between a “collector spool” and a “supply spool” is applied onto the stamp for ink transfer. Peeling-off (after sufficient ink transfer) and indexing of the collector spool (to begin the next printing cycle) follow next. The mechanism for substrate application and peel-off emulates rolling – as if the substrate was wrapped around a very large wheel which was made to roll over the PDMS stamp. This gives an effect of “linear propagation” of the substrate to push out any air while the substrate is being applied. This further avoids any air-trapping which is detrimental to quality. The mechanism is realized through two extra soft foam covered horizontal “wipers”, whose motions in the vertical plane are programmed. The foam cover on the “wipers” ensures uniform contact and minimizes the distortion of the stamp due to excessive pressure. During the entire process, a tension-control system ensures that the tension in the substrate is always as desired.
The side-view of the printing station is as shown in Figure 5.1. The PET/PEN substrate was fixed by the rolls, rollers and peg.

5.1.3. The physical layout of the machine

The whole micro-contact printing and inking machine consists of the printing station, the inking station and the rotary table/Z-machine. Each of them is stand-alone independent machine which could function alone. But yet the three machines were integrated together to generate continuous production flow.
5.1.3.1. The Printing

Figure 5.3 shows the layout of the stamping station. The components for the printing station include:

- The take-up and pay-off spool
- Two pegs
- The tension meter
- The two XY tables
- the printing stage
- The wall for fixing bearings
- The floor

The two XY tables stand on two ends of the floor and in the middle, not really in the center line of the floor, stands the wall. The printing stage sits in the exact middle of the floor with a square hole in its base.
Figure 5-3 the Printing Station
5.12. Concept analysis for the inking station

The final inking design is shown step by step by Figure 5.5. This design is based on the inking roller idea discussed in chapter 4.3.1.2 and takes considerations of weight balance and position control. The roller is placed on the inking rails. The inking roller is first inked while rolling over the ink pad. Then the inked roller will roll over the retainer to get the stamp inked. The rotary table will rotate 180 degree to bring the new stamp to the roller for inking and the inked stamp back to the printing station.

The inking roller is supported by two arms and arm connector, which are driven by the lead screw. The roller was glued to a steel shaft and the shaft will be connected with the arms. Two pulleys are fixed at each side of the roller. The pulleys will actually reside on two rails which supported by the frame system. The total weight of the roller and the shaft will be
supported by the rails through the pulleys. Besides, the travel routine would also be fixed by the rail-pulley assembly.

The ink pad will be set up under the rails. The conjunction between the roller shaft and the arms is slotted to give more flexibility of the vertical position of the roller.

The nitrogen stream will be applied to the roller to dry the ink at the meanwhile. The ink will be almost dried before being transferred to the stamps. With this dry inking design, the actual drying and inking time to the stamp will be dramatically shortened and yet the quality is assured.

The fresh stamp will be positioned on the other side of the inking stage. After being inked, the roller will be brought to the stamp by the lead screw and start inking the stamps. The vertical position of the roller can be adjusted to the point that there will be close contact for the ink transfer but there will be force applied to the stamp features to avoid any deformation.

After the inking completed, the newly inked stamp will be transferred to the printing stage through our rotary table design. More details of the rotary table and the set up will be covered in later chapter. On the other end of the rotary is the new stamp or the stamp need re-inking after printing. While the inked stamp is sent for printing, the new stamp will be brought to the roller for inking. A new cycle starts over.

With this design, the two challenges to the previous roller design have been overcome. The weight of the roller will be supported by the rail together with the frame system. The
vertical position can be adjusted along the slots on the two roller arms. More importantly, with the dry inking design, the inking and dry time for the PDMS stamp will be shortened, which will largely improve the production rate.

Meanwhile, the advantages of the roller design remains. The linear propagation effect will reduce the air trapping during inking stage. It’s convenient to shift between the inking pad and stamps with the automation setup.

There can still be improvement to the design as well as the final prototyping. We will cover more of the future recommendations and improvement in Chapter 6.

5.1.3. **Physical layout of the inking station**

Figure 5.4 shows the layout of the inking station. The basic components for the inking station include:

- the inking roller and rails
- the inking lead screw actuator
- the rotary table, arms and retainer
- the Z-machine
- the inking pad
- the frame for the inking roller
- the frame for the rotary table and z-machine

The z-machine is the lead screw driven actuator that generates the motion for the PDMS retainers. Two sets of stamp retainer on both sides of the rotary arms. At any time, the
stamp on one arm is being inked and the other being stamped. The motor-driven rotary table will rotate the arms to change the state after both the inking and stamping completed. The lead screw of the inking station will provide the motion for the inking roller. The roller will get inked first through rolling over the ink pad located right below the rails. Then the ink will be transferred to the PDMS stamps through rolling.

Figure 5-5 The Printing Station
5.1.4. The design requirement and key mechanism design issues

The objective of this machine is to simulate the micro-contact printing at the required rate and accuracy. The substrate material is Au (70nm vapor-deposited) coated PET. The product size is 3” by 3”. The feature size is on the millimeter level and the minimum resolution is 1 micron. More importantly, the printing time should be restricted below 5 seconds and 60 seconds for the etching time. With this project scope, the printing and inking time will be the primary focus.

5.3. Component design and analysis

The inking station is the critical component in this prototype. Its function includes not only inking the stamp but also transporting the inked stamp to the printing stage. Besides, it should also provide seamless integration with the printing station. The final design implemented should provide the following mechanisms:

a. The inking roller should be able to generate the linear propagation along the new stamp while inking to avoid air trapping

b. The newly inked stamp should be sent to the printing station right after inking and the transportation process should be easy to implement and requires low maintenance cost and effort
c. Each of the newly inked stamps should be shifted to the same initial position on the printing stage. Too much position variations in any directions will cause the non-uniformity across the printing products.

d. During the inking process, any form of deformation caused to the PDMS stamp should be avoided.

There are more design considerations besides those listed above and we will cover more of them in the later chapter. The actual design of the inking station was composed of four major functional units:

a. the inking roller with the frame support

b. the rotary table system

c. the printing stage with the z-machine

d. the support frame

The inking roller performs the inking function. The frame associated with it will provide the weight support to the roller and the ink pad.

The rotary table system will take the inked stamp to the z-machine before ultimately sending the stamp over to the printing station. It will also brings the stamp back to re-inking after the printing process.

The printing stage with a flat top plate is where the printing will take place. The z-machine will generate the motion of bringing the stamp up to and down from the printing stage. The
printing stage will be located in between the wall and the two XY motors. The z-motor is right under the printing stage.

The support frame system, made 1.5” aluminum square frame, is the “steel body” of the whole machine. It supports the weight of the whole printing station and the floor on top of it. Also, it provides space and weight support to the rotary table and the z-machine. Besides, all the 9 motor drivers, 3 UMIs and the power generator will be located on the bottom layer of the support frame.

5.3.1 the inking roller with the frame support

![Figure 5-6 The inking roller with its support frame](image)

The inking roller will be connected with the lead screw of motor driven. The lead screw actuator will push the inking roller back and forth at the controlled speed. In the solid model drawing above, the inking pad has not yet been included. In the final prototype, a layer of inking pad was placed right underneath the inking rails. The inking roller with PVC will roll over the inking pad.
5.3.1.1. Inking station lead screw with motor

The inking roller, which collects ink on its surface over a pad soaked with alkanthiol (the ink) before applying the ink on the PDMS stamp, rolls on a flat urethane timing belt fixed to parallel tracks. The forward movement is provided by a precision lead screw that has a pitch of 0.1", straightness error of less than 1 micron per foot of travel and a total travel length of 28.4 inches. This lead screw is rigidly mounted parallel to the u-channel. Together with the U-channel, the lead screw is fixed onto the supporting frame ceiling.

Figure 5-7 Solid Model for the lead screw actuator
For the lead screw, the slides can be set up with mechanical crank handles and wheels as well as motors. End plates and guide blocks are aluminum. Rails are hardened and ground steel and have unthreaded 3.5 mm mounting holes with 6.5 mm Dia. x 4.5 mm Dp. counterbore. End plates have unthreaded 6 mm mounting holes with 9 mm Dia. x 6 mm Dp. counterbore.

5.3.1.2. U-channel for lead screw

The U-channel was designed to fix the lead-screw. The U-channel is 31.75” in length and 4” wide. The two end plates of the lead screw will be fixed at two ends of the u-channel. The inking motor mounted on the motor mount will be connected with one end. The U-channel will be fixed onto to the ceiling frames.
The initial design was merely the top plate without the two flanges. The U-channel design provides extra protection to the lead screw. Currently the material used is aluminum. With the further improvement, the aluminum can be replaced by polycarbonate or other more transparent materials so that the motion of the lead screw and the guide block can be more visible. There were indeed some problems tracking the motion errors with the current design.

5.3.1.3. **Inking roller**

Two pulleys and the roller are fixed on a steel shaft which is 12” long and 0.5” in diameter. And the shaft will go through the two slots of in the arms. The arm connector are connected with the guide block of the lead screw. The inking roller is placed on rails which supported by two frames, like a train traveling on railways. The two strips of rails are made of plastic and 0.5” wide and 20” long. The gear teeth of the rails matches with that of the two pulleys.
The other purpose of the rails is to support the weight of the roller system. If the roller rolls directly over the inking pad and the stamps, the weight of the roller will cause large deformation of the pad and especially the stamp.

![Diagram of inking roller and arm](image)

**Figure 5-10** The solid model for the inking roller and arm

### 5.3.1.4. The inking rails

The inking rails design is one of the novelties in our design. After deciding on the inking roller design, the challenge is how to ink the stamp without deforming it. The inking rails will support most of the weight of the roller. At the meanwhile, it also functions as the guide of the roller when it’s traveling between the inking pad and the stamp retainer.
The inking rails consists of two parts, the track and the frame support it. The track was hard plastic which has been glued to the supporting frame. There were six “L-connectors” used to fix the frame tightly to the vertical frames and make sure the two rails are always on the same vertical height.

![Inking Rails Track](image)

**Figure 5-11 the inking rails**

5.3.1.5. Inking roller arm

The arm is 8.5” long and has a hole with 0.33” in diameter near to the top. The hole is needed to connect with the arm connector using the L-connector. (In this prototypes, there are a number of L-connectors of the same sizes have been used). Instead of simply having a hole to fix the vertical position of the shaft, a slot of 1.9” long is used to bring more flexibility in the vertical direction. The arm is ¼” thick and machined using water jet. Figure 5.11 shows the drawing for the roller arm design. The arm was machined using a
water jet cutting machine. The drawing and cutting path for the water jet OMAX machine can be found in the Appendix A.

![Figure 5-12 The design of the roller arm](image)

5.3.1.5 Arm connectors

The design for the arm connector is shown as in Figure 5.13. Similar to the arm design, it has two slots at both ends instead of just having holes. The slots which are both 0.5” long will bring flexibility of the distance two arms. The four holes on the lower part of the connector will be used to connect with the lead screw crank handle. Thus, all the dimensions and the hole sizes match with the lead screw handle.
The material used for the connector is ¼” thick aluminum. The arm connector was machined using water jet and the drawing for the cutting path can be found in Appendix.

5.3.2. The rotary table system

In this micro-contact printing design, the plan is to have the printing and inking stations run in parallel. Since the inking time takes longer than the printing, it would make sense to have separate PDMS stamps being inked while printing is taking place. However, the challenge is how to synchronize the two separate operations. We came out with the idea of a rotary table, which has two arms. There is a PDMS stamp on each arms. While the stamp on one arm is stamping, the other stamp is being inked. When both the printing and inking are done, the rotary table will rotate 180 degrees to send the inked stamp for printing. The rotary system was made of 3 major components: The rotary table, the rotary arm and the retainer.
The rotary table acts as a coupler between the inking and stamping operations by conveying PDMS stamp retainers back and forth between the two stations. The table is timing belt-pulley driven with a 6:1 reduction from the motor axis pulley to the table pulley. With the rotary motion generated by the rotary table, the rotary arm (with the supporting frame attaching to it) will deliver the actual transition between printing and inking station. It supports the stamp retainer and driven by the rotary table.

The PDMS stamps is placed on the stamp retainer. While inking, the retainer will be placed on the rotary arm. Before the printing takes place, the retainer will be pushed up from the arm by the z-lead screw and reach the printing stage. Figure 5.14 is the assembly drawing for the rotary system.

![Rotary Table and Arms](image)

**Figure 5-14 the solid model for the rotary table and arms [33]**
5.3.2.1. The Rotary positioning table

The rotary table was acquired from a vendor, Arrick Robotics (http://www.robotics.com/z2.html) and was used as such without much modification. The table is timing belt-pulley driven with a 6:1 reduction from the motor axis pulley to the table pulley. With the rotary motion generated by the rotary table, the rotary arm (with the supporting frame attaching to it) will deliver the actual switching between printing and inking station. It supports the stamp retainer and driven by the rotary table. Picture 5.2 shows the rotary table and Figure 5.15 shows the layout and specification of the table.

Picture 5.2 The rotary table purchased from Arrick Robotics Inc.
Figure 5-15 the layout and specifications of the rotary table [36]

5.3.2.2. The Rotary arms

The rotary arm is 28” inch long. The total length was decided by the size of the rotary table and the size of the retainer. The dimensions of the rotary table are fixed as we purchased it from the vendor. As the goal is to have 4 3”x3” panels stamped, we decided to the make the retainer top plate 7” x 7”. The width of the arm is 10.5” to give enough space for screw holes and holes to fix the rotary table.
In the initial design of the rotary arm, the two square holes for the retainer base were made larger. Only after the whole piece was made and tested, we realized the side beam as shown in the picture above will be very possibly deformed by the stamp retainer, taking into account the large weight of the retainer.
Suppose the side beam can be simplified as a beam with only one end fixed. To simplify the calculation, assume uniform weight distribution along the side beam.

![Beam Diagram]

With a force/pressure applied at one end of the beam with the length $L$, the maximum deflection and equation of elastic curve:

Maximum deflection: $V_{\text{max}} = \frac{wL^4}{8EI}$

Equation of elastic curve: $v = -\frac{wx^2}{24EI} (x^2 - 4Lx + 6L^2)$

The moment of initial $I_x = \frac{bh^3}{12}$

The young’s modulus for aluminum is $E = 69 \text{ GPa} \text{ or } 10^7 \text{ psi}$

In the case of rails, the material is aluminum. The applied force $P$ is approximately the weight of the inking roller. With $b=1.5 \text{ inch}$ and $h=4 \text{ inch}$, the maximum deflection will in the $10^{-7} m$ scale, which is negligible. In this design, the width of the sidebar has been intentionally set to be bigger so that the maximum deflection with the loan can be minimum.
The material used for the arm is 1/4 "thick aluminum and water jet was used for machining. The drawing for water jet machining can be found in Figure 5.16. . . The drawing for the arm and the cutting for OMAX can be found in Appendix A.

5.3.2.3. Retainer

The stamp retainer acts as the carrier (the rotary table itself is the conveyor) from the rotary table to the printing stage. It consists of the retainer base, the wing and the top plate.

![Figure 5-17 The stamp retainer assembly](image)

![Figure 5-18 The design of the top plate](image)
The top plate serves also as the PDMS mount. It is 7" by 7" which is sufficient to print 4 3" by 3" panels. There are various small holes through the plate to minimize the potential air trapping during the printing process.

The retainer wing holds both the top plate and the retainer base. One important function of the retainer is to make sure of the alignment of the retainer with the printing stage so that the PDMS stamp can always be brought up to the same location. This will ensure the initial setup for every round of printing is the same. There are four holes with diameter of 0.56" at each corner. When the retainer was pushing up, the four guide pins with slightly smaller diameters will find the holes. As the retained pushed up further, the mating between the guiding pin and the retainer will make sure the stamp sent to the right place.

The wing has also a 5"x5" hole in the middle which performs the similar function as the holes on the top plate. Air can go through the holes on the top plate and the wing. The wing was also machined using the water jet.

Figure 5-19 The design of the retainer wing
The retainer base is fixed with both the wing and the top plate. It is 6’x6’ and ¼” thick. The bottom surface of the base is also covered with PVC sheet to allow slipping between the manipulator head and the bottom surface of the retainer so that retainer is free to move in the horizontal plane for alignment while rising upwards along the guide pins.

5.3.3. Stamp Delivery to the Printing stage

5.3.3.1. Z-machine – the motor driven lead screw for the vertical lifting

When a fresh stamp reaches the stamping station from the inking station, it is lifted to the level of the stamping stage by a lead screw actuator. The manipulator is a flat head covered with PVC sheet.
The z-machine is actually the lead-screw-driven actuator with the supporting arm for the stamp retainer. The z-machine will generate the motion to push up or bring down the stamp retainer at the predetermined speed and timing. Figure 5-21 shows the physical layout of the lead screw used for the z-motion.

Slides have a wear-compensating acetal nut for smooth, consistent operation and include a flexible helical coupling. The frame and guide block are aluminum. The lead screw is Type 303 stainless steel. The rails are made of hardened and ground steel. Maximum motor speed is 2200 rpm.

The supporting arm, whose design is as shown in Figure 5-22, links the lead screw with the retainer. The retainer resides on the top plate of the supporting arm during printing. The arm is connected with the lead screw through the side plate.
The backplane is the last piece for the z-motor. The plane is used to fix the lead screw with the frame. The dimensions and layout of the backplane can be found as Figure 5-23 shows.

Figure 5-22 Z-machine supporting arm

Figure 5-23 The dimensions of the back plate
5.3.3.2. The printing stage

![The printing stage assembly](image)

**Figure 5-24. The printing stage assembly**

The printing stage is where the stamp is located when the printing is taking place. The design consists of the top plate, the supporting frame, the guiding pins and the stamp retainer.

The top plate was made of polycarbonate to bring more visibility of the retainer motion. There is a 4.7" by 4.7" square hole in middle to accommodate the retainer top plate when it is pushed up. Besides the square, there are also the four holes for the guiding pins on the top plate.
The guiding pin design is one of the novelties in this project. When the retainer is brought up, the challenge is how to make sure each time the retainer top plate is placed at exactly the same position. There will be too much variations in the final work piece if the initial setup is not uniform. It is especially important for the manufacturing at large volume.

In this design, four guide pins are fixed perpendicular to the stage top plate with the heads facing down. The pins are made of a couple of male and female threaded rods. The rod with 3/8"-24 threaded female ends has 6" overall length and the rod outside diameter is 7/16". The rod with male ends has the same length and 7/16" inside diameter. The female rod will be inserted into the male rod and screwed together with it. The other end of the female rod will be fixed into the screw holes on the top plate. The male rod, which is towards down facing the retainer, will perform the guiding function.

Picture 5.3 The Guide Pins on the Printing Stage
Figure 5-25. The match up of the guiding pins and the retainer

Guiding Pin Threaded Female end, 6" overall length
Go into the male rod
Fix to the stage top plate
Guide Pin with threaded male end

Figure 5-26. The Guiding Pins Components

The overall dimension of the printing stage can be found from Figure 5-27. The width of the middle square hole is 7" so that there can be enough space for 4 3" by 3" stamps. The material used for the printing stage can be found from the printing stage material list from
the appendix. Hyung-Jun Kim will cover more details of the printing stage in chapter 5 of his thesis [add formal reference to his thesis here].

Figure 5-27 The top view of the printing stage

5.3.3. Supporting frame

On the top of the tool delivery station is the floor that supports and locates the printing station. In the second level, there are four sections. In the middle, it is the space for Z-motor and lead screw, which pushes the printing retainer from the rotary table to the printing stage. The panel for the power supplier which supplies power to all the nine motors is located to the left of the Z-machine. On the right, it is the panel for all the 9 motor drivers. The
material used for the inking frame can be found from the material list for the support frame in Appendix A.

Figure 5-28. The design of the rotary table and Z-machine supporting frame

5.4. Machining and Material

All of the machining for this project was done in the MIT Laboratory for Manufacturing & Productivity Cross lab, the MIT hobby shop and the Nano Terra research lab. The machines used to make this prototype include an Omax water jet machine, a milling machine, a vertical saw, a band saw and so on. Most of the cutting, shaping, carving and reaming processes have been performed on the water jet machine.
### Table 5-1: The inking station machining list

<table>
<thead>
<tr>
<th>Name of Items Machined</th>
<th>Machining Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>The inking roller/frame</td>
<td></td>
</tr>
<tr>
<td>The inking frame</td>
<td>Vertical saw, band saw</td>
</tr>
<tr>
<td>the U-channel</td>
<td>Vertical saw, milling machine</td>
</tr>
<tr>
<td>The inking roller arm</td>
<td>Water jet</td>
</tr>
<tr>
<td>The roller arm connector</td>
<td>Water jet</td>
</tr>
<tr>
<td>The ink pad holder</td>
<td>Water jet, milling machine</td>
</tr>
<tr>
<td>The rotary table/frame</td>
<td></td>
</tr>
<tr>
<td>The motor mount</td>
<td>Water jet</td>
</tr>
<tr>
<td>the rotary arm</td>
<td>Water jet</td>
</tr>
<tr>
<td>the top plate of retainer</td>
<td>Water jet</td>
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<td>The retainer wing</td>
<td>Water jet</td>
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<td>The retainer base</td>
<td>Water jet</td>
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<tr>
<td>The floor for drivers</td>
<td>Water jet, band saw, milling machine</td>
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<tr>
<td>The floor for UMI</td>
<td>Water jet, band saw</td>
</tr>
<tr>
<td>The z-lead screw backplane</td>
<td>Water jet</td>
</tr>
<tr>
<td>The rotary table frame</td>
<td>Band saw, vertical saw</td>
</tr>
</tbody>
</table>
6 Design Novelties, Potential Problem and Future Development

6.1. Design Novelties

There are several novelties in the design of this micro-contact printing system.

- Deformation is minimized. The PET/PEN substrate will be applied onto a fixed PDMS stamp. In the existing academic and industrial practice, it is the PDMS which is used to roll over the substrate for ink transfer. The biggest advantage of this design is the dramatic mitigation of stamp deformation.

- Reel to reel process. The use of the take-up and pay-off reels, guiding rolls and pegs will create linear propagation of the PET onto the substrate. Because of this, the air trapping can be minimized. Meanwhile, the reel to reel design also makes mass production possible.

- The design is theoretically scalable. Besides the reel to reel setup, the designs like the printing stages and the rotary table also make the design theoretically scalable to one square meter level or even larger.

- Mechanics are easily adjusted. Parameters like the speed of printing and inking, the size of substrate, the materials and others are all adjustable and easy to implement the changes.
• The integration of the inking and printing processes improves the production rate and reduces product variations. The design can be extensible to commercial scale giving high volume production.

• Production rate depends almost entirely on the Chemistry and not the mechanics of the machine.

Besides those listed above, in the inking system itself, there are some novelties in the design and machining of various components:

1. **The inking roller rails.** This design overcomes two challenges to the roller design. First, it provides weight support for the roller which would otherwise can cause great deformation to the stamp. Second, as the roller’s pulleys reside on the tracks, the route of the roller must follow the tracks. Thus at each inking cycle, the starting position of the roller on the stamp will be the same.

2. **The rotary table system.** We couldn’t think about any ways to integrate the inking function into the printing work station for a long time until we came across the rotary table idea. The rotary table switches between the ink station and printing station and transfer the stamps back and forth. So far, with one rotation, the inaccuracy caused by overshoot or insufficiency is not more than 15 degree, which is 5%. Though there could still be potential for improvement, the rotary system functions well as the linkage of two separate machines.

3. The guiding pins to direct the stamp retainers. How can you make sure every time the stamp retainer can get to exactly the right position? Is there any way if self-
aligning between the printing stage and the retainer? Is there any mechanism to correct any position shift of the retainer during the inking and z-motor pushing? The guiding pins solved them all. It firstly guides the retainer to a fixed position every time the holes on the retainer wing meet the pins. The holes were designed to be slightly larger than the guiding pins. Thus, if there is any minor misalignment, the guiding pins and the retainers can be self-aligned while the Z-motor is still providing the pushing motion. Once printing completed, the guiding pins can also guide the falling motion of the retainer to make sure the retainer remains at the right position for inking.

6.2. Potential problems and future improvement

Despite the design novelties, there is also some danger of problems with the current components. The problems could be with the inking roller bushings, the junction of the rails and the retainer, the set screws for the lead screw motor, and potential misalignment.

6.2.1. Roller Bushing Problems

Currently plastics bushings with outside diameter of exactly the same size as the inking arm slot (1/4”) are used for to fix the shaft to the arm slot. The inside diameter of the bushings is slightly larger than the shaft so that it would fit in tight. The bushing worked well during the testing trials.
However, there is no actual fixing mechanism between the plastic bushings and the slot. With time, the deformation may become permanent. In that case, there is danger that the bushings may lose the ability to fix the shaft in place accurately.

The other function of the bushings is to smooth the rotation of the shaft and thus the roller. However, with the plastic bushing, the surface of the inside circle, which is also the contact surface between the shaft and the bushing will wear over time. If the material is not highly chemical-resistant, there will also be erosion to the surface. Furthermore, the hardness of the material (plastic) is not high so there could easily be deformation of the surface because of higher torque or force applied to the shaft.

6.2.2. The end of the rails in contact with the stamp retainer

Picture 6-2 shows the overlapping area of the inking rails and the retainer. The inking roller will roll over the stamp on the retainers while supported by the rails. To ensure
that the retainer can rotate freely without any blocking, the rails in this area have little support from the main frame as shown in Picture 6-3. It acts almost like a cantelever beam. Significant deflection in the beam will be very likely in this case.

Picture 6-2. The overlapping area of the rails and the retainer
With a force/pressure applied at one end of the beam with the length \( L \), the maximum deflection and equation of elastic curve:

Maximum deflection: \( V_{\text{max}} = -\frac{PL^3}{3EI} \)
Equation of elastic curve: 

\[ v = \frac{Px^2}{6EI} (x - 3L) \]

Where I is the area moment of inertia of the beam and E is Young's modulus.

In the case of rails, the material is aluminum. As the rails have large length and small width, it will lead to large deflection. In order to reduce the deflections, one simple solution is to make the width of the rails larger, or to use a deeper cross section to increase the area moment of inertia I.

6.2.3. The rigid vs flexible coupling

In the current design, a rigid coupling, has been used to connect the motor shaft with the lead screw. The connection between the lead screw shaft and motor shaft is set up by sliding on the coupling and tightening the two set screws for a positive lock on the two shafts.

![Figure 6-1. The rigid coupling [37]](image)

However, when linking the two shafts together there can be a number of possible misalignments caused. The misalignment could come in the form of angular, parallel and
axial misalignment, as shown in Figure 6-2. In any case, there can be danger that the motor be damaged when it’s turned on.

Figure 6-2. Possible misalignment with the rigid couplings [38]

The solution to the rigid coupling problem is to use the flexible coupling which provides the flexibility for parallel, angular and axial misalignment. There are several types of couplings which functions as flexible coupling. One of them is the helical beam couplings. Instead of the rigid body, there are several beams of cuts on the strong metal body which can provide the precise positioning.

Not true; neither the rigid or flexible coupling will cause backlash as long as the set screws are tight.
6.2.4. The misalignment issues

Besides the possible misalignment between the motors and lead screw, there are other misalignment issues that need to be addressed. For example the possible misalignment between the rotary table and the inking roller and the vertical positioning misalignment between two rails.

6.2.4.1 The angle alignment between the rotary retainer and the inking rails

Every time the rotary table sends the retainer for inking, because of rotary momentum of the table or the small inaccuracy of the stepping motor, there might be a small misalignment between the rotary retainer and the inking rails.
6.2.4.2 The vertical positioning misalignment between the two rails

The inking rails could possibly have misalignment issues also. The first type of misalignment is when one of the rails sink, as shown in Figure 6-5. This type of misalignment is easy to detect and overcome. A beam level can be used to test whether the two rails are on the same level.

In order to prevent the misalignment caused by bad parallelism, several pieces of square frame can be used to be fixed to the two parallel rails from underneath, at different points along the rails. Because the distance between two holes on the square frame is fixed (1.5"), the parallelism of the two rails will therefore be assured.
The best and easiest way to prevent the sunken rail problem is to have the rails fixed tightly to the inking main frame. The levels can be used to test whether two rails are on the same height.

Figure 6-5. The sunk rail problem

Figure 6-6. The bad parallelism problem

6.3. Alternative designs for the inking station

6.3.1. Air cylinder design to replace the Z-machine

Currently the lead screw actuator is used as for the Z-machine used to lift the retainer into the printing station. An alternative way of doing this is to make use of the air cylinder
Comparing with the current lead screw actuator, air cylinder can provide higher rate and is easier to operate and more cost effective. Since the printing stage top plate acts as the stopper and the guiding pins provides self-aligning, the Z-machine doesn’t actually require the high position accuracy provided by the lead screw. Instead, the air cylinder would be better fit to the industrial given its simplicity and the usual availability of a compressed air source.

The double acting cylinder is commonly used in the industry. Cylinders with various fully contracted length, stroke length and overall extended length can be selected for the machine need. The extension speed and maximum extending/contracting force also vary.

![Double Acting Air Cylinder](image)

**Figure 6-7. The layout of the double acting air cylinder [40]**

The double acting air cylinder can perform both the “push” and “pull” function as required by the Z-machine. It has two compressed air ports; one to extend in the "push" direction and another to retract in the "pull" direction.
A 4-way valve two-position air cylinder controller is needed to control the “pushing” or “pulling” function. There are 4 ways, A, B, Exhausted A (EA) and Exhausted B (EB). While the controller is on the pushing function, the pressure is flowing to the outlet port A. Outlet port B is flowing to EB. The cylinder acts “push” function. In the same manner, when in the full position, the pressure goes to port B and port A is exhausted.

Currently, the inking frames are supported by the leveling mounts which are directly connected with the internal connector. The height of the inking frame will be decided by the length of six levelers. However, the current level system has several critical shortcomings which need improving.
1. There is no position control mechanism with high precision. Different levelers can have different height which will lead to the slight imbalance. The current method to avoid imbalance is to have small pieces of rubber, which can absorb the imbalance to certain degree, at the bottom of each leveler.

2. The lifting has to be done manually and not easy to implement.

3. There is no automatic positioning system which can lift up or bring down the inking station to the appropriate position.

Figure 6-10. The current vertical positioning system

The alternative design is as shown in Figure 6-10. The whole frame will be standing on a wall which is supported by the lead screw actuators with precision position sensor. The lead screw can generate the motion to lift up or bring down the floor. Since the whole machine is standing on the floor now, the position difference among the legs would be minimal.
Figure 6-11. The proposed design – lifting floor

Further develop and potential issues with the idea above could be done in the future continuous work.
Conclusions and Future Work

7.1 Conclusions

The ultimate goal of this research is to achieve the printing and inking requirements of specific industrial products. The very first step is to design and implement a printing and inking machine, which the future improvement can be based upon. The second step is to improve the rate and quality based on the prototype.

The inking station achieved the goal of generating the linear propagation of the PET substrate on the ODMS stamp. The desired motions of each functional unit, the wipers, the spools, the XY table etc, were all met. The inking station managed to generate the motion to the roller on both the ink pad and the stamp retainer. The possible misalignment issues with the inking stations were also considered and mitigated. The rotary system can switch the stamp between inking and printing at high speed with good accuracy. It also generates the motion of bringing the retainer up and down.

The prototype built has achieved the goal of the first step as building up the platform. Each of the major components in the initial design have been machined and tested. The automation software which controller the motions and order of all the nine motors has also been developed and tested. The inking and printing stations have been integrated together.
Both the printing and inking mechanisms, as well as the automation software, have been demonstrated in the presentation (or "defense") day.

Alternative designs to the major components have also been explored. The possibility of replacing the current z-machine lead screw by an air cylinder has been discussed. What can go wrong with the current system has also been considered.

7.2 Future work

The rate and quality of the printing have not been fully evaluated. The next step is to improve the printing rate and ensure quality at the same time. Currently, 4 3” by 3” panels can be printed at the same time. Since the required printing time for each panel is 5 seconds, the design requirement for printing could be met if the current printing process can be completed within 20 seconds. Future work could be on a deeper look into the automation software and the XY table so that the optimal travel speed of the wipers and also the appropriate contact time between the stamp and the PET could be found and met.

The other important area for the future work is the inking pad on the inking station. The ink used for the demonstration is not same type of ink required. The inking pad needs improving to contain the ink and transfer the ink more easily. Besides, the inking quality and rate have not been tested and evaluated. It could possibly be the limiting factor of the design. A closer look into inking should definitely one of the priorities.

The current automation mechanism can also be further developed. The software heavily replies on the National Instruments provided services. From time to time, upgrades of the
software are needed because of the changes from NI, which has already brought some inconvenience. The possibility of writing our own code for the motors which is independent of the NI interface can be explored. Furthermore, a graphic user interface for the automation software is needed.

Last but not least, as mentioned in chapter 6, there are several components that can be improved or replaced.
A Water jet Omax drawings

A.1 Arm connector

A.2 Retainer Wing
A.3  Rotary arms

A.4  Motor mount:

A.5  Wall:
A.6 Bracket spacer:

A.7 Retainer base:
A.8 Floor for inking

A.9 Floor:
A.10 Head connector:

A.11 Motor mount for inking lead screw
A.12 Inking roller side plate:

A.13 Spool motor mount 1&2:
A.14 Top plate
### Material List

<table>
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<tr>
<th>Parts</th>
<th>Description</th>
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<tbody>
<tr>
<td>Bush Bearings for XY Table</td>
<td>Nylon Bearing Flanged, for 1/2&quot; Shaft Dia, 5/8&quot; Od, 3/4&quot; Length (5 Pack)</td>
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<td>Unhardened Precision Steel Drive Shaft 1/2&quot; Od, 12&quot; Length</td>
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<tr>
<td>Unhardened Steel Shaft (for inking)</td>
<td>Unhardened Precision Steel Drive Shaft 3/8&quot; Od, 12&quot; Length</td>
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<td>Hollow Rod (1 ft)</td>
<td>Polycarbonate Hollow Rod 5&quot; Od, 4-3/4&quot; Id</td>
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<td>Grommets (25 Pack)</td>
<td>Vibration Damping Grommet Low-Damp TPR, Ribbed,.180&quot; Hole Dia, .049&quot; Groove W</td>
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<td>Bolts &amp; Nuts &amp; Grommets</td>
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<tr>
<td>nuts for 10-32</td>
<td>Zinc-Plated Steel Machine Screw Nut 10-32 Screw Size, 3/8&quot; Width, 1/8&quot; Height</td>
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<tr>
<td>10-32 Bolts - 1&quot;L (100 Pack)</td>
<td>Alloy Steel Socket Head Cap Screw 10-32 Thread, 1&quot; Length</td>
</tr>
<tr>
<td>10-32 Bolts - 1.125&quot;L (25 Pack) for Fixing RT Arms</td>
<td>18-8 Stainless Steel Socket Head Cap Screw 10-32 Thread, 1-1/8&quot; Length</td>
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<tr>
<td>M5 Bolts for Inking&amp;Z Lead Screw (25 Packs)</td>
<td>Metric 18-8 Ss Socket Head Cap Screw M5 Thread, 35mm Length, .8mm Pitch</td>
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<td>Metric Zinc-Plated Steel Hex Nut Class 6, M5 Screw Size, .8mm Pitch, 8mm W, 4mm H</td>
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<td>RT Base Support</td>
<td>Alloy 6063 Aluminum Rectangular Tube 1&quot; X 1-1/2&quot;, .125&quot; Wall, 3' Length</td>
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<td>RT Arm Base</td>
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<tr>
<td>Screws for fixing RT ARM</td>
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<td>Bolts for Fixing RT ARM</td>
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<td>Set-Screw Coupling</td>
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<td>Nylon Corner Bracket White, 29/32&quot; Length Of Sides, 15/16&quot; Width</td>
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<td>Floor for Tension meter</td>
<td>Alloy 3003 Aluminum Sheet .125&quot; Thick, 24&quot; X 36&quot;</td>
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149
24"

Bottom Floor Sheet (15" X 6"
Alloy 3003 Aluminum Sheet .125" Thick, 12" X 24"

Wall Sheet (33" X 8"), & Rotary Arm (24" X 10.5"
Alloy 3003 Aluminum Sheet .250" Thick, 24" X 36"

Rotary Arm Connecting Bolts
18-8 Ss Precision Hex Socket Shoulder Screw 1/4" Shoulder Dia, 1-1/2" L Shoulder, 10-32 Thread

Bolts for fixing Tension meter
Grade 5 Zinc-Plated Steel Hex Head Cap Screw 1/4"-20 Thread, 3/4" Long, Fully Threaded

Retainer Connecting Bolts (8-32)
18-8 Ss Precision Hex Socket Shoulder Screw 3/16" Shoulder Dia, 3/4" L Shoulder, 8-32 Thread

Bolts for fixing rotary table (1/4"-20)
Military Specification Ss Hex Head Cap Screw 1/4"-20 Thread, 5/8" L, Dash No.305, Fully Thrd

NUTs (1/4"-20)
Grade 5 Plain Steel Hex Thick (Heavy) Nut 1/4"-20 Screw Size, 1/2" Width, 15/64" Height

Floor Connecting Bolts (25Pack)
Grade 8 Coated Alloy Steel Hex Head Cap Screw 5/16"-18 Thread, 3-1/2" Length

NUTs (8-32)
Zinc-Plated Steel Machine Screw Nut 8-32 Screw Size, 11/32" Width, 1/8" Height

L-connector (for Rotary Table Framing System and Framing System for Tension meter)
Aluminum Bolt-Together Framing System External Corner Connector with Two Holes, 1-1/2" L

Frames for Tension meter & 6' Extrusion, 1-1/2" X 1-1/2" for Aluminum Bolt-Together Framing System
Rotary Table

Guiding Pins
- Right-Hand Threaded Connecting Rod 6" Overall Length, 3/8"-24 Threaded Female Ends, ROD OD 7/16"

Bolts for Guiding pins
- 18-8 Ss Fully Threaded Hex Head Cap Screw 3/8"-24 Thread, 1" Length

Inner Connector
- Aluminum Bolt-Together Framing System Internal Standard Connector, 7-7/16" L

Retainer Plate - Middle
- Alloy 6061 Aluminum Rectangular Bar 1/4" Thick, 8" Width, 1' Length

Retainer Plate mount
- Alloy 6061 Aluminum Sheet .500" Thick, 8" X 8"

Rotary Table Arm
- Alloy 6061 Aluminum Oversize Sheet .250" Thick, 18" X 18"

Printing Station Ceiling and Retainer Plate
- Alloy 5052 Aluminum Sheet W/#8 Mirror Finish .250" Thick, 12" X 24"

standard supporting frame (6')
- 6' Extrusion, 1-1/2" X 1-1/2" for Aluminum Bolt-Together Framing System

standard supporting frame (4')
- 4' Extrusion, 1-1/2" X 1-1/2" for Aluminum Bolt-Together Framing System

End cap

Corner External Connector
- Aluminum Bolt-Together Framing System End Cap for Extrusion

Swivel Stem Caster (Wheels)
- Economy Threaded-Stem Caster 2-1/2" X15/16" Rubber, Swivel, Brake, 5/16"-18 X 1" Stem

Internal Connector for
- Aluminum Bolt-Together Framing System Internal Extended Length Connector, 2-15/16" L
Wheels

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<th>Aluminum Bolt-Together Framing System External Connector, Joining Plate W/2 Holes, 3&quot; L</th>
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<td>Alloy 5086 Aluminum Sheet .125&quot; Thick, 24&quot; X 24&quot;</td>
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<td>6' Extrusion, 1-1/2&quot; X 1-1/2&quot; for Aluminum Bolt-Together Framing System</td>
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<td>Caps</td>
<td>Aluminum Bolt-Together Framing System End Cap for Extrusion</td>
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<td>Anchor Fastener</td>
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<tr>
<td>Tee Connector</td>
<td>Fractional T-Slotted Framing System Tee Connector for 1-1/2&quot; X 1-1/2&quot; Extrusion</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Floor Connector (0.53&quot;)</td>
<td>Fractional T-Slotted Framing System Floor Connector for 1-1/2&quot; X 1-1/2&quot; Extrusion</td>
</tr>
<tr>
<td>45 Deg Bracket</td>
<td>Fractional T-Slotted Framing System 6&quot; L, 45 Deg Bracket for 1-1/2&quot; X 1-1/2&quot; Extrusion</td>
</tr>
<tr>
<td>Panel</td>
<td>Polycarbonate Sheet 1/4&quot; Thick, 12&quot; X 24&quot;, Clear</td>
</tr>
<tr>
<td>Single Panel Retainers</td>
<td>Fractional T-Slotted Framing System Panel Retainer for 1-1/2&quot; SQ &amp; 1-1/2&quot; X 3&quot; Extrusions</td>
</tr>
<tr>
<td>Panel</td>
<td>Polycarbonate Sheet 1/4&quot; Thick, 12&quot; X 12&quot;, Clear</td>
</tr>
<tr>
<td>Bolts (25 Pack)</td>
<td>18-8 Ss Pan Head Phillips Machine Screw 10-32 Thread, 2&quot; Length</td>
</tr>
<tr>
<td>Block</td>
<td>Grade XX Garolite Rectangle 1&quot; Thick, 4&quot; X 6&quot;</td>
</tr>
<tr>
<td>Rod</td>
<td>Fiberglass Threaded Rod 3/8&quot;-16 Thread, 1' Length</td>
</tr>
<tr>
<td>Form</td>
<td>Silicone Foam Pipe Insulation 3/8&quot; Id, 7/16&quot; Thickness, 6' Length, Black</td>
</tr>
</tbody>
</table>
REFERENCES


[37] http://www.mcmaster.com/, page 1075

[38] http://www.mcmaster.com/, page 1075


[40] http://www.mcmaster.com/, page 922