Design of a Slurry Layer Forming Station and Improved Fluid Handling System for Raster Processes in 3DP™

by

David C. Ables
A.B., Harvard University (1995)

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

Three-Dimensional Printing (3DP™) is a rapid-manufacturing process originally developed at MIT for building parts directly from CAD-generated models. Parts are fabricated in “slices” by creating a complete layer of powder and then selectively joining powder particles with a polymer binder deposited using a moving printhead. Traditional 3DP™ builds layers by spreading dry powder and prints binder using a rastering scheme with a continuous-jet printhead. For smaller parts and greater accuracy, a variation on the process called slurry 3DP™ (s3DP™) uses raster-built slurry layers and a vector-printing scheme with a drop on demand (DoD) printhead. This thesis presents efforts to improve core technology in both dry-powder 3DP™ and slurry 3DP™.

One of the most critical steps in s3DP™ is the building of the slurry layers. To avoid intra- and interlayer defects the slurry layer must be rastered at high deposition rates to promote line merging and better layer quality. The difficulty lies in the design of a machine capable of oscillating the slurry nozzle at the required frequencies. Fortunately, such a design was completed and the machine built as part of a collaborative effort with TDK Japan to build an s3DP™ machine for manufacturing small parts. The design uses a reciprocating countermass strategy to recycle mechanical energy and eliminate troublesome vibrations. A general overview of this slurry layer forming station (LFS) is given, along with an in-depth treatment of several components, including the forcers, centering system, and interface software.

And speaking of rastering, dry-powder 3DP™ relies on this strategy for printing binder, just as the LFS uses a raster method to build powder layers. Beginning with observations made during the design of the LFS, the fluid-handling system was redesigned to improve binder droplet stream stability during the carriage traverse and turnaround. The improvement was made possible by repositioning a smaller version of the “Clamshell” constant pressure vessel used to set the fluid flow rate to the printhead carriage itself and using a closed-loop control system to maintain a constant fluid level in the Clamshell. Drawings, parts lists, schematic diagrams, and assembly instructions are included for building additional fluid control systems.

Thesis Supervisor: Emanuel M. Sachs
Title: Professor of Mechanical Engineering
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Part I

Preamble
Chapter 1

Introduction to Everything

1.1 The 3DPTM Process

In the never-ending saga of life imitating Star Trek, efforts have intensified over the past few decades in trying to build parts directly from computer models. 3D Printing (3DPTM), a processes developed at MIT in the early 1980s, is one such solid freeform fabrication process that holds several advantages in terms of geometric and material flexibility.

1.1.1 How Does it Work?

The 3DPTM process is an additive process that builds up a part layer by layer based on a CAD file that has been “sliced” using post-processing software. The following process is then repeated for each slice:

1. Spread powder to provide material.
2. Print binder to define geometry of slice.
3. Dry binder (if necessary).
4. Drop piston to make room for next layer.

This process, illustrated in Figure 1-1, culminates in our part held together by the binder encased in a block of dry powder. The excess powder is removed to produce a green part skeleton that is not at full density. We can then improve the strength and density of the part by either sintering in a furnace or by infiltrating with another substance.
1.1.2 What is it Good For?

There are two primary advantages to 3DPTM: First, since a complete powder layer is always spread, the unprinted powder can support complicated overhangs and other geometries. Second, the process works for any material available in powder form so long as a suitable binder can be identified. 3DPTM technology has been applied to a number of different classes of parts, both at MIT and by commercial licensees working with MIT.

- Model Prototyping
- Metal Parts
- Injection Molding Dies
- Machining Tooling
- Timed-Release Drugs
- Ceramic Parts
- Electronic Components
- Medical Prosthetics
- And much, much more...
1.1.3 Slurry 3DP™ v. Dry Powder 3DP™

In order to achieve better resolution in printed parts we must print with finer powder. However, we run into physical limits for submicron-sized powder, where van der Waals and electrostatic forces prevent us from dry-spraying effectively. For small, fine-featured parts we instead use slurry processing to form our layers, suspending our particles in a slurry and building a wet layer which we then dry to provide dry powder in which to print binder. This extra step means s3DP™ is slower than dry powder-based 3DP™, so we generally only use this method for printing very small, fine-featured parts.

![Diagram of the s3DP™ process](image)

**Figure 1-2: The s3DP™ Process Illustrated**

The complete s3DP™ process is illustrated in Figure 1-2. Note that it is now more difficult to extract our green part since we must redisperse the unbound powder. s3DP™ is generally used for printing ceramic parts.

1.1.4 Vector v. Raster Printing

Slurry layers are an improvement over dry powder layers in terms of thickness and particle size, but we also would like to improve the resolution of the binder printing step. For this, we use vector printing instead of raster printing. Vector printing is to raster printing as old ink pen plotters are to modern inkjet printers. Vector printing, as illustrated in Figure 1-3, first draws the outline of the part before filling it in using raster methods. This initial outline step improves the surface finish of the part.
1.2 The Slurry Layer Forming Station

The most fundamental piece of an s3DP™ machine is the Layer Forming Station (LFS), since all subsequent steps depend on having a layer of slurry on which to print. The LFS described here was designed and built as part of a collaborative effort with the TDK Corporation of Japan to build a slurry-based 3D Printer.

The LFS is a complicated piece of machinery and the result of the efforts of a talented team of people. This thesis being submitted for my degree, it is most appropriate if I focus on the portions of the LFS for which I was directly responsible, rather than trying to grab credit for everyone else’s work.

However, some sort of context for the overall LFS machinery is necessary, so I will provide a brief overview of all of the different subsystems comprising the machine, followed by in-depth treatments of the elements I designed, namely the linear drives, the centering mechanism, and the software interface. Part II of this thesis deals with my efforts in this arena.

1.3 The Raster Fluid Handling System

Any 3DP™ process involves much moving around of fluids. The particular problem of jetting slurry from a moving nozzle during layer formation brought to light some issues in fluid handling that were also found to exist in more traditional powder-based 3DP™ as part of raster printing the binder. This somewhat tenuous bridge connects Part II with Part III, which details the design of an enhanced fluid-handling system for use with binder.
in raster-based 3DP™.

The main text will deal with the theory, design process, and results for the new system, and detailed plans for constructing additional systems are included in the Appendix.
Part II

The Slurry Layer Forming Station
Chapter 2

Introducing the LFS

The process for forming slurry layers is at the core of s3DP\textsuperscript{TM}. Unfortunately, it is quite a bit more complicated than spreading dry powder. Fortunately, previous efforts have lead to a recommended approach which is encapsulated in the LFS design for the MIT/TDK machine [4, 11].

2.1 Slurry Layers are Hard to Make

In order to print binder to form a 3DP part we must first have a layer of powder on which to print. When a layer is built from a slurry this process becomes more complicated than simply spreading out dry powder at the desired thickness. Instead, the slurry must be deposited and then the liquid removed to leave only the dry powder ready to receive the binder. The liquid is removed via the process of slipcasting, where the liquid is absorbed into a porous substrate (which may include previously slipcast layers), in a manner similar to soaking up water with a sponge. The trick is getting the liquid to slipcast without producing bubbles, cracks, or other defects in the slurry layer whilst simultaneously creating a flat layer. This is the fundamental problem the LFS attempts to solve.

2.2 Where Others Have Tread

One obvious scheme for forming layers of a reliable thickness from a fluid would be to spin-coat the substrate, as is done in photodeveloping and microelectronic fabrication [3]. However, the need for the fluid to slipcast eliminates this possibility.
Another method might be to spread a layer in a single strip using tape casting. This method has been investigated, but layers formed in this fashion contained far too many defects to be usable in the 3DPT process [11].

Work by DeBear and Saxton [4, 11, 5] found that the most effective means for building slurry layers was to raster the layer, one line at a time, using a single nozzle on a moving carriage. This lead to the development of the infamous “bicycle wheel” apparatus [11, 4].

While rastered slurry layers met the criterion of a low percentage of defects, the overall layer quality was not particularly good due to the preservation of individual slurry lines in the final layer. The solution to this problem is then to deposit slurry lines fast enough that they can merge and eliminate the ridges resulting from depositing completely slipcast lines next to one another. Under this approach, the slurry lines must be deposited faster than the wet front can advance. Results using this method as tested on the LFS described here have proven to be quite successful [9].

![Diagram of Conventional and Rapid Line Deposition](image)

**Figure 2-1:** Rastered Slurry Layers with and without Line Merging
Chapter 3

Functional Overview

The TDK/MIT Slurry-based 3DPrinter (Figure 3-1) was built as part of a collaborative effort between the MIT 3DPT\textsuperscript{TM}lab and the Mechatronics Division of TDK Japan. MIT was responsible for developing the Layer Forming Station and the Printhead, while TDK designed the overall software and hardware platform that integrated the various processing stations together into the overall printer.

![Figure 3-1: The TDK/MIT Slurry Printer](image)

The printer itself consists of 4 stations, illustrated in Figure 3-2:

- Layer Forming
- Convective Drying
The Layer Forming Station (LFS) is described in this chapter. The Convective Drying station, ironically enough, blows heated air on the powderbed to dry the new slurry layer or freshly printed binder. The Layer Height Measurement station is used to obtain accurate measurements of the layer thickness for eventual feedback control of Layer Forming parameters. The Binder Printing station is an \(x-y\) table with 8 DoD printheads that uses a vector printing scheme.

To actually print a part, the movable powderbed is shuttled along a linear stage among the 4 stations in the following order to make-up a single cycle which is repeated layer by layer until the part is finished.\(^1\) A print cycle looks like

1. Layer Forming,

2. Slurry Drying,

3. Height Measurement,

\[^1\text{This takes approximately a million hours. Several efforts are currently underway to speed up this process.}\]
4. Binder Printing, and

5. Binder Drying.

This chapter focuses on the Layer Forming Station, first describing the LFS as a whole and then briefly discussing the components critical to its operation that were the focus of my efforts. The LFS builds layers by rastering them out one line at a time onto a moving substrate. The combination of flyover speed of the slurry nozzle, slurry flow rate, and substrate traverse speed determines the resulting layer height. In addition, the nozzle speed and substrate speed are chosen so that the wetting front will promote line merging before slipcasting occurs.

3.1 Design Overview

In a nutshell, the LFS builds layers by oscillating the slurry nozzle back and forth along the y-direction. In the meantime, the substrate moves along at a constant velocity in the x-direction. The resulting slurry lines then scan along to form a layer which then slipcasts to form a dry powder layer.

![Rastering a Slurry Bed](image)

Figure 3-3: Rastering a Slurry Bed

\[\text{2 It takes a rather large nut to provide a shell big enough to hold our machine.}\]
Achieving the necessary speeds of 1.5 m/s and interarrival times of ≤ 0.3 ms on a 2 kg carriage requires massive accelerations during turnarounds. These types of accelerations would potentially melt any electromechanical system asked to accelerate such a mass in such fashion [13], in addition to shaking the heck out of the machine. Clearly, a more clever mechanical method is needed.

After the success of the bicycle wheel [4, 11, 5], a new scheme was developed that also uses recycled mechanical energy to accelerate the carriage. In this system, a large, reciprocating countermass collides with a lighter carriage. If the countermass is sufficiently larger than the carriage, then the collision will just reverse the velocities of each body with a low change in momentum, resulting in minimal vibration of the unit. Careful design can assure minimal energy loss during the collision, which can be most efficiently be done by pumping the energy back into the countermass due to its lower velocity and kinetic energy.

Altogether, then, there are 4 main subsystems to the Layer Forming Station:
3.2 Slow Axis

As was mentioned above, layers are formed using a raster process with a nozzle moving back and forth. With the velocities and accelerations needed for the nozzle carriage, it is easier to move the substrate beneath the carriage. The substrate upon which the powderbed is built rides on a linear stage, which is generally referred to as the “Slow Axis” due to its not-so-blinding speed.

In order to achieve ideal bed quality we want the slurry rastered as parallel lines for uniform thickness across the bed. However, due to the high speed of the nozzle and narrow
line spacing, it is not possible to move the substrate in a step-like fashion, so instead it is moved at constant velocity. This has the unfortunate fact that the slurry lines are formed in a zig-zag pattern, while parallel lines are obviously preferable in terms of bed quality.

![Diagram of slurry lines formed by stationary nozzle](image)

Figure 3-6: Zig-zag Lines Formed by Stationary Nozzle

The linear stage selected includes a linear optical encoder capable of resolving to 0.1 \( \mu \)m, which allows for very precise and reliable control of the Slow Axis speed. To compensate for the fact that the slurry lines aren’t parallel the nozzle is actually maneuvered using a laser-scanning Galvanometer, described below in Section 3.3.2, in order to produce parallel lines.

### 3.3 Carriage

The Carriage is the heart of the LFS, it being the part that actually jets the slurry to the substrate below, and it is shown in all its splendor in Figure 3-7. The carriage rides on air bearings for low friction and contains a number of components to allow for accurate control over the nozzle position, slurry flow, and carriage velocity and position.

#### 3.3.1 Baby Clamshell

The "Clamshell" is a staple of 3DP\textsuperscript{TM} machines, used to deliver fluids at a constant flow rate by maintaining a specified pressure in said fluid. The Clamshell maintains a constant pressure in the fluid in order to provide a constant flow rate. Since a rather large portion of this thesis is dedicated to the art and science of clamshells, I will skip the thorough ex-
planation until Part III. Traditionally the Clamshell is located away from the carriage, the pressurized fluid being delivered by an umbilical cable. However, this standard approach was found to yield poorly formed slurry beds, and the Clamshell was reduced in size (hence the affectionate name “Baby Clamshell”) and placed on board the carriage to keep the fluid pressure constant at delivery. This change in design formed the basis for more extensive work redesigning the binder fluid system for raster-based 3DP™, which is discussed in excruciating detail in Part III. For now I’ll stipulate that the presence of the Clamshell eliminates troublesome pressure pulses in the fluid lines due to the high accelerations produced in the carriage turnaround.

3.3.2 Galvanometer

The slurry nozzle is attached to an arm whose angle with the y-axis can be precisely controlled. There are two different schemes, then, for straightening the slurry lines. The first, known as unidirectional forming, involves switching the nozzle back and forth so that
two beds are formed simultaneously, one using positive-\(y\) passes and one using negative-\(y\) passes. This method also allows the flexibility of placing the lines with precise registration between layers, as indicated below, as well as compensating for any error in the Slow Axis position. The limitation under this scheme is that the beds cannot be wider than a maximum limit determined by the range of motion of the Galvanometer arm.

The bidirectional forming scheme uses both positive- and negative \(y\)-passes. While the interarrival times along the slurry lines will no longer be constant, this method allows for the formation of larger beds. This method is dependent on the motion controller's ability to update the Galvanometer position often enough to keep the lines straight. It is also limited by the travel of the Galvanometer inasmuch as it can only compensate for a finite amount.
of Slow Axis position error.

3.3.3 Carriage Linear Motor

A small linear forcer is used on the Carriage for the purposes of starting up the LFS and positioning the Carriage when the station is not in use. The motor also gives the option, not currently utilized, of actively maintaining a constant velocity over the powderbed. A linear encoder is used to determine the carriage position and velocity, used by the PMAC motion controller (see Section 3.5.1). The design and performance of this Linear Motor is detailed in Chapter 4.

3.4 Countermass

The Countermass fulfills the dual purpose of (1) providing the energy input to the system to keep the nozzle moving and (2) minimizing the change in momentum during the turnarounds of the carriage so that there is a minimum amount of vibration transmitted to the overall printer. It consists of two stainless steel rails riding on air bearings for low friction, two large stainless steel blocks with springs for the carriage collision, and the linear forcer that drives the system. Its mass is approximately 10 times that of the carriage.
3.4.1 Countermass Linear Motor

A non-commutated Linear Motor similar in concept to the Carriage Forcer (Section 3.3.3 is used to drive the Countermass. Since no commutation is needed, supplying the needed force output from the motor is accomplished simply by reversing the current through the motor armature when the Carriage changes direction. There is no direct feedback for the position or velocity of the countermass, although some proportional control is done based on the Carriage velocity. The design and performance of this Linear motor is detailed in Chapter 4.

3.4.2 Centering System

Since the force on the Countermass must reverse with each collision with the Carriage, some mechanism is needed to keep the center of mass for the system from drifting and the resulting error from crashing everything into the bearing blocks. (This is generally
Nozzle Arm Must Continually Adjust Over Powder Bed to Keep Lines Straight While Slow Axis is Moving

Figure 3-12: Bidirectional Bed Formation

an undesirable thing.) The necessary restoring force is provided by 3 magnets, 2 fixed and one moving magnet attached to the Countermass. The polarities are set so that both fixed magnets repel the moving magnet—the (small) resultant force is sufficient to make the center of mass behave. A slight damping force is applied to the Countermass by attaching an aluminum sheet to the armature coil. The resulting Eddy Currents caused by moving the aluminum in the magnetic field assembly produce enough damping force to keep the system stable.

This particular system is discussed in more detail in Chapter 5.

3.5 Software

Something has to make all of these motors and things go, and that thing for the LFS is an 8-axis PMAC motion control board. All of the necessary brainpower for operating the LFS resides on the PMAC, which then uses a driver library to interface between the PMAC and the overall control software for the printer.
3.5.1 PMAC Code

As was mentioned before, there are a total of 8 available axes on the PMAC motion control board. Five of them are utilized for the LFS:

- Slow (Powderbed) Axis
- Countermass Motor
- Carriage Motor
- Nozzle Arm
- Air Pressure

The PMAC offers two different methods for controlling each axis: motion control programs or PLC programs. Motion Controls are suitable when a normal-flavored motor is connected in a servo loop configuration. In our case, only the Slow Axis can be controlled in this manner. All other axes are controlled using custom PLC code. A master scheduling PLC manages all of the different axes.
3.5.2 Driver API

While the PMAC can put the LFS through its paces, so to speak, something has to tell it which pace is currently appropriate. A driver API is defined for the LFS that communicates with the PMAC by sending ASCII commands over the ISA bus, into which the PMAC is plugged. This allows for a clean split of responsibilities, allowing changes to be made to the inner workings of the LFS software while still maintaining compatibility with the main control software.

3.5.3 TDK Program

The entire printer is controlled by a Windows Win32-style Application on a computer running Windows 98. Users interact with the software via both standard keyboard/mouse inputs and a touch-screen interface. This main control software is responsible for managing the overall print process, which includes scheduling and operating the different stations, interpreting the slice data and generating vector paths, and a very long laundry list of other tasks needed for printing to go, er, smoothly.

---

\(^3\)It's partial to the foxtrot, for some reason, while the rest of us prefer the mambo.
Figure 3-15: The Countermass Linear Motor
Chapter 4

The Linear Motors

In order to make the LFS do the shake-and-bake required to raster-build a layer, something has to actually make the nozzle carriage move back and forth. I was anointed with the task of making this happen, either through selecting an appropriate commercial solution or constructing a custom design. Since the Carriage and Countermass are not directly coupled, two different forcers would be needed. This chapter describes the design of both of these critical components, work which took place between August 1999 and March 2000.

4.1 Background

Before diving into “How I spent my first semester graduate school,” some brief information on the initial efforts is in order, including some of the theory behind what makes a motor mote.

4.1.1 How a Linear Motor Works

The existence of electric motors stems from the simple equation describing the force $F$ on a conductor of length $l$ carrying current $I$ through a magnetic field of strength $B$:

$$ F = BIl $$

(4.1)

with the direction of the force given via the right hand rule between the magnetic field and electric current [7].
Rotary Motors  Since current must travel in a loop, one problem in motor design is configuring the magnetic field so that the force on the wire carrying the current “in” does not cancel out the force on the wire carrying the current “out.” A typical solution, shown in Figure 4-2, uses opposite-poled magnets on two halves of the motor. In order to maintain the proper alignment of current and magnetic field, a brush commutator is used to “swap” the current as the conductor rotates through the transition between magnetic fields.

Non-Commutated Linear Motors  A linear motor in its simplest form is just an “unwrapped” rotary motor. “Non-commutated” means that the force remains constant in direction for constant current. Two possible configurations for non-commutated linear motors are shown in Figure 4-3.

In Configuration A, only one leg of the coil is used to generate force, so the motor is not very efficient. The travel of the motor is theoretically unlimited, but since we need to catch all of the magnetic flux lines in the rail for maximum efficiency, we end up needing a larger and larger rail, which eventually becomes a problem as we start to saturate the metal. Another problem is that the constant magnetic field produces a bending moment in the magnet rail, and a longer travel and therefore magnetic rail equals a larger deflection,
which can be bad.

Configuration B uses two legs of the coil, but since we get constant force for current in one direction, we can't run the coil past the edge of the magnetic area or we will suddenly have the force reverse itself.

Commutated Linear Motors  If we want Configuration B to have a larger travel distance we must change the current as we get to the oppositely-aligned set of magnets. This is the principle behind commutated linear motors, as shown in Figure 4-4. It uses two legs of the current loop, so it is more efficient. The armature coil is shown in two different
Figure 4-4: Schematic of Commutated Linear Motor

positions. Note that due to the different alignment of the magnets, opposite current flow is needed to produce the same force vector. Commercial linear motors will generally consist of multiple phases, where each phase is a separate current loop offset so that the force remains constant as the coil moves among the different magnet pairs. In Figure 4-4, connecting both of the coils to the same carriage would produce a two-phase motor.

Unlike a rotary motor, where commutation can be done using a constant current supply and a mechanical method such as brushes, linear commutation generally requires a varying current supply to each phase to eliminate force ripple. Multiple phase sinusoidal commutation is a rather high-maintenance scheme, requiring a sophisticated amplifier and linear encoder.¹

Since the magnets are oriented in opposing pairs, the rail does not have to form a continuous loop, meaning the travel is only limited by the length of the magnet rail. An additional advantage of the commutated configuration is that no bending moment is exerted on the magnet rail since alternating magnet pairs are of opposite polarity and each pair cancels out another.

4.1.2 Commercial Options

Commercially available linear motors require a necessarily complicated scheme involving a linear encoder and motion controller to perform the necessary commutation. In an effort to buy something off the shelf that would be relatively simple to operate we evaluated a

¹On the plus side, the units can be sold for a lot of money.
3-phase linear motor available from Aerotech that used Hall Effect sensors to detect the switched-polarity magnet pairs rather than a precise linear encoder. The amplifier itself then switched phase polarity appropriately. Unfortunately, the limited resolution of the commutated drive current (imagine a 2-bit encoded sine wave) produced a very noticeable step-like force ripple in the motor, shown in Figure 4-5.

![Figure 4-5: Icky Force Ripple in Commercial Linear Motor](image)

Such behavior is inherent to the design of such self-commutating motors, so our next option was to examine the difficulty in designing and fabricating our own motors.

### 4.1.3 Design Metrics

The number of available geometries for a non-commutated linear motor are somewhat limited due to the fact that current must travel in a loop, meaning that for at least part of the loop, the geometry must be designed to either change the magnetic field over different legs of the loop or portions of the loop must remain outside of the magnetic field. The latter approach was used for the Carriage motor, while the former was used for the Countermass.

When designing the motor, we are concerned with how to achieve maximum force under the constraints of available power and heat dissipation. Our power is limited both by what
we can achieve with a reasonable servo amplifier and by what the wire can handle before melting. Heat dissipation is more of a concern under an impulse, namely can we apply peak forces with the motor without the entire thing turning into a molten mess?

**Motor Efficiency** To first examine the relationship between force and power, we take note of the following key relations for force, power, and resistance.

\[
F = BInl \quad (4.2)
\]

\[
P = I^2R \quad (4.3)
\]

\[
R = \frac{\rho RL}{A} \quad (4.4)
\]

where \(F\) is the force output, \(B\) is the magnetic field strength, \(I\) is the current in the wire, \(n\) is the number of turns, \(l\) is the “active” length of wire subject to the magnetic field, \(R\) is the resistance of the wire, \(\rho R\) is the resistivity of the wire, \(L\) is the total wire length, and \(A\) is the cross sectional area of the wire.

If we then define the following terms

\[
A^* = nA \quad (4.5)
\]

\[
l = \eta \Pi \quad (4.6)
\]

\[
L = n \Pi \quad (4.7)
\]

where \(A^*\) is the total conductive cross sectional area, \(\Pi\) is the length of a single winding, and \(\eta\) is the active length fraction, we find the following equation for the power input to the motor:

\[
P = \frac{F^2 \rho R}{(B\eta)^2 \Pi A^*} \quad (4.8)
\]

Our design metric for Force v. Power is then

\[
\frac{F^2}{P} = \frac{(B\eta)^2 \Pi A^*}{\rho R} \quad (4.9)
\]

From this we can conclude that our motor efficiency is ideally unrelated to the number of
turns of our wire. However, the total conductive cross sectional area $A^*$ depends on the packing density of the wire. The ideal scenario would be one turn of a large conductor that fit the required space completely, but this is impractical from a design and manufacturing standpoint, so smaller, 24 AWG wire was chosen since it was easy to work with and would pack densely.

**Impulse and Heat Dissipation**  The change in temperature for power input of a fixed duration depends on the following formulae:

$$\Delta T = \frac{q}{mc}$$  \hspace{1cm} (4.10)

$$q = Pt$$  \hspace{1cm} (4.11)

$$m = LA\rho_D$$  \hspace{1cm} (4.12)

where $\Delta T$ is the rise in temperature, $q$ is the energy input, $m$ is the mass of the wire, $c$ is the specific heat capacity of the wire, $\rho_D$ is the density of the wire, and $t$ is the duration of the impulse.

The rise in temperature is then given by

$$\Delta T = \frac{F^2t\rho_R}{(B\eta IIA^*)^2\rho_Dc}$$  \hspace{1cm} (4.13)

so that the design metric for impulse heat dissipation is given by

$$\frac{F^2t}{\Delta T} = \frac{(B\eta IIA^*)^2\rho_Dc}{\rho_R}$$  \hspace{1cm} (4.14)

Here we can conclude that we want to maximize our conductor volume, $IIA^*$, which then provides the biggest heat sink. In practical terms, we want to maximize the packing density of our windings. This is why encapsulating the coil in epoxy is done—it fills in the air gaps and increases our bulk thermal mass while also improving thermal conductivity.

The end result of maximizing these design measures is that we want lots of turns of “reasonably” fine gauge wire. The driving factor becomes finding a wire gauge that’s easy to work with so that we can pack our turns as tight as possible. In both cases we want to maximize our active fraction $\eta$ and subject as much of the conductor as possible to the magnetic field. This is subject to geometric constraints, however.
4.2 Design

After deducing all of the important considerations in designing a motor (which were largely intuitive, but it’s always good to have centuries of physics to back up our ideas) we actually had to design and build them.

4.2.1 Geometry

Much of the design of the motors was mandated by the geometrical constraints of the machine. The Carriage motor needed to be small and light with a long stroke (see Configuration A from Figure 4-3). The Countermass motor had a short stroke and little space constraint, so its design measures could be maximized with less constraint, as in Configuration B from Figure 4-3.

Carriage  The Carriage motor configuration is shown in Figure 4-6. The armature is a square loop with one leg of the magnet rail running through its center axis. Only one leg of the coil is then used to actually provide the force, making the motor less efficient. In order to have a return path for the magnetic flux the magnet rail must form a loop, which limits

Figure 4-6: The Carriage Linear Motor
the total stroke of the motor.

**Countermass** The Countermass motor configuration is shown in Figure 4-7. It uses a square loop for the armature coil with two of the legs subject to the magnetic field. The stroke of the motor is then limited by the coil size, since the opposite legs must have opposing field directions. It would be rather disastrous if one leg of the coil found its way into the wrong field area since the direction of force would suddenly be reversed. This can be prevented via mechanical constraints, and the necessarily smaller stroke is acceptable in this case since the Countermass stroke need only be about 3 cm.

### 4.2.2 Field Assemblies

A field assembly must form a loop in which the magnetic flux can travel. Low carbon steel was used as the magnetic conductor with size chosen so as to allow for minimal field leakage and nickel-plated to prevent rust.² The magnets were of a special blend developed

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²Since the possibility exists of working with ferrous slurries, it would be very bad to have the slurry being jetted in the presence of a strong magnetic field, which would at best affect the flow and layer quality and
by Crumax, chosen for its high field strength, available size configurations, and resistance to corrosion.

<table>
<thead>
<tr>
<th>Shape</th>
<th>1 in. Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.25 in.</td>
</tr>
<tr>
<td>Material</td>
<td>Crumax™</td>
</tr>
<tr>
<td>Model</td>
<td>D40727</td>
</tr>
<tr>
<td>Magnetic Field at 0.25 in.</td>
<td>0.15 T</td>
</tr>
</tbody>
</table>

Table 4.1: Magnet Properties

Each field assembly was also designed with threads for jacking screws so that the opposing halves of the magnet loop could be more easily separated and joined. The magnets are extremely strong, and it is very difficult to align the field assembly pieces and even more difficult to separate them without a little help.

**Carriage** The Carriage needed a long stroke and had minimal space available for the motor. The field assembly was therefore designed as a long, thin loop. One side-effect was that only single magnets could be used rather than pairs, which provide double the field strength. The constraint was maximizing the stroke with minimum field leakage. Since the motor and field assembly were right next to the carriage this was of definite importance.

One concern was deflection of the flux return bar under the distributed load caused by the attractive force of all of the magnets. If we model the rail as a simply supported beam 300mm long with square cross section of 30mm x 30mm, then the maximum deflection at the midpoint is given by Equation 4.15.

\[
\delta = \frac{5wL^4}{384EI}
\]  

Here \( w \) is the distributed load, found to be 736 N/m, \( L \) is the span length of 300mm, \( E \) is the Elastic Modulus (190 GPa), and \( I \) is the moment of inertia, which is \( 6.75 \times 10^{-8} \text{m}^4 \). Under these conditions the maximum deflection \( \delta \) was calculated to be 0.01 mm, which is actually a conservative overestimate since our actual rail is supported more rigidly than a simply-supported beam and will thus have even less deflection.

A solid model of the magnet rail is shown in Figure 4-8. The flux return bar has radiused corners to match the shape of the armature coil (See Section 4.2.3), which allows it to be

---

at worst make a huge, nasty mess.
larger and thus reduce magnetic field line leakage. The opposite end of the field assembly loop has a slight well machined in order to keep the magnets in place. This is necessary because while we want a minimal gap between the magnets to improve field uniformity, the magnets themselves will naturally move to maximize this distance since they are all aligned with the same polarity.

The average field strength of the magnet rail was measured to be $0.39 \text{T} (\sigma = 0.02)$ with field uniformity as shown in Figure 4-9.

**Countermass** Since the Countermass had little in the way of space constraints and only needed a short stroke, more care could be taken in maximizing its efficiency. The field assembly was then designed to create opposing magnetic fields over opposite legs of a square coil. This way half of the winding perimeter can be utilized to produce force.

Figure 4-10 shows the field assembly for the Countermass motor with the top and one side removed for easier viewing. Two magnet wells are visible, although magnets are only shown in one. All four magnets in each well are of identical polarity, but the front well is
reversed from the back well since they act on opposite sides of the armature coil. The gap between the magnets visible in the front magnet well is needed because the magnets are simply too strong to fit into a group of 4 without being extremely unstable. Since the wire in the armature coil spans across the magnet well, this gap will not cause any variance in the force. Holders for the centering system magnets (See Chapter 5) are also visible on the bottom of the field assembly.

The top half of the field assembly, visible in Figure 4-11, is identical to the bottom half with the magnet polarities reversed. Having the magnets configured in opposing pairs doubles the strength of the magnetic field. The top and bottom plates which hold the magnets are machined from low-carbon steel, which is good for directing magnetic field lines. The side spacers also act as the mounting pieces that attach the field assembly to the rest of the LFS. The spacers are machined from Aluminum, which is not ferrous, thus focusing the magnetic field more intensely in the field assembly. Field lines were shown previously in Figure 4-7.

The magnets were oriented in pairs to produce an average field strength of 0.5 T. Field uniformity is shown in Figure 4-12. The gap between the magnets is clearly visible, but field is symmetric about this point, so we can still expect solid response from the motor.
Once the number of turns was determined and wire gauge chosen, we needed to know what to wrap it all around. Other issues with which to concern ourselves included heat dissipation and the connection with the drive wires. Heat dissipation was improved by encapsulating the coil in transparent epoxy, a technique that provided the added benefit of improving the mechanical strength so that more of the coil support could be machined away.\footnote{It also looked much cooler this way.} Both armatures, then, followed the same essential procedure for production:

1. Machine coil for winding with extra mass for support
2. Wind the coil with the specified number of turns
3. Attach coil leads to connectors

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4-10}
\caption{Countermass Motor Field Assembly (Top Half Removed)}
\end{figure}
4. Add fixtures to contain epoxy

5. Encapsulate coil in transparent epoxy under vacuum

6. Machine away epoxy fixtures and excess material

The armature bobbins were machined from Ren Shape Express 2000 (Ciba Specialty Chemicals, Inc.), an Aluminum-loaded epoxy chosen for its high thermal conductivity \( k = 1 \text{W/m} \cdot \text{K} \). The wire used was 24 AWG copper wire (O.D. = 0.022 in., insulation thickness = 0.001 in., resistivity = 28.2\( \Omega \)/1000 ft.), and the epoxy was Epotek 301, chosen for its optical clarity and low viscosity, which made encapsulation easier.

**Carriage**  The Carriage motor required a relatively long travel distance of approximately 20 cm. The height of the coil was constrained by the size of the carriage, while the length was relatively unconstrained. The various relevant dimensions are shown in Figure 4-13.

To determine the required geometry and permitted number of turns, a "square stacking" arrangement was assumed for the wire. In the ideal case we could pack round wire more densely, but in reality we cannot expect to wind the coil perfectly, so this rather conservative model should be okay.
From the information given in Table 4.2, the theoretical motor constant $K_a$ is calculated to be 4.0 N/A. An input of 4 A would then produce 16 N of force and require approximately 88 W according to Equation 4.9 and raise the temperature of the coil at approximately 2°C/s (See Equation 4.14). This calculation does not account for normal heat transfer due to convection and conduction through the epoxy and into the Aluminum carriage, and since the carriage motor will see low duty, there should be no problem with it overheating and we would expect the measured value to be smaller than predicted.

The actual motor constant was measured as 2.3 N/A. This is somewhat less than the predicted value, which is probably due to the assumption that the magnetic field acts on
a straight section of wire over a distance of exactly 1 in. on each turn. Stray field lines acting on the other legs of the coil could have such a detrimental effect. The temperature rise for a 4A current was measured to be $0.66^\circ$C/s, which is much less than the predicted value. However, the prediction assumed no heat transfer out of the coil, and the measured temperature was on the outside of the bobbin directly above the coil. Clearly the encapsulation step was a good idea. Applying the 4 A drive current to the motor required 92 W, which agrees well with our predicted value of 88 W.

The ends of the coil are soldered to short lengths of brass rod, which are encapsulated in the epoxy with the rest of the coil. We can then drill and tap into the brass rod to create easy screw terminals for connecting with the drive lines. Figure 4-14 shows a solid model rendering of the finished Carriage Motor armature. The contact holes are visible in the front, and the encapsulated coil appears as the darker color.

A parts list and process instructions for the Carriage Motor armature and field assembly are found in Appendix A.

**Countermass**  The Countermass motor only needs a short (approximately 3 cm) stroke, so two different legs of the coil can be used to produce force. Although there was little constraint on the size, a square coil was used so that it would be easier to maintain tension in the wire during winding. The main geometrical constraint is due to the fact that closer spacing between the magnet pairs creates a larger magnetic field. A schematic of the design dimensions is given in Figure 4-15.
For the given specifications in Table 4.3, the theoretical motor constant $K_a$ is 10.2 N/A. According to Equations 4.9 and 4.14, a 4 A drive current would produce 40.8 N of force, would require about 95 W power input, and cause a temperature change of $2^\circ$C/s. Again, we would expect our actual temperature change to be even less since in actuality we have a good deal of additional thermal mass drawing heat away from the coil.

The actual motor constant was measured to be 10.7 N/A, which agrees very well with our predicted value. The temperature rise was much smaller than predicted at only $0.66^\circ$C/s.
(Both the predicted and actual values here are very similar to those for the Carriage motor. This is because we coincidentally used almost identical lengths of coil wire to make each armature.) The 4 A drive current required 90 W input power, again agreeing well with our predicted value of 95 W.

![Figure 4-16: Solid Model Rendering of Finished Countermass Motor Armature](image)

A solid model rendering of the Countermass motor armature is shown in Figure 4-16. To support the coil, a support structure is fabricated from copper-clad Garolite G10, which is etched to provide traces for the current supply to the coil, which is then soldered to the tips of the traces. This support is then tacked to the coil before the encapsulation step so that it becomes rigidly attached.

A parts list and process instructions for the Countermass Motor armature and field assembly are found in Appendix B.

### 4.3 Conclusion

After the motors were installed on the machine they have required essentially no maintenance or modification, so apparently the design was a success. Future versions of the LFS might better be served with a few enhancements, however. More work could be spent investigating a voice coil-type actuator for the Countermass motor. Inquiries into such devices
before did not turn up anything with a long enough stroke that still produced constant force, but an appropriate assembly might exist somewhere. It would also be desirable to eliminate the need for the Carriage motor. This would require some other method of starting up the LFS, as well as another method of positioning the carriage during standby mode, but this may be possible through careful design.
Chapter 5

The Centering Mechanism

Since the actual driving of the Countermass is open-loop, there is nothing to prevent the center of mass of the Countermass-Carriage system from migrating. If it drifts far enough (for example, if the machine is not perfectly level), the Countermass will eventually crash into the bearing blocks and the machine will stop operating, thus ruining the current bed and potentially damaging the LFS.

To help prevent such a calamity, two elements are needed. One must apply a slight restoring force that constantly coaxes the Countermass to keep the center of mass correctly centered. The other element must provide a bit of damping to the Countermass system to keep the system stable.

5.1 Design

A non-contact centering mechanism is the most desirable for the obvious reasons of no fatigue and less mechanical craziness for which to account. Fortunately, we had numerous sources of force-at-a-distance in the form of the various magnets used to build the field assemblies for the linear motors. When held so that the poles produced a repelling force, the force v. distance curve was found to be as shown in Figure 5-1. In this case the nonlinearity is actually desirable as the effect of the centering assembly is much smaller when the Countermass is already centered. The effective spring constant, and therefore the natural frequency of the system, is then less when the system is close to being centered.

\[1\] Say that five times real fast!
Figure 5-1: Repelling Force v. Distance for Magnets

(When the natural frequency of the countermass due to the centering system approaches the frequency at which the countermass is oscillating the system will go unstable.)

The magnets were configured with two fixed magnets each repelling a moving magnet attached to the Countermass. (See Figure 5-2.) The relative spacing between the three magnets was adjustable so that the “strength” of the centering assembly could be adjusted as necessary.

The remaining need was to have a damping force on the Countermass for greater system stability. For this we took advantage of the Eddy Current phenomenon in Aluminum. A thin strip of Aluminum was attached to the Countermass armature coil so that it would move in and out of the magnet field assembly. The Eddy Currents produced in the Aluminum then provided the required amount of damping force.

5.2 Results

Once the centering magnets were placed and the appropriate width was chosen for the damping strip, the system has remained stable and centered with no need for further adjustment.
Stationary Magnets

Magnet Detail

North Pole Side
South Pole Side

Figure 5-2: The Countermass Centering Assembly
Chapter 6

Control Software

As the Countermass and Carriage do all of the hard work, something must be the brain to their brawn. For the LFS, the system is managed by a custom program running on an 8-axis motion controller that interfaces with the main printer control software via a simple driver API. The various interface layers between the components are described in this Chapter.

Figure 6-1: The Layered Interface Design for the LFS Software
6.1 Driver API

The driver for the Layer Forming Station is constructed as a simple Application Programming Interface (API). It provides the software layer between the main printer control program and the subroutines running on the PMAC motion controller. The API functions communicate with the PMAC by sending ASCII commands over the ISA bus.¹ The driver is contained within a Dynamically Linked Library (DLL) that is loaded when the main printer control software runs so that the driver can be updated without requiring the entire main program to be recompiled.

The following functions are defined for the API. More detailed descriptions including arguments, types, and return values are listed in Appendix C.

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MITCTRL_Init</td>
<td>Sets up driver communication, downloads our custom code to the PMAC, and prepares the hardware to receive commands.</td>
</tr>
<tr>
<td>MITCTRL_Back</td>
<td>Moves the slow axis in the negative direction until it stops due to hitting the limit flag.</td>
</tr>
<tr>
<td>MITCTRL_0Return</td>
<td>Causes the slow axis to find its home position and the Carriage to find its home position.</td>
</tr>
<tr>
<td>MITCTRL_Stop</td>
<td>Halt the Carriage/Countermass and the slow axis.</td>
</tr>
<tr>
<td>MITCTRL_Setup</td>
<td>Prepare the PMAC to build a layer by downloading the appropriate information.</td>
</tr>
<tr>
<td>MITCTRL_Idling</td>
<td>(Legacy Function) Does nothing; merely a relic from an earlier version.</td>
</tr>
<tr>
<td>MITCTRL_Build</td>
<td>Tells the LFS to build a single slurry layer according to the parameters already set.</td>
</tr>
<tr>
<td>MITCTRL_JOG</td>
<td>Moves the slow axis.</td>
</tr>
<tr>
<td>MITCTRL_GetPos</td>
<td>Returns the position of either the slow axis or the galvanometer.</td>
</tr>
<tr>
<td>MITCTRL_CheckDone</td>
<td>Queries to see if a particular action is complete.</td>
</tr>
<tr>
<td>MITCTRL_CheckSpeed</td>
<td>(Legacy Function) Does nothing; merely a relic from an earlier version.</td>
</tr>
<tr>
<td>MITCTRL_PTP</td>
<td>Moves the slow axis to the given position.</td>
</tr>
<tr>
<td>MITCTRL_PTP_Spd</td>
<td>Moves the slow axis to the given position at the specified speed.</td>
</tr>
<tr>
<td>MITCTRL_SetGain</td>
<td>Changes the proportional gain for the slow axis.</td>
</tr>
<tr>
<td>MITCTRL_Send_Command</td>
<td>Sends the given ASCII command directly to the PMAC.</td>
</tr>
</tbody>
</table>

Table 6.1: The Functions in the LFS Driver API

Any interaction between the main program and the Layer Forming Station is done

¹Without the software we would have been dangerously short on acronyms.
through these 9 functions (2 are no longer operational but are left in the API so as not to break old code. They simply return immediately with no error condition.) A more complete description of each function, including names and types of arguments is given in Appendix C. Each function generally only returns a single integer error code which is zero on success.

6.2 PMAC Software

The motion controller is a Turbo PMAC model manufactured by Delta Tau. It can be programmed using one of two different types of instruction sets, motion programs and PLCs. Motion programs are designed for calibrated servo systems using encoders and flags for home and travel limits. PLC programs use a low-level programming style suitable for simple, custom applications.

The goal of the PMAC software is to provide a simple interface for the main printer control program and offload all control flow and primary routines to the PMAC. By doing this, functionality of the LFS can be changed without needing to recompile the printer control software.

A total of 5 axes of the PMAC are used to control the LFS:

- Slow Axis Motor,
- Countermass Linear Motor,
- Carriage Linear Motor,
- Galvanometer Position (Nozzle Arm), and
- Piezo-Actuated Air Regulator (for Air/Slurry Pressure).

A single master control program on the PMAC oversees all aspects of LFS operation and is responsible for setting the operating mode of the system. Each axis in addition has an “axis manager” that encapsulates all of the “intelligence” necessary for its operation. There are also various routines running continuously that read and convert data and perform timing operations.

The organization of the various PLCs on the PMAC is shown in Figure 6-2. This code is all downloaded to the PMAC when the main printer control program is executed
Information, Commands, etc. from Win32 App

LPS Driver

PMAC Master Control Program

Fluid Pressure Axis Manager

Powderbed Axis Manager

Carriage Motor Axis Manager

Countermass Motor Axis Manager

Nozzle Arm Axis Manager

Figure 6-2: Organization of the PMAC PLC Code

(See MITCTRL_Init in Table 6.1). Of particular note is the Nozzle Arm Scheduler routine. This routine actually appears as multiple copies, each with different functionality, in order to implement formation of different types of beds, such as unidirectional or bidirectional. The master control program has the responsibilities of activating appropriate managers, preventing conflicts between managers, and passing any necessary arguments received from the printer control software. All of the Axis Managers also communicate with a set of routines that read data from the PMAC axes, perform unit conversions, and track time intervals for certain operations.

The organization into Axis Managers with one master control PLC performing all state checking allows for different configurations to be used with minimal headaches. Since each Axis Manager is responsible for its own calculations, control flow, and data management, we are left with essentially an abstract interface between the control PLC and the manager. So long as one “high-level” PLC does not depend on the inner workings of another high-level PLC and instead only looks at arguments and results, the code should remain relatively...
easy to maintain and modify.
Chapter 7

LFS: Conclusion

Our trek through the world of the Layer Forming Station has included a tremendous amount of work by many talented people. I also contributed. The LFS uses a raster method to form slurry layers by jetting slurry from an oscillating nozzle onto a porous substrate moving at a fixed velocity. A system using a large, slowly moving countermass was used to drive the carriage while maintaining minimal transfer of momentum and not shaking apart the entire machine.

The primary LFS subsystems include the Carriage, Countermass, Slow Axis, and Software. The carriage includes a linear motor for positioning and startup purposes, a laser-scanning galvanometer for precise positioning of the slurry nozzle, and a "clamshell" constant pressure device for providing stable slurry flow. The countermass includes a linear motor and a centering system to prevent drift of the center of mass during operation. Both the carriage and countermass ride on air bearings for minimal friction. The slow axis carries the substrate in whatever configuration is appropriate. Finally, the software ties everything together and runs the machine through a combination of custom software on the motion control board communicating with the printer control software through a driver API.

The system has proven to be quite successful and flexible and thus far has been one of the most reliable systems on the slurry printer. Go team.
Part III

The Raster Printing Fluid System
Chapter 8

Introducing the Mini Clam Shell

The very nature of the 3DP™ process requires running around with a nozzle and squirting fluids in certain locations. The fluid delivery system had remained relatively unchanged for the past several years until the design of the LFS for the MIT/TDK machine, at which time some dirty laundry was aired during slurry jetting that was found to also exist on the Alpha machine during binder printing as well. This chapter outlines in mind-numbing detail the efforts undertaken to combat this scourge of 3DP™.

8.1 Old System

The previous fluid delivery system included a constant pressure “Clamshell” vessel with the fluid output connected to the printhead by means of an umbilical cable a few meters in length. A capacitive sensor turned a peristaltic pump on and off when the membrane position moved above and below particular setpoints with some hysteresis in order to keep the Clamshell full. This system is diagramed in the Figure 8-1:

8.2 Some Theory

Unfortunately for 3DPers everywhere, a rather significant problem was discovered during the design of the LFS. In an early prototype, the slurry flow was controlled by a normal Clamshell setup and the slurry was connected to the nozzle via an umbilical cable. The result? Nasty layers. After some experiments and deep thought, it was discovered that the problem arose from the same conditions as standard hydrostatic pressure. A normal such
Figure 8-1: Schematic of Old Clamshell Style System

Pressure head is given by

$$\Delta P = \rho g z$$

where $\Delta P$ is the pressure drop, $\rho$ is the fluid density, $g$ is the acceleration due to gravity, and $z$ is the vertical distance component. In our case we turn the above situation on its side and have a similar situation (Figure 8-2), with the difference that the acceleration is horizontal rather than vertical and is not constant in this case. If we want to know the pressure pulse caused by accelerating the fluid in our line, we must perform the integral

$$P = \int_0^L \rho a_t dx$$

(8.1)

where $P$ is the pressure pulse, $L$ is the length of fluid line in the umbilical, $\rho$ is the fluid density, and $a_t$ is the tangential acceleration of the fluid in the line.

If we apply our horizontal acceleration $a$ when the umbilical makes an angle $\theta$ with the vertical, then our angular acceleration is given by

$$\dot{\theta} = \frac{a \cos \theta}{L}$$

(8.2)
This acceleration remains constant along the umbilical, so at some point $x$ on the umbilical, the tangential component of the acceleration, (i.e. the actual acceleration of the fluid) is

$$a_t = \frac{ax}{L} \sin \theta$$

Combining Equation 8.3 with Equation 8.1, we get

$$P = \int_0^L \rho \frac{ax}{L} \sin \theta \, dx$$

Integrating Equation 8.4 gives the following expression for the maximum pressure in the fluid line at the carriage.

$$\Delta P = \frac{1}{2} \rho al$$

where $l$ is the horizontal distance component. ($l = L \sin \theta$) On the Alpha Machine, the total traverse distance is 1 m, so $l = 0.5m$, and $a$ is about 2g. Under normal operating conditions, the pressure pulse resulting from turnaround accelerations can easily reach more than 0.5 psi.
By contrast, consider that previous work found that any change in pressure greater than 0.025 psi will deflect a droplet by one spacing at the powderbed [12]. Clearly such pressure pulses could wreak havoc on our unsuspecting droplet stream.

8.3 Motivation for Improvement

However, we can already print nice parts on the Alpha Machine, and all of this transient pulse nastiness happens while the printhead is off the powderbed, so what's the problem? One consideration is simply the lifetime of the printhead. During the turnarounds, the printhead is in “catch” mode, meaning all droplets are deflected into the catcher. When a sudden and large pressure pulse propagates through the fluid supply lines, the resulting surge in flow can cause the delicate charging-deflection cell (CDC) or the catcher to flood. While this is normally not enough to require halting the printing process, it could have potentially reduce the lifetime of the CDC and/or catcher.

A second potential concern is in general print quality. While it may be true that the harmful turnaround occurs outside of the powderbed, the fluid supply lines run a long way between the clamshell and the printhead. Even only slight disturbances in the lines can deflect droplets by multiple drop spacings. As we continue to push the envelope of accuracy in continuous-jet, dry powder 3DP™, such improvements in accuracy will be necessary.

8.4 New System

The solution to this problem of transient pressure pulses, as we learned in designing the LFS, is to move the clamshell to the carriage itself. By lining up the clamshell with the nozzle, the horizontal distance between the nozzle and the pressure source can be zero, so that the $l$ term in equation 8.5 is minimized and the change in pressure is zero.

To ride on the printhead carriage and handle flow rates on the order of 10 cc/min., the clamshell should be even smaller than the so-called “Baby Clamshell” from the LFS carriage. Not only is the clamshell smaller, but even greater precision in fluid pressure is needed, which translates to a need for precise control over the fluid level, since deflections in the membrane lead to a pressure drop (see Section 11.1). The schematic of the new system is shown in Figure 8-3. Note which components are now located on the carriage.

In order to control the fluid level, an infrared LED photosensor (Chapter 10) is used
to measure the membrane position. Since the membrane will deflect at a rate proportional to the difference between the inflow and outflow for the clamshell, the photosensor then integrates this difference. When the flow in and flow out are perfectly balanced, then the membrane should remain flat and the pressure in the fluid will equal the air pressure set by the regulator.

This chapter will examine the design and performance of each of the components in the raster fluid system. Detailed plans for replicating this system for other 3DP™ applications are found in Appendix D.
Chapter 9

The Pump

A pump is obviously needed to actually fill the clamshell, and a peristaltic pump is the best way of dealing with the multitude of icky fluids that will go inside. The question was which was the best option for the peristaltic pump.

9.1 Requirements

The requirements for the pump were actually somewhat demanding. We will need the Clamshell to be as small as possible in order to fit comfortably on the printhead carriage without adding an inordinate amount of mass, so we will need to use feedback control to regulate the flow into the Clamshell rather than the traditional on/off level switch. This means our pump must accept an external control signal and be able to operate at variable speed under continuous duty. Driving a peristaltic pumphhead produces peak torques of more than 20 oz.-in., so the pump drive must be able to output that sort of torque without any drop in velocity.

9.2 Evaluation of Options

A number of different options were investigated in an attempt to find a solution that was flexible, simple, robust, and cheap. Often these terms may be mutually exclusive, but we were determined to forge ahead.
9.2.1 Direct Control of Masterflex Drive

The first option was to use a standard 90 V drive motor from a Masterflex pump powered by a Burr-Brown OPA549 60 V, 10 A op-amp. This configuration, shown in Figure 9-1,

![Diagram of Direct Control of Masterflex Drive](image)

Figure 9-1: How to Hook Up and Kill an Op-Amp

performed in a very consistent manner. Namely, it consistently fried the op-amps. This approach was ultimately abandoned before the exact cause for the op-amp failure could be determined, but it likely had something to do with running the op-amp at too close to its maximum rated temperature with an inadequate heat sink combined with the large inductance of the motor causing strange voltage spikes.

9.2.2 Direct Control of Gearmotor

![Diagram of Direct Control of Gearmotor](image)

Figure 9-2: Building a Pump from a Small Gearmotor

Option number two was to drive a small gearmotor (Figure 9-2), which would be less inductive a load and also a lower voltage, hopefully making it easier to drive in a humane manner. In order to cope with the needed torque output, however, it was necessary to use

---

1While op-amps are not outrageously expensive, the ASPCIC (American Society for the Prevention of Cruelty to Integrated Circuits) was rather upset about the high death toll during IC testing.
velocity feedback via a tachometer to get good response from the motor. This required a custom motor that could not be easily reproduced, so a standard gearmotor was investigated with an IR compensation scheme.

In the end, longevity issues (The gearmotors were only rated for 1000 hours continuous duty.) led the search to larger gearmotors, in which case a commercial speed controller or servo amp would be the best choice for powering the motor. Once this was the situation, however, the difference in price between a gearmotor, pumphead, speed controller, and remote input adapter and a complete pump system became rather small. The search continued...

9.2.3 Programmable Masterflex Pump

In the end, the search came full circle and returned to the Masterflex LS7523-50 Programmable Drive, the same pump as was used for the slurry supply on the LFS (See Figure 9-3). The LS7523-50 includes a flow rate display (calibrated against the tubing size),

![Diagram of Masterflex Pump](image)

Figure 9-3: Remote Control of a Masterflex Pump

as well as various controls for starting and stopping the pump and running in open-loop mode with a set flowrate. The response time for the pump was measured to be less than 2 seconds, which was suitable for the control system, and it accepts either a 0-10 V or 4-20 mA control signal for its setpoint.

The pump uses an SCR speed controller with tachometer feedback and can drive over a range from 1.6-100 rpm. With #14 tubing (inner diameter = 0.06 in.), the pump can provide flow rates of 0.4-21 cc/min.

9.3 Results

The Masterflex pump proved to be the best choice for the lab setting, due largely in part to its display, selection of on-board controls, and ease of integration into the overall system.
While the flexibility afforded by the Masterflex unit is desirable for a lab setting, a more realistic solution for commercial 3DP™ systems would utilize a gearmotor driven directly from a power op-amp due to the smaller size and lower cost. Another option worth considering would be the possibility of driving the pumphead with a stepper motor, which could be done cheaply, assuming a suitable motor could be found to produce the necessary torques without missing too many steps.
Chapter 10

The Sensor

In order to control the fluid level, an infrared LED photosensor is used to measure the membrane position. Since the membrane will deflect at a rate roughly proportional to the difference between the inflow and outflow for the clamshell, the photosensor then integrates this difference. When the flow in and flow out are perfectly balanced, then the membrane should remain stationary, so if we configure the system so that the membrane is flat at this point the pressure in the fluid will equal the air pressure set by the regulator. (See Section 11.1.)

10.1 Description and Characterization

The photosensor is made up of two pieces in a single package: an infrared LED and a npn-style phototransistor. The LED illuminates a target area, and the reflected light causes current to flow through the phototransistor.

The response of the sensor includes a roughly linear region beginning approximately 0.375 in. from the sensor. The critical points at around 0.25 in. are due to the fact that at extremely close distances the angle of reflection is so shallow that not enough of the IR light is reflected back to the phototransistor. To achieve an approximately linear response the sensor must be located so that even at its closest point the membrane is still farther out than the sensor signal maximum (See Section 11.2.4). Figure 10-2 shows the sensor response for a number of different membranes. From the graph it is clear that we want the sensor to be located between 5/16 in. and 3/8 in. from the air cavity. (“Latex 2” indicates a natural-color Latex colored on the opposite side with a black permanent marker.
10.2 Modulated Driver Design

One problem exists with the sensor, namely that it always senses. While we want the phototransistor to only respond to the light emitted from the LED, there are many other sources of IR light that can yield false readings, such as general sunlight and ambient light,
the lamps needed to inspect the droplet streams, and the variation in light and shadow that naturally result from moving the carriage back and forth. Simply masking off the dry half of the clamshell is not desirable as we need to be able to do visual inspections of the membrane to calibrate the zero position.

The solution to this problem is to use something other than a DC drive voltage for the LED. A modulated carrier signal will effectively reject any baseline offset due to any light source not modulated at the same frequency and phase as the carrier.

10.2.1 Concept

Before charging into how the modulator/demodulator system works, let’s briefly look at the principles behind this sort of signal processing to see why it’s necessary to be so complicated.

**Modulation** First let’s imagine we have an arbitrary signal $f(t)$ that we want to encode, such as the one shown in Figure 10-3. To encode our signal we will modulate it by applying a simple transformation. In our case we will multiply by our carrier signal, $c(t)$, shown in Figure 10-4. Here our carrier signal is a square wave with amplitude ±1, chosen for its mathematical simplicity. Note that our square wave must have a duty cycle of exactly 50% for our scheme to work, an assertion which will be explained shortly when we are decoding our signal.

![Sample Function $f(t)$ to be Modulated](image)

Figure 10-3: Sample Function $f(t)$ to be Modulated
To modulate $f(t)$ we just multiply it by our carrier, which gives us the result as shown in Figure 10-5. We will call this $m(t)$.

**Demodulation**  Now let’s imagine that we didn’t actually know the shape of our signal $f(t)$ beforehand and we need instead to decode something out of thin air. (Lucky for us we already know what it looks like.) Now let’s imagine we excite some sensor with our carrier signal $c(t)$ and our sensor spits out $m(t)$ as a result. To get back the original signal we
now do the inverse transform, which in this case means multiplying by $1/c(t)$, which in our case is just $c(t)$ due to our selection of the $\pm 1$ square wave for $c(t)$. For the "well-behaved" modulated signal $m(t)$ this simply gives us back our original signal $f(t)$.

Big deal. Now let's imagine we have the slightly uglier situation where $m(t)$ is offset by a constant amount, such as we would see from our photosensor due to ambient light. This is shown in Figure 10-6, and we'll call it $m^*(t)$. We continue as before, multiplying by $c^{-1}(t)$, which is just $c(t)$, and we get the result shown in Figure 10-7. Our carrier is now

![Figure 10-6: Modulated Signal $f(t)$ with Offset](image1)

![Figure 10-7: Demodulated Offset Signal $m^*(t)$](image2)
superimposed on our signal, so we run this output through a low-pass filter to remove all high-frequency stuff. Note that in order for our result not to suffer too much distortion we must be sure that our carrier frequency is much higher than our expected signal frequency.\(^1\)

The result after filtering reproduces \(f(t)\) and is shown in Figure 10-8 as \(r(t)\). Notice that

\[
\begin{align*}
\text{Figure 10-8: Filtered Modulated Signal with Offset Removed}
\end{align*}
\]

the offset has been removed from our signal. This is cause for much rejoicing, since this result can actually be extended significantly: any spurious signal that isn't at the same frequency and phase as our carrier will be rejected. The catch is that our carrier must have a perfect 50% duty cycle or our inverse carrier signal becomes more complicated and our filter will not work correctly. We also must make sure that the carrier we use for our inverse is exactly in phase with the carrier used to excite our sensor.

A block diagram of the modulated sensor scheme used to create our circuit is shown in Figure 10-9. The LED is driven with a square wave carrier signal, and the resulting response of the photosensor is amplified, demodulated, and filtered.

10.2.2 Driver

The square wave drive signal cannot be of a frequency higher than about 200 Hz or the wimpy photosensor is unable to respond with anything resembling a square wave in return.

\(^1\)This is why radio stations broadcast using carrier frequencies in the Megahertz range. Audio signals are way down at 20–20,000 Hz.
In order for this to work our expected signal bandwidth must be significantly less than 200 Hz. Our sensor and membrane will give essentially a DC output, so a 200 Hz carrier frequency is fine. The simplest way of generating a frequency is using a standard '555 oscillator, but this does not produce a 50% duty cycle. We also need to drive our LED at about 20 mA, which is likely beyond the capabilities of any IC we will find. To generate the perfect square wave, we set the oscillator to give a frequency of 400 Hz and used that signal to clock a D-type flip-flop configured in toggle mode. This way, each rising edge from the oscillator will toggle the flip-flop state, resulting in a divide-by-2 timer with 50% duty cycle.

Since the 20 mA needed to drive the LED is more than the output capacity of the flip-flop, an n-channel MOSFET is used to switch the diode on and off at 200 Hz. The actual schematic for the drive is shown in Figure 10-10: In this configuration, the '555 output frequency is given by

\[
f = \frac{1}{0.693(12k + 2(12k))0.1\mu F} = 400.8 \text{ Hz}
\]

The actual oscillator frequency is measured as 382.3 Hz and the square wave output is 191.1 Hz. The duty cycle is measured at 50% to within 20 µs.
Driving the phototransistor with a 12V source and a 5.1k bias resistor we get signals in the range of about 0.7V–1.9V for $V_{\text{mod,raw}}$ and a 0–5V square wave for $V_{\text{carrier}}$.

One thing to mention is that we don’t get a perfect excitation of our sensor. Since we’re using an LED as our IR light source, we will only get a response on half of each duty cycle and nothing on the “low” half. This is okay, however, because we will already be filtering the signal and this will let us correct for the non-continuous nature of the signal.

10.2.3 Isolator

The Isolation block is needed between the Sensor and the Demodulator for two reasons. First is that the input impedance of the demodulator chip does not remain constant during its operation, and we don’t want to load the sensor asymmetrically and mess up the output. Second is that we need to change the polarity of the sensor signal for use with our control circuit. (See Chapter 12.) An added benefit is that we can now apply gain to the signal before it is demodulated in case we have an extremely weak sensor voltage, although in the current configuration that is not necessary.

An inverting amplifier is inserted between the sensor output and the demodulator input (Figure 10-11). This accomplishes all of the goals mentioned above since an inverting op-amp configuration naturally has very low output impedance, so we don’t have to worry about loading the sensor. The output from this stage is on the order of $-0.7V$–$-1.9V$.

10.2.4 Demodulator

Demodulation is performed courtesy of a nifty chip from Analog Devices (AD630). The IC is essentially comprised of two op-amps, one inverting and one non-inverting, with a comparator that selects which op-amp will be tied through to the output [1]. The carrier signal is fed into the comparator, and the modulated output signal goes into the op-amp.
inputs. Figure 10-12 shows an internal representation of the demodulator chip. From

![Figure 10-12: Schematic of AD630 Demodulator Chip](image)

Figure 10-12 we see that the isolation stage output $V_{\text{mod}}$ is fed into op-amps A and B, where A is the inverting amplifier (gain = $-1$) and B is the non-inverting amplifier (gain = $+1$). The carrier signal $V_{\text{carrier}}$, which is the 0–5V square wave, is fed into the comparator C, which uses 2.5V as the baseline for comparison, supplied by the $10k \times 10k$ voltage divider. When the carrier signal is greater than 2.5V, the comparator causes the non-inverting amplifier B to send its output through the multiplexer amp M. When the carrier signal is low ($< 2.5V$), the inverting amp A’s output is sent through amp M.

The resulting signal $V_{\text{demod}}$ ranges from about 0.1V—0.6V to 0.1V—1.9V for the actual membrane response, so we should be able to reject a DC offset of up to an additional order of magnitude, which is quite good. Note that since we can’t get a sensor response symmetric about zero due to the asymmetric nature of the LED, we should normally see one diode drop for the “low” half of the square wave cycle unless there is a DC offset, which explains the 0.1V baseline. All of this will be corrected in the next stage when we filter the output to remove the higher-frequency component of the square wave.

### 10.2.5 Filter

The first step in choosing an appropriate active filter is to choose the low-pass frequency. Anything above this frequency should be rejected. We know that our carrier signal will be
approximately 200 Hz, and our sensor output signal is essentially DC. This means we can have an extremely low low-pass frequency on our filter. 8 Hz was chosen, which is an order of magnitude less than our carrier but still gives plenty of dynamic range for our sensor response.

Since even 8 Hz is an extremely fast response for our system, we won’t worry too much about the rolloff characteristics of our filter and can make our selection based on simplicity of design. A 2-pole active Butterworth filter is well-documented and easy to make, as shown in Figure 10-13. Component values were chosen based on recommendations from Horowitz & Hill’s *The Art of Electronics* [6], which gives a very thorough treatment of active filters, as well as just about anything else having to do with electronics. After filtering, the output signal $V_{\text{sensor}}$ is on the order of $-0.5V$-1.8V.

### 10.3 Results

The modulated sensing scheme has proven to be quite effective, as the comparison graphs below show. The same light source is used in both cases. With the modulated sensor, the effect of the light interference is negligible compared to the actual sensor signal range, whereas for the DC sensor, the output appears to indicate a very large (and very non-existent!) change in membrane position. The sensor showed no response to the inspection lights, drying lamp, or any other ambient light sources during print tests on the Alpha Machine.
Figure 10-14: Response of Modulated v. DC Sensor Configuration
Chapter 11

Itsy-Bitsy Clamshell

At the end of the day, it's the Clamshell that actually does our dirty work, producing a constant pressure in our fluid to set the flow rate. The basic Clamshell design (Figure 11-1) consists of two cavities, one filled with pressurized air and the other with the fluid to be squirted, separated by a flexible membrane.

![Basic Clamshell Design](image)

Figure 11-1: Basic Clamshell Design

The Clamshell must be small enough to ride on the printhead carriage while still having enough fluid capacitance to maintain steady flow. This chapter describes the three parts of the Clamshell: the membrane, the wet and dry halves, and the air reservoir.
11.1 Membrane

11.1.1 Modeling the Membrane

In order for the pressure to actually be the same on both the wet and dry halves of the clamshell, the membrane must be in its flat, center position. Intuitively this makes sense since we’re not wasting energy deforming the membrane and are instead transmitting the pressure directly from the air to the fluid. Fortunately, math and physics back us up on that claim, as we can see in the following model derived by Sachs [10]:

We begin by considering a membrane of thickness $t$ in a cavity of diameter $D$. The membrane will then deflect a distance $\delta$ to form a section of a sphere of radius $R$, as shown in Figure 11-2. We will assume $E$ is the Elastic Modulus of the membrane, $\varepsilon$ is strain, $\sigma$ is stress, and $\nu$ is the Poisson Ratio. The stresses in the membrane in the $x$ and $y$ directions are related by

$$\varepsilon_x = \frac{1}{E} \left( \sigma_x - \frac{\sigma_y}{\nu} \right) \quad (11.1)$$

For rubber the Poisson Ratio is $1/2$, and since our membrane is circular and deflecting in the shape of a sphere, $\sigma_x = \sigma_y$ so that

$$\varepsilon = \frac{1}{E} \frac{\sigma}{2} \quad (11.2)$$

Solving for $\sigma$ we get

$$\sigma = 2E\varepsilon \quad (11.3)$$

Now let’s balance the force associated with the pressure on the membrane $P$ against
that from the stress in the membrane for a hemisphere.

\[ 2\pi R t \sigma = P \pi R^2 \]  
(11.4)

which simplifies to

\[ \sigma = \frac{PR}{2t} \]  
(11.5)

To next look at the geometry of this setup, we need an expression for \( \delta \) in terms of \( D \) and \( R \). By the Pythagorean theorem we have

\[ R^2 = (R - \delta)^2 + \frac{D^2}{4} \]  
(11.6)

so that

\[ R^2 = R^2 - 2R\delta + \delta^2 + \frac{D^2}{4} \]  
(11.7)

After canceling terms and neglecting the \( \delta^2 \) term since \( \delta \ll R \) and \( D \), we end up with

\[ \delta = \frac{D^2}{8R} \]  
(11.8)

When the membrane deflects as a sphere, the diametral length will increase to \( D_{def} \) as the membrane stretches according to the following expression

\[ D_{def} = 2\pi R \frac{2 \sin^{-1} \left( \frac{D}{2R} \right)}{2\pi} \]  
(11.9)

This is unnecessarily complicated, however. Since our deflections are necessarily small we will use a straight-line approximation for the stretched diametral length of the membrane. With this approximation, we can again use the Pythagorean theorem.

\[ D_{def} = 2 \left( \delta^2 + \frac{D^2}{4} \right)^{1/2} \]  
(11.10)

Doing some creative factoring and approximating we get

\[ D_{def} = 2 \frac{D}{2} \left( \frac{4\delta^2}{D^2} + 1 \right)^{1/2} \approx D \left( 1 + 2 \frac{\delta^2}{D^2} \right) \]  
(11.11)
So our fractional increase in length, which is just \( \epsilon \), is given by

\[
\epsilon = 2 \frac{\delta^2}{D^2}
\]  

(11.12)

Now we can get down to business. Combining Equations 11.5 and 11.3 we get

\[
P = \frac{2t\sigma}{R} = \frac{2t}{R} 2E\epsilon
\]  

(11.13)

In our case let’s imagine we have an initial strain \( \epsilon_0 \) as a result of stretching the membrane before putting the clamshell together.

\[
P = \frac{2t}{R} 2E(\epsilon_0 + \epsilon)
\]  

(11.14)

Now we can use equations 11.12 and 11.8 to finish things up.

\[
P = \frac{2t}{R} 2E \left( \epsilon_0 + 2 \frac{\delta^2}{D^2} \right)
\]  

(11.15)

\[
= \frac{8\delta}{D^2} 2t2E \left( \epsilon_0 + 2 \frac{\delta^2}{D^2} \right)
\]  

(11.16)

Ultimately, then, we get the equation for the pressure drop across the membrane as a function of the membrane deflection (Sachs [CITE]).

\[
P = \frac{32Et\delta}{D^2} \left( \epsilon_0 + \frac{2\delta^2}{D^2} \right)
\]  

(11.17)

And summarizing, \( E \) is the elastic modulus of the membrane, \( t \) is the initial thickness of the membrane, \( D \) is the diameter of the pocket, \( \delta \) is the deflection of the membrane at its center, and \( \epsilon_0 \) is the pre-stretch strain in the membrane.

For a typical silicone rubber membrane (\( E = 4 \text{ MPa} \)) of thickness 0.018 in. on a 1.25 in. diameter pocket and using Equation 11.17, we predict the response for varying degrees of pre-stretch as shown in Figure 11-3. The dependence on pre-stretch strain is quite obvious, as the response is far more linear for increased pre-stretch. However, we want to have a good “cushion” so that we don’t have to worry about a large pressure drop developing across the membrane during fluid pulses when the membrane is out of position. Recall that the critical pressure change is 0.025 psi, at which point a droplet is deflected by one spacing.
By its very nature the peristaltic pump delivers fluid in pulses. These pulses were measured to be approximately 0.05 cc for Masterflex #14 tubing, so the membrane must be chosen so that the corresponding deflection will produce a pressure pulse of less than 0.025 psi. The change in volume when the membrane deforms as a section of a sphere is given by

$$\Delta V = \frac{\pi}{24} \left( 3D^2\delta + 4\delta^3 \right)$$  \hspace{1cm} (11.18)

Working backwards with Equation 11.18 we find that a volume of 0.05 cc produces a deflection of about 0.005 in. for a membrane with pocket diameter 1.25 in. We can use this with our model from Equation 11.17 to make sure our membrane will damp out the pulses from the pump.

### 11.1.2 Membrane Design

In selecting a membrane there are 4 major characteristics around which we want to design.

**Reflectivity** A bigger signal is obviously better, so we want a membrane that will reflect
as much IR light as we can find.

**Opacity** The reflectivity to IR light should not depend on the presence or type of fluid behind the membrane.

**Finish** If the membrane is too glossy then the curvature resulting from spherical deformation in the cavity will form a lens and wreak havoc with the sensor reading.

**Flexibility** We want a large range of deflection in which the pressure drop across the membrane is less than our magic number of 0.025 psi, which means we need a soft membrane.

**Reflectivity** We examined the sensor response against a number of different flat membranes in Figure 10-2. The red Silicone rubber membrane yielded the strongest signal, so it earns points. The regular and the colored Latex also look good, but they aren't as chemically compatible as is the Silicone. Note that for the red Silicone the sensor must be located 0.375 in. from the membrane's closest point in order to avoid some initial critical points.

**Opacity** We want to be able to use the Clamshell with a variety of different combinations of binder, color, and such, so we want to be sure that the signal we get from our sensor is the same regardless of which fluid is on the other side of the membrane. Figure 11-4 shows the response of different membranes with and without water on the wet side. The graph shows quite clearly that the reflectivity of the Latex membranes, as well as a cream Silicone, depends on the presence of fluid on the opposite side. The “Black” Latex was colored on the wet side with a black marker to improve opacity, but the 3 colored Silicones still win.

**Finish** If the membrane always remained completely flat then finish would not be an issue. However, in a circular pocket the membrane deforms in a spherical shape. A glossy membrane will have the unfortunate effect of focusing the IR light from the LED, creating weird parallax effects and ugly sensor response curves. Figure 11-5 shows the response of the Silicone membranes in a Clamshell with diameter 1.25 in. and depth 0.25 in. The vertical scale of the graph shows normalized sensor response over the total output range, but we already know how the relative magnitudes compare from Figure 10-2. We see that the black membrane gives the smoothest response as the membrane deforms from just touching the near wall to the far wall. The gray membrane gives a horrible response with lots of extra
critical points and a quite uncontrollable signal. The red membrane is not exactly linear, but at least the critical point remains below the “zero” position signal. We still like this one because of its strong signal, so it’s worth looking at a bit more.

Figure 11-6 shows two different responses for the red membrane, one untreated and the other abraded with 600 grit sandpaper. Here the membrane was deformed from flush against the near wall to flush against the far wall. As a result, there is no constant length scale to use for the horizontal axis. In both cases there is slightly bizarre behavior as the membrane goes from assuming the shape of the cavity back to a spherical deformation at the near end and vice versa at the far end. However, the abraded membrane clearly gives a more consistent response. Once again, our red membrane wins, albeit with some slight alteration.

**Flexibility**  By odd coincidence, it just so happens that the parameters used to model the pressure drop across the membrane in Figure 11-3 match those for the red Silicone membrane, namely an 18 mil initial thickness (the nominal thickness is listed as .020 in.,
but obviously there's some variation in manufacturing), 1.25 in. diameter cavity, and elastic modulus of 334 psi.

From the model, we see that adding pre-stretch to the membrane increases its sensitivity to deflection in terms of accurately transmitting the pressure in the air to the fluid. Our key fact here is that we don't want the pulses from the pump to cause more than a 0.025 psi change in the pressure drop. From the model we can see that even for a 2% pre-stretch the slope of the curve is such that we can tolerate the 0.005 in. deflection caused by the pump pulse as long as the membrane is within 0.1 in. of the zero position. We can probably expect to place the membrane to within 1/16 in. of zero, so we can use anywhere between 0% and 2% pre-stretch depending on what is necessary. 1% should probably be enough for our purposes.

Verdict In the end, a membrane was chosen with characteristics as shown in Table 11.1. It would have been nice had the extra step of abrading the membrane not have been necessary, but we can live with it. We also have the funny glitch in the sensor reading when the membrane is deformed flush against the side nearest the sensor, but there are two reasons why this doesn't overly concern us, both of which stem from our control strategy
as discussed in Chapter 12. First, the sensor level during the entire "glitch" stays above the center/zero level, so a linear controller will only change the magnitude of its response but will not do anything fundamentally different. Second, we only control on one side of the membrane zero position since we only want to run the pump in one direction and add fluid to the Clamshell rather than ever pumping any out, which means the pump will just shut off if the membrane ever moves towards the near side anyway. Any further curiosity in this matter will be satisfied after reading Chapter 12.

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Stockwell Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Red</td>
</tr>
<tr>
<td>Durometer (Shore A)</td>
<td>50</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>4 MPa (334 psi)</td>
</tr>
<tr>
<td>Pre-Stretch Strain</td>
<td>1%</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.020 in.</td>
</tr>
<tr>
<td>Treatment</td>
<td>Abraded with fine (600) grit sandpaper</td>
</tr>
</tbody>
</table>

Table 11.1: Clamshell Membrane Characteristics
11.2 Clamshell Geometry

Choosing the actual geometry of the Clamshell is a matter of balancing the necessarily small size against the required capacitance and fluid residence time. The shape of the membrane is quite naturally a circle since the membrane can then deform as a section of a sphere. It's also an easy shape to machine and does not create any stress concentrations where tearing could occur.

11.2.1 Air and Fluid Pockets

We tend to flow binder at rates on the order of 10 cc/min., and we would like to be able to have the capacity to flow for several seconds during any disastrous errors without having the fluid sit in the clamshell for too long.

The pocket depth was set at 0.25 in., which means it would take the Clamshell approximately 30 s to fill or drain at 10 cc/min. The pocket has a bottom fillet radius of 0.125 in. with a diameter of 1.25 in., producing a measured volume of about 5 cc.

11.2.2 Membrane Seal

To achieve a seal against the membrane, a boss is left around the pocket that will compress the membrane by a specified amount. The air pressure required for our flowrates is usually around 10–15 psi, so we should seal to 25 psi just to be safe. For our membrane with elastic modulus 334 psi we need a compression of 7.5%. On a 0.020 in. membrane like ours, this means we want to compress by 2.25 mil. Compressing by 0.003 in. is a strain of 15%, which will seal to 50 psi. If we compress too much we risk both permanently deforming the membrane, ripping it, or buckling the membrane inside the Clamshell cavity so that it will not ever actually be flat.

Two bosses are used to get this desired compression (see Figure 11-7), so that when the higher of the two bosses comes to rest against the other half of the Clamshell, the remaining space defines the compression of the membrane. Since our 0.020 in. membrane was actually 0.018 in. thick, the sealing boss is 0.010 in. high and the compression boss is 0.026 in. high, thus compressing the membrane by 2 mil to 0.016 in. This should compress to seal against 36.7 psi. Making the width of the boss 0.010 in. reduces the volume of Silicone that will actually be compressed, which further reduces the propensity of the membrane to wrinkle.
11.2.3 Inlet/Outlet Holes

Another consideration is in sizing the inlet/outlet holes into the wet and dry halves of the clamshell. When the membrane bottoms out against the cavity wall, the membrane could actually deform into the holes and ultimately tear. Knowing the maximum pressure we are likely to require for our fluid flow, we want to calculate the largest holes we can use for air and fluid inlet/outlet before it would be possible for the membrane to tear. According to an analysis done by Sachs, the worst case is when the rubber deforms into the shape of a hemisphere in the hole [10]. The hoop stress and hoop strain at the point of hemispherical deflection are related by

\[ \varepsilon_{\text{hoop}} = \frac{\sigma_{\text{hoop}}}{E} \left(1 - \nu\right) \]  \hspace{1cm} (11.19)

Where \( \varepsilon_{\text{hoop}} \) is the hoop strain, \( \sigma_{\text{hoop}} \) is the hoop stress, \( E \) is the Elastic Modulus of the membrane, and \( \nu \) is the Poisson ratio. Using the fact that the hoop strain for a hemisphere is \( \pi/2 \) and that \( \nu = \frac{1}{2} \) for rubber, we find the following expression for the hoop stress:

\[ \sigma_{\text{hoop}} = \pi E \]  \hspace{1cm} (11.20)

Next we balance the force resulting from the hoop stress multiplied by the stretched thickness of the membrane against the force found by multiplying the fluid pressure by the area
of the hole. The membrane thickness is found by multiplying the initial thickness \( t \) by the area of the hole divided by the surface area of the hemisphere, which ultimately gives \( t/2 \). The expression for the pressure which would form a hemisphere is then given by

\[
P_{\text{max}} = 2\pi E \frac{t}{D}
\]  

where \( P_{\text{max}} \) is the maximum fluid pressure, \( E \) and \( t \) are as before, and \( D \) is the hole diameter.

For our membrane as specified in Table 11.1, a hole diameter of about 1/16 in. can withstand pressures of up to 671 psi. We're safe.

One note about the water inlet: we want it to be aimed so that the water flow into the clamshell is not directed right at the membrane where the mild jet might wiggle the membrane and cause fluctuations in the fluid pressure.

11.2.4 Sensor Mount

Since the sensor has a maximum response when the membrane gets too close, the sensor must be positioned far enough from the membrane so that it is shy of the maximum even at its closest point. From Figure 10-2 we saw that we should position the sensor 0.375 in. from the dry half cavity for the red Silicone. The sensor housing has a mounting hole that clears a 2-56 screw, so we include a clearance hole and thread so we can clamp the sensor down.

11.2.5 Viewing Windows

Although we have a display that indicates the membrane position (See Section 12.2.1), it would be nice to actually be able to see the membrane and visually verify that it is in the center. Besides, at some point we need to calibrate the system against the center position, so we need to be able to see inside to know when we’re there. The dry half of the sensor is machined from clear acrylic, so optical quality is not a problem. However, a flat side and curved cavity produce a lens that will distort the view. To improve visibility, sections of the dry half are machined away so that the wall of the cavity is concentric with the cavity radius.
11.2.6 Summary

Figures 11-8 and 11-9 highlight some of the design features of the Clamshell geometry. The inlet and outlet holes shown are threaded to accept Leur fittings for easy connecting and disconnecting. Note that the sensor is turned on one side to allow for easier disconnection when the Clamshell is mounted on the printhead carriage.

Figure 11-8: Front Exploded View of the Clamshell

Figure 11-9: Rear View of the Clamshell
11.3 Air Reservoir

11.3.1 Compressible Gas Theory

We saw above that the pulse-like nature of the pump adds fluid in 0.05 cc quanta. We have already satisfied ourselves that the deflection of the membrane will produce a suitably small change in pressure of the fluid. However, remembering our high school chemistry, the pressure and volume of a gas are inversely proportional. In our case, the 0.05 cc change in fluid volume corresponds to a \( \frac{0.05}{5} = 1\% \) reduction in air volume, and thus a 1\% rise in air pressure. If we have our air pressure set at even just 10 psi this corresponds to a pulse of 0.1 psi, which is an order of magnitude higher than our maximum acceptable pressure pulse.

The solution? Simply increase the volume of the dry half of the Clamshell. Obviously this cannot be easily done on the Clamshell itself, so instead a large air reservoir is added upstream of the dry half. So long as sufficiently large tubing is used to connect the two, both the reservoir and the Clamshell can be treated as a single volume. To reduce the pressure pulse by a factor of 100, we must have a reservoir volume of 5 cc \( \times \) 100 = 500 cc.

11.3.2 Air Reservoir Design

Ideally we want the reservoir to be as close to the Clamshell as possible. On the Alpha Machine, the most likely space is then at the top of the umbilical pendulum (See Figure 11-10). This structure was not designed to hold much in the way of a load, so the reservoir must be light, and we also don't want all of the mass concentrated at the top to create an unstable inverted pendulum.

The final design used a section of garden variety PVC pipe capped at both ends. With an inner diameter of 1.75 in. and a length of 20 in., the reservoir volume is actually 62.8 cu.in., or 1029 cc. This is larger than we needed, but we had the room to spare, so there’s no problem with being conservative. With our total volume now 1034 cc, the 0.05 cc pulse now only represents a relative pressure change of 49 ppm. We use a thin-wall 3/32 in. ID tubing to connect the reservoir to the Clamshell so that there is negligible line resistance to the air moving between the reservoir and the dry half.
Figure 11-10: Air Reservoir Location on Alpha Machine
Chapter 12

The Controller

The point of the Clamshell concept is to create a constant flow rate in the fluid by keeping it at a constant pressure. We have already seen in Section 11.1 that for this to happen the membrane must be kept flat and with zero, or at least minimal, deflection from its center position. The previous off-board Clamshell design used a capacitive sensor with a hysteresis loop to turn the pump on and off to keep the fluid at this constant level. Since the new design has such a small fluid volume, we must take more care in keeping the membrane flat and centered. This means we must use a continuously varying pump under feedback control rather than an on-off switch.

12.1 Theory

The IR photosensor (Chapter 10) is suitable for measuring the membrane position, so we want to use this reading to control our pump flow. For a first-order model, we can assume that the membrane moves with velocity proportional to the difference between the fluid flowrate in and the fluid flowrate out. The membrane position is then the integral of this difference in flow rate, as shown in Figure 12-1.

Although this model neglects any dynamics in the pump, this is a relatively safe assumption since the overall response will be quite slow. A simple proportional controller is appropriate, but we need the ability to add a constant offset to counteract the steady-state error that will inevitably result. In our case, steady-state error manifests itself as a deflection in the membrane and therefore a pressure difference between the dry and wet halves. Proportional control is also much simpler to implement and less likely to throw the system
into an unstable mess.

We also have another wrinkle to throw into the mix. At all costs we want to avoid clogging the fluid system, which can cause flooding and other nasty things.\footnote{Printing is also mysteriously less effective when no binder comes out of the printhead.} To avoid this, we don’t want to change the direction of fluid flow, which means we only want to run the pump in one direction. (This has another added benefit of increasing the pump’s lifetime since direction changes are much tougher on the gearbox than stopping and starting.)

### 12.2 Analog Design

Somehow our block diagram from Figure 12-1 must manifest itself as an actual circuit. The sensor driving and demodulation was already discussed in Section 10.2, so we will pick things up starting with the output of the filter stage, $-V_{\text{sensor}}$, remembering that we’re dealing with a negative voltage after our inverting isolation amplifier before the demodulator. (Review Chapter 10.) We implement our feedback controller in two stages: Sensor Scaling and Proportional Control. In addition, we want some sort of display for viewing the membrane position.

#### 12.2.1 Sensor Scaling and Display

We generally don’t get an identical response for any combination of membrane and sensor simply due to general process variation. Not only do we want the ability to correct for

\[ \text{Photosensor} \]

\[ G_f \]

\[ X_{\text{ref}} \]

\[ K_c \]

\[ P_{\text{offset}} \]

\[ \text{Controller} \]

\[ \text{Masterflex Pump} \]

\[ G_{\text{pm}} \]

\[ Q_{\text{in}} \]

\[ K_x/s \]

\[ \text{Membrane} \]

\[ X \]
this so we can expect a consistent signal going into the proportional controller circuit, but we also want the ability to adjust the sensitivity of the system if such a thing is deemed necessary.

The sensor scaling stage allows us to choose a gain and offset for the sensor signal. It is fabricated using an inverted summing amplifier with schematic shown in Figure 12-2. The offset allows us to counteract the natural bias baseline voltage in the sensor response. This way we can adjust the system so that our membrane position produces a 0V signal when flat and centered and a negative voltage as the Clamshell empties itself of fluid.

\[
-V_{\text{mem}} = \frac{10k + R_{\text{gain}}}{10k} (V_{\text{sensor}} - V_{\text{bias}})
\]  

We adjust \(V_{\text{bias}}\) with the potentiometer so that the sensor reads zero when it is centered in the clamshell. The negative sign on the stage output \(V_{\text{mem}}\) indicates that the sensor reading will then go negative as the clamshell empties once \(V_{\text{bias}}\) is set correctly. \(R_{\text{gain}}\) is a 100k potentiometer wired as a variable resistor that can be used to adjust the gain from 2 to 22. (On the control block diagram shown in Figure 12-1, \(V_{\text{bias}}\) is akin to the set membrane position \(X_{\text{ref}}\).) The output of this stage will typically range over about ±4V.

**Sensor Display** To visualize the membrane position, we use an analog needle milliammeter. The meter displays ±1mA centered about zero, so all we need to do is run our \(V_{\text{mem}}\)
signal through the meter. By choosing the resistor that converts the sensor voltage to a current for the meter reading, we can change the display gain to make it more or less sensitive. The display wiring is also shown in Figure 12-2.

12.2.2 Proportional Controller

Recall from above that we will use proportional control to maintain membrane position. We need to apply the controller gain and be able to apply a fixed offset to counteract the steady-state error inherent in any proportionally controlled system.

Circuit-wise, this is done with another inverting summing amplifier, as shown in Figure 12-3. Note that we now use a negative voltage for our $V_{\text{offset}}$ so that it will match the polarity of $V_{\text{mem}}$ since we need to add in some extra flow to cancel the undershoot caused by the steady-state error.

The pump control signal is then almost given by the equation

$$V_{\text{pump}} = \frac{560k}{100k} (V_{\text{mem}} + V_{\text{offset}})$$

(12.2)

Our gain of 5.6 is seemingly rather small for a proportional controller, but there are two reasons why we prefer a modest gain. First, components like the motor, sensor, membrane, and the various electrical bits are not in fact linear like we approximated. If we start cranking up the gain then the poles and zeros from these non-linear devices start to produce higher-order effects, which can lead to instability. Second, we already know that the pump pulses cause tiny deflections in the membrane. If we crank up the gain really high then our
system will start responding to these perturbations and sending a more variable signal to the motor. Our pump has some built-in protection and input filtering, but it is obviously better for the motor to receive a DC signal than it is for it to receive a varying signal.

Also note that we said the pump control signal was “almost” given by Equation 12.2. Our op-amp takes ±12V supplies, meaning the output can swing over a ±12V range. Our pump, as you recall, uses a 0–10V input signal to command the flowrate. However, due to the nature of our design, any negative output for \( V_{\text{pump}} \) corresponds to the Clamshell being over-full, and we have already stated that we do not want to control over this region since that would imply running the pump in reverse to draw fluid out of the clamshell.

Our challenge then is to limit the output from our op-amp to be 0–10V. It turns out this isn’t completely necessary. While we cannot send a ±12V signal to the pump, a few volts too high or too low is okay. The diode clamp on the op-amp output ensures that our voltage will be constrained to one diode drop below 0V on the low end and 12V on the high end. This amounts to approximately -1V–12V, which is acceptable to the pump.

12.3 Electronics Summary

The complete schematic of the control circuit is shown in Figure 12-4. The 4 TL074C operational amplifiers are all contained within a single 14-pin DIP package. In total, 4 ICs are needed: the op-amps, the demodulator, the flip-flop, and the oscillator. The circuit is powered by a single ±12 V power supply with a single 78L05 5V voltage regulator. Instructions for duplicating the control circuit are given in Appendix D.

When using the system, the built-in display can be used to do all of the calibration. When we know the membrane is centered we can adjust the sensor bias potentiometer until the display reads zero. We can then add some fluid to deform the membrane to a known position and adjust the sensor gain potentiometer until the needle points to a spot we like. Finally, while the system is running at steady-state the needle will not be centered due to the steady-state error of the system. We can then adjust the offset voltage until the needle points to zero and our system is completely tuned.
Figure 12-4: Complete Control Circuit Schematic
Chapter 13

Overall System

The improved fluid system has worked quite well on the Alpha Machine during preliminary testing. Unfortunately there was not sufficient time for long-term tests on the order of a year or so, but the notable improvement in response is extremely encouraging.

13.0.1 Common Disturbances

Under normal operation there are a relatively limited set of scenarios with which we are concerned regarding the system response.

- Drained Clamshell (Membrane deformed against cavity)
- Leaks (Reductions in flow resistance)
- Pressure Change (Change in the Air Pressure)
- Clogs (Increases in flow resistance)
- Pressure Pulse (The evil and disruptive carriage turnaround)

For all of the tests the Clamshell was filled with water, the pressure was set to 16 psi., and the outlet was fed through a single 203 micron nozzle.

Drained The question arises as to how the system will respond if the wet half is completely evacuated of fluid, i.e. the membrane is fully deflected into the wet half cavity. The system is able to handle this extreme condition with response as shown in Figure 13-1. The vertical dashed line at 4 s represents the point at which the pump was turned on under system
control. The entire re-filling process takes approximately 20 s, with no overshoot observed. The ripple in position after steady-state is obtained is due to the pulses from the pump rollers. We also see that steady-state was not exactly zero but instead has a steady-state error of -0.005 in. This is because we couldn’t resolve the position from the meter with enough precision to get the exact offset required. This is something we will have to live with, but it’s okay since the pressure change is so small at these deflections and turning up the gain any higher would lead to instabilities in the control signal.

As it turns out, the response to this scenario was so good that this method can actually be used to fill and start-up the Clamshell, as described in Appendix D.

**Leak** Figure 13-2 shows the membrane position after a leak has opened up in the fluid line. For this experiment, the “leak” was created by halving the fluid resistance by opening up an additional nozzle. The extra nozzle was opened at 4 s and closed at 16 s. The system recovers and reaches steady state after about 6 s in both directions. The steady-state position changes, but only by about 0.017 in. From our model we see that this corresponds to a pressure change of about 0.025 psi. for a membrane with 1% pre-stretch. This tells us we can handle any fluid leak short of halving the flow resistance and still maintain the
desired flow.

**Pressure Change** Figure 13-3 shows the membrane position during a step change in the air pressure, simulating a leak or clog or other irregularity in the air supply. A pressure "leak" was created at 4 s and closed at 16 s. The system recovers and reaches steady state after about 5 s in either direction. The overshoot in each direction is due to the fact that the pump and overall system react slow in comparison to the rate of change of the pressure. The 0.01 in. change in membrane position corresponds to approximately 0.015 psi.

Also notice that the pump pulses cause a "wiggle" of about 0.005 in., as we predicted earlier. This only corresponds to a change of about 0.010 psi, so we’re safe.

**Clog** Figure 13-4 shows the membrane position after the fluid line has been clogged. For this experiment, the entire nozzle was closed off at 4 s and opened again at 16 s. There is some overshoot before flow stops and the membrane is still due to the offset voltage applied at the controller to counteract steady-state error. The extra critical point at about 6 s is from one last pulse of the pump as it slows down. The deformation of 0.022 in. corresponds to a pressure difference of 0.035 psi (See section 11.1). This is large, but since we’re not flowing fluid we don’t really care. Once the nozzle is re-opened it only takes about 6 s to
return to our set value, so we shouldn’t print binder within 6 s of turning on the nozzle flow.

**Pressure Pulse** This is what we really care about: how well does it work during the dreaded carriage turnaround while the printhead is in catch mode?

The photographs in Figures 13-5 and 13-6 show the droplet streams during the carriage turnaround when the large pressure pulse is produced. Figure 13-5 shows the results from the old off-board Clamshell design, while Figure 13-6 shows the response of the new Mini-Clamshell design.

The time interval between images is approximately 0.1 s and the streams are illuminated with an LED strobe at the same frequency as the piezo generating the droplets. With the off-board clamshell the stream can be seen to nearly completely lose its droplet formation during the turnaround, so for an instant we essentially have a jet of binder rather than a droplet stream. The on-board Clamshell, on the other hand, maintains droplet formation, although we can still see some sort of jolt in the strobed droplet stream as evidenced by the dual droplet images in the second frame. There is a difference, although not quite as dramatic as we had hoped.
13.0.2 Results Summary

So what did we learn from all of this? Apparently all of the work was worth it, as our droplet stream is more stable during turnaround. We also saw that our steady-state membrane position, and thus the pressure and flow rate, depend on the nozzle resistance and air pressure. This is not surprising since we are using a proportional controller and our membrane position depends on the difference between flow rates into and out of the clamshell. Still, the main thing we wanted to do was prevent binder from going where it wasn’t wanted during carriage turnarounds with the printhead in catch mode. Any satellites formed or fluid sloshing during catch mode risks causing a flood or potentially decreasing the lifetime of the printhead, so we can be glad to have prevented this to some degree.

Future work should focus on identifying a better membrane material, as the Stockwell red Silicone has a tendency to wrinkle and maintain shape after it has been used for a short while. This results in a less-stable droplet stream, which is less than ideal. While the current results are encouraging, they are not yet complete, so it would be well worth the time to make additional improvements.
Figure 13-5: Off-Board Clamshell Streams During Turnaround

Figure 13-6: Mini-Clamshell Streams During Turnaround
Chapter 14

Fluid System: Conclusion

This part outlined the design and development of an improved fluid handling system for raster processes in 3DP™. The primary change, which was initially discovered during design of the Layer Forming Station, was to shrink the “Clamshell” and place it on-board the moving carriage to eliminate pressure pulses resulting from accelerating the fluid supply lines.

In order for drop placement to be accurate during binder printing the fluid pressure must be kept constant to within 0.025 psi, so a continuously varying pump under feedback control must be used to maintain the fluid level in the Clamshell. An infrared photosensor was used to detect the membrane deflection, and a simple proportional controller was used with a Masterflex peristaltic pump to drive the system.

The system has responded favorably during printing test on the 3DP™ Alpha Machine. Possible enhancements for commercial applications include eliminating the Masterflex pump and instead driving a gearmotor directly from a power op-amp.
Part IV

Conclusion
Chapter 15

Tying it All Together

And thus our 3DPTM odyssey is drawn to a close. The journey began in an effort to drive the rapidly oscillating motion of the slurry Layer Forming Station necessary to produce line merging and high-quality powderbeds. From initial work done in this realm in order to supply slurry to the carriage nozzle, a thorough design effort was launched to reevaluate the Clamshell method used for binder supply in raster-based 3DPTM using the dry powder Alpha Machine as a testbed.

Both efforts have been quite successful and can be duplicated by following the assembly and process instructions found in the Appendix. Improvements can still be made in both systems, but the current designs are more than adequate for the jobs for which they are asked to fill.

In the case of the Layer Forming Station, the hope is for the TDKTM/MIT slurry printer to become a testbed for slurry 3DPTM, much in the same way as the Alpha Machine serves for dry powder-based 3DPTM. The LFS has already proven to be sufficiently flexible and stable to achieve that goal.

In the case of the improved raster fluid system, we managed to converge on a workable solution. While the system was not as inexpensive or suitable for commercial/OEM applications as was originally hoped, it is a stable and versatile design that can be replicated for any other 3DPTM system (most likely in a laboratory setting) simply by following the fabrication and assembly instructions found in Appendix D.

In closing, the only hope is that the general state of the technology is left at least somewhat higher than it was before we began. Hopefully these efforts will be of use to
future researchers, and we wish you an experience free of clogged lines, spewing slurry, and fried op-amps. May the Force be with you.
Part V

Appendix
Appendix A

Carriage Motor HOWTO

This Appendix describes the fabrication of the linear motor used to position the slurry nozzle carriage and startup the system on the Layer Forming Station. The drawings and parts lists here are only reflective of the system as it currently exists. If you choose to build additional motors you should use the electronic versions of the documents found on the 3DPTM server, as they will reflect any modifications made to the design. All drawings appear at the end of this Appendix.

There are two parts to the Carriage Motor, as there are for any linear motor: the armature and the field assembly. The general design is shown in Figure A-1. The motor uses one row of magnets with a flux return bar to guide the magnetic field lines. The flux return bar passes through the armature coil, which is a coil wrapped around a bobbin encapsulated in epoxy. The armature coil attaches to the nozzle carriage and the magnet rail attaches to the side of the Layer Forming Station.

A.1 Armature

The armature consists of a bobbin wrapped with wire. The bobbin is machined from a special epoxy loaded with Aluminum particles and 400 turns of 24 AWG copper wire are used for the coil. The coil is then encapsulated in epoxy for better thermal conductivity and more thermal mass. Since winding the coil can exert quite a bit of stress on the bobbin, final machining is not done until after the encapsulation step is completed for added strength. The Aluminum-loaded epoxy has a high thermal conductivity (1W/m·K) without being electrically conductive, so it will stay cooler without producing harmful eddy currents. The
completed armature coil is shown in Figure A-2.

A.1.1 Materials List

The materials needed to manufacture the Carriage Motor Armature are given in Table A.1.

Table A.1: Materials List for Carriage Motor Armature

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ren-Shape Express 2000</td>
<td>Ciba Specialty Chemical</td>
<td>Manufacturer Direct</td>
<td>Bobbin Material</td>
</tr>
<tr>
<td>Aluminum-Loaded Epoxy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 AWG Magnet Wire (.001 in. Insulation)</td>
<td>Irrelevant¹</td>
<td>McMaster-Carr</td>
<td>Armature Wire</td>
</tr>
<tr>
<td>3/16 in. Ø Brass Rod</td>
<td>Irrelevant</td>
<td>MSC, McMaster-Carr, Small Parts, etc.</td>
<td>Coil Contacts</td>
</tr>
</tbody>
</table>

¹Only irrelevant in that we don't care who makes it as long as it matches our specifications.
In addition to the listed materials it would be advisable to have some 5-minute epoxy for tacking things together before encapsulation, acrylic cement for building the potting fixture, and some RTV silicone for sealing said fixture.

A.1.2 Drawings

Two sets of drawings are included for the carriage motor armature:

- Bobbin (Pre-Winding)
- Completed Armature (Post Encapsulation and Finishing)

A.1.3 Process Plan

Our goal here is to wind the bobbin and then encapsulate the coil in epoxy for better thermal conductivity and strength. We also want to machine away as much of the bobbin material as possible so that our armature isn’t any heavier than necessary, but we need to start with a beefy bobbin and then encapsulate or it will not withstand the stresses caused by winding the coil. The encapsulation step is done under vacuum to remove any air trapped in the coil to maximize our thermal conductivity. The process plan for doing all of this is given in Table A.2.
Figure A-2: Solid Model Rendering of Finished Carriage Motor Armature

Table A.2: Process Plan for the Carriage Motor Armature

Start with the empty bobbin machined from the Ren-Shape 2000.

continued on next page
Wind the bobbin with 400 turns of 24 AWG magnet wire. Prof. Trumper's lab has a simple machine designed for this purpose that includes a built-in counter for counting turns. Take care to keep tension in the wire and don't let the wire overlap. When you are finished the coil should not protrude above the top edges of the bobbin. If this is not the case the coil should be rewound.

Use some 5-minute epoxy to hold the end of the coil so it doesn't unwind. Leave about 2" for each lead.

Cut short (between .75 in. and 1 in.) lengths of the brass rod. Strip some insulation from the wire and solder the leads to the ends. Drilling a small hole in the end can make this step easier.
Tack the brass rods into place in the wound bobbin. The tips of the rods should be just shy of flush with the edge of the bobbin.

Build the potting fixture around the wound bobbin from the .25 in. acrylic using the acrylic cement. The edges of the acrylic pieces should be faced off so that the fixture will go together and seal correctly. The acrylic cement should only be applied to the acrylic-acrylic junctions.
Seal the acrylic-bobbin junctions and any other suspect joints in the potting fixture with RTV Silicone.

Mix up the Epotek 301 epoxy according to its included instructions. Bring the mixture to a vacuum 2–3 times or until it no longer bubbles after vacuum is achieved.
Fill the potting fixture with the vacuumed epoxy and bring it to vacuum 2–3 times or until it no longer bubbles. Placing the bobbin at a slight angle will help the air escape.

Cure the epoxy in a furnace as specified in its documentation.

The armature is now ready for final machining. The acrylic pieces should just snap off since unabraded acrylic doesn’t bond well to the Epotek 301. This will leave a very nice, optically clear finish on the sides. This isn’t necessary, but it sure looks cool.
A.2 Field Assembly

The magnet rail is constructed from two pieces which attach to form a loop to contain the magnetic field lines. It is machined from low-carbon steel which is Nickel-plated to prevent corrosion. The magnets are placed in a recessed magnet well which keeps them in position. Two jacking screws are also included to ease aligning the pieces when joining the two halves and separating them. Standoffs are machined from Aluminum and are used to attach the field assembly to the side of the LFS. The finished field assembly is shown in Figure A-3.

A.2.1 Materials List

The materials and parts needed to manufacture the Carriage Motor Field Assembly are listed in Table A.3.
Figure A-3: Solid Model Rendering of Carriage Motor Field Assembly

Table A.3: Materials List for Carriage Motor Field Assembly

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Carbon Steel</td>
<td>Irrelevant</td>
<td>Machine Shop, MSC, etc.</td>
<td>Magnet Rail Material</td>
</tr>
<tr>
<td>Aluminum 6061</td>
<td>Irrelevant</td>
<td>Machine Shop, MSC, etc.</td>
<td>Standoffs for mounting magnet rail on LFS</td>
</tr>
<tr>
<td>10 Magnets (Crumax D40727 Blend, 1 in. square × 0.25 in. thick)</td>
<td>Crucible Magnetics, Inc.</td>
<td>Manufacturer Direct</td>
<td>Providing the magnetic field</td>
</tr>
<tr>
<td>4 M5×25 mm Socket Head Screws (Stainless Steel)</td>
<td>Irrelevant</td>
<td>McMaster-Carr, etc.</td>
<td>Attaching magnet rail to flux return bar</td>
</tr>
<tr>
<td>2 M6×25 mm Socket Head Screws (Stainless Steel)</td>
<td>Irrelevant</td>
<td>McMaster-Carr, etc.</td>
<td>Jacking screws</td>
</tr>
</tbody>
</table>

*continued on next page*
A.2.2 Drawings

Three sets of engineering drawings are included:

- Magnet Rail
- Flux Return Bar
- Mounting Standoffs

Note that the magnet rail and flux return bar are to be Nickel-plated after machining and the standoffs are to be anodized.

A.2.3 Process Plan

The process plan for putting the field assembly together is quite simple. Safety goggles and gloves should be worn when handling the magnets since they are quite strong and will happily fly around and shatter without regard to any fingers or other body parts in the way. The steps are given in Table A.4.

Table A.4: Process Plan for the Carriage Motor Field Assembly

| Place the magnets in the magnet well of the magnet rail. Use extreme caution and wear gloves and safety goggles. When the well starts to become full it's best to place the magnet on the rail and then slide it into the well. |

continued on next page
Slide the Carriage Motor Armature over the flux return bar.

Screw the jacking screws into the jacking screw threads in the flux return bar.

Align the jacking screws with the jacking wells and put the two halves together.
Loosen and remove the jacking screws.

Attach the mounting standoffs using the low-profile screws.

End of Carriage Motor Field Assembly Process Plan
Appendix B

Countermass Motor HOWTO

This Appendix describes the fabrication of the linear motor used to input power to the system and drive the nozzle carriage by oscillating the countermass on the LFS. The centering system used to keep the oscillating countermass from drifting is also described. The drawings and parts lists here are only reflective of the system as it currently exists. If you choose to build additional motors you should use the electronic versions of the documents found on the 3DPTM server, as they will reflect any modifications made to the design. All drawings appear at the end of this Appendix.

There are two parts to the Countermass Motor, as there are for any linear motor: the armature and the field assembly. The general design is shown in Figure B-1. The motor uses paired “clusters” of magnets with one cluster acting on each of two opposite legs of the armature coil. The armature coil moves freely inside the field assembly and is attached to the countermass via a support that is encapsulated in with the coil. The field assembly attaches to the sides of the Layer Forming Station.

B.1 Armature

The armature consists of a bobbin wrapped with wire. The bobbin is machined from a special epoxy loaded with Aluminum particles and 200 turns of 24 AWG copper wire are used for the coil. The coil is then encapsulated in epoxy for better thermal conductivity and more thermal mass. Since winding the coil can exert quite a bit of stress on the bobbin, final machining is not done until after the encapsulation step is completed for added strength. The Aluminum-loaded epoxy has a high thermal conductivity (1W/m·K) without being
electrically conductive, so it will stay cooler without producing harmful eddy currents. The mounting support for the armature is tacked to the coil and then permanently attached in the encapsulation process. The completed armature coil and mount is shown in Figure B-2.

B.1.1 Materials List

The materials needed to manufacture the Countermass Motor Armature are given in Table B.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ren-Shape 2000 Aluminum-Loaded Epoxy</td>
<td>Ciba Specialty Chemical</td>
<td>Manufacturer Direct</td>
<td>Bobbin Material</td>
</tr>
</tbody>
</table>

*continued on next page*
### Material List

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 AWG Magnet Wire (.001 in. Insulation)</td>
<td>Irrelevant&lt;sup&gt;1&lt;/sup&gt;</td>
<td>McMaster-Carr</td>
<td>Armature Wire</td>
</tr>
<tr>
<td>.25 in Copper Clad Garolite G10</td>
<td>Core-Tek</td>
<td>Manufacturer Direct</td>
<td>Armature mount and coil contacts.</td>
</tr>
<tr>
<td>Copper Foil</td>
<td>Irrelevant</td>
<td>McMaster-Carr, etc.</td>
<td>Soldering coil leads to mount traces.</td>
</tr>
<tr>
<td>Epotek 301 Epoxy</td>
<td>Epotek</td>
<td>Manufacturer Direct</td>
<td>Encapsulating the coil</td>
</tr>
<tr>
<td>Toluene</td>
<td>Irrelevant</td>
<td>VWR, McMaster-Carr, etc.</td>
<td>Mixing masking paint</td>
</tr>
<tr>
<td>Etching Wax</td>
<td>Irrelevant</td>
<td>VWR, McMaster-Carr, etc.</td>
<td>Defining contact traces on mounting arm.</td>
</tr>
<tr>
<td>Ferric Chloride Solution</td>
<td>Irrelevant</td>
<td>VWR, Digikey, Newark, etc.</td>
<td>Etching contact traces on mounting arm.</td>
</tr>
<tr>
<td>1/4 in. Acrylic Sheet</td>
<td>Irrelevant</td>
<td>McMaster-Carr, MSC, etc.</td>
<td>Potting fixture for encapsulation.</td>
</tr>
<tr>
<td>1/16 in. Acrylic Sheet</td>
<td>Irrelevant</td>
<td>McMaster-Carr, MSC, etc.</td>
<td>Potting fixture for encapsulation.</td>
</tr>
</tbody>
</table>

---

In addition to the listed materials it would be advisable to have some 5-minute epoxy for tacking things together before encapsulation, and some RTV silicone for sealing the fixture.

**B.1.2 Drawings**

Five sets of drawings are included for the Countermass Motor Armature, mounting arm, and mounting standoffs.

- Bobbin (Pre-Winding)
- Mounting Arm (Pre-Etching)
- Mounting Arm (Post-Etching)
- Complete Armature (Post-Encapsulation and Finishing)
- Mounting Standoffs

<sup>1</sup>Only irrelevant in that we don't care who makes it as long as it matches our specifications.
B.1.3 Process Plan

Our goal here is to wind the bobbin and then encapsulate the coil in epoxy for better thermal conductivity and strength along with attaching the mounting arm. We also want to machine away as much of the bobbin material as possible so that our armature isn’t any heavier than necessary, but we need to start with a beefy bobbin and then encapsulate or it will not withstand the stresses caused by winding the coil. The encapsulation step is done under vacuum to remove any air trapped in the coil to maximize our thermal conductivity. The process plan for doing all of this is given in Table B.2.
Table B.2: Process Plan for the Countermass Motor Armature

Start with the empty bobbin machined from the Ren-Shape 2000.

Wind the bobbin with 200 turns of 24 AWG magnet wire. Prof. Trumper’s lab has a simple machine designed for this purpose that includes a built-in counter for counting turns. Take care to keep tension in the wire and don’t let the wire overlap.

Use some 5-minute epoxy to hold the end of the coil so it doesn’t unwind. Leave about 2” for each lead.

Machine the G10 as per the drawings. The water jet cutter is best for this due to the highly abrasive nature of the G10.

*continued on next page*
Mask off the G10 leaving the correct parts of the copper exposed as per the etched drawing.

Mix the Toluene and etching wax until it forms a thick paint.

Cover the exposed Copper with the etching wax "paint"
continued from previous page

After the paint dries, remove the masking tape

Submerge the G10 in the Ferric Chloride solution and agitate until all of the unpainted copper is removed

Remove the etching paint with Toluene and drill the contact holes as specified in the drawings

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Solder a short piece of Copper foil to the tip of each trace and fold it over the tip of the mounting arm. Do not leave a large bead of solder or the mounting arm will not fit inside the bobbin.

Slide the mounting arm around the coil until the total length is 241.50 mm. If it does not fit then the coil is not wound densely enough and should be rewound. Note how much of the mounting arm goes inside the bobbin and abrade this area for better epoxy adhesion later. Strip some insulation off the ends of the coil leads and solder them onto the folded-down pieces of Copper foil.

Tack the mounting arm in place with 5-minute epoxy. Use shim stock to align the mounting arm so that it is parallel with the top and bottom of the bobbin.

continued on next page
Cut pieces of the 1/4 in. acrylic the width of the bobbin and machine the edges so they are parallel and flat. Attach them to the bobbin with 5-minute epoxy. Bend a strip of 1/16 in. acrylic around the bobbin and heat it with a hot air gun so that it will keep its shape. Seal with RTV Silicone.

Mix up the Epotek 301 epoxy according to its included instructions. Bring the mixture to a vacuum 2–3 times or until it no longer bubbles after vacuum is achieved.

Fill the potting fixture with the vacuumed epoxy and bring it to vacuum 2–3 times or until it no longer bubbles. Placing the bobbin at a slight angle will help the air escape.
Cure the epoxy in a furnace as specified in its instructions. If no furnace will hold everything then a single light bulb inside a box lined with Aluminum foil should get warm enough.

The armature is now ready for final machining. The acrylic pieces should just snap off since they don’t bond well to the Epotek 301 when unabraded.

The encapsulated bobbin is now ready for final machining according to the “CMLM Armature Post-Encapsulation” drawings. Take care to not cut into the coil when machining the top and bottom of the bobbin since reference dimensions are taken from the mounting arm, which may not be perfectly aligned.

---

End of Countermass Motor Armature Process Plan

---

B.2 Field Assembly

The field assembly is constructed from two pieces which contain the magnetic field lines and two non-ferrous spacers which also mount the assembly to the LFS. The top and bottom are machined from low-carbon steel which is Nickel-plated to prevent corrosion. The magnets are placed in recessed magnet wells which keep them in position. Four jacking screws are
also included to ease aligning the pieces when joining the two halves and separating them. The spacers are machined from Aluminum and are used to attach the field assembly to the LFS. The finished field assembly is shown in Figure B-3.

![Figure B-3: Solid Model Rendering of Countermass Motor Field Assembly](image)

**B.2.1 Materials List**

The materials and parts needed to manufacture the Carriage Motor Field Assembly are listed in Table B.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Carbon Steel</td>
<td>Irrelevant</td>
<td>Machine Shop, MSC, etc.</td>
<td>Magnet Rail Material</td>
</tr>
<tr>
<td>Aluminum 6061</td>
<td>Irrelevant</td>
<td>Machine Shop, MSC, etc.</td>
<td>Standoffs for mounting magnet rail on LFS</td>
</tr>
<tr>
<td>16 Magnets (Crumax D40727 Blend, 1 in. square × 0.25 in. thick)</td>
<td>Crucible Magnetics, Inc.</td>
<td>Manufacturer Direct</td>
<td>Providing the magnetic field</td>
</tr>
<tr>
<td>16 M6×15 mm Socket Head Screws (Stainless Steel)</td>
<td>Irrelevant</td>
<td>McMaster-Carr, etc.</td>
<td>Attaching magnet rail to flux return bar</td>
</tr>
</tbody>
</table>

*continued on next page*
### B.2.2 Drawings

Three sets of engineering drawings are given:

- Field Assembly Top
- Field Assembly Bottom
- Spacer/Mounting Block (2 pieces)

Note that the top and bottom are to be Nickel-plated after machining and the spacers are to be anodized.

### B.2.3 Process Plan

The process plan for putting the field assembly together is quite simple. Safety goggles and gloves should be worn when handling the magnets since they are quite strong and will happily fly around and shatter without regard to any fingers or other body parts in the way. The steps are given in Table A.4.

#### Table B.4: Process Plan for the Countermass Motor Field Assembly

| Place the magnets in the magnet well of the top and bottom. Use extreme caution and wear gloves and safety goggles. When the well starts to become full it’s best to place the magnet on the rail and then slide it into the well. Be sure that the front and back wells are of opposite polarity. |
|---|---|
| continued on next page |
continued from previous page

Attach the bottom to the spacers using the shorter M6 screws.

Screw the jacking screws into the jacking screw threads in the top.

Align the jacking screws with the jacking wells and put the two halves together. Don’t worry about aligning the magnets correctly—they will only go one way and will refuse anything else.

Loosen and remove the jacking screws.

End of Countermass Motor Field Assembly Process Plan

B.3 Centering Assembly

There are four pieces to the Centering System: two stationary magnets attached to the Countermass Motor Field Assembly, one moving magnet attached to the Countermass, and the Eddy current damping strip attached to the Countermass Motor Armature. The general
design is shown in Figure B-4.

Figure B-4: The Countermass Linear Motor (Previously Shown as Figure 5-2)

B.3.1 Parts List

The materials needed to fabricate the Countermass Centering Assembly are given in Table B.5.

Table B.5: Materials List for Countermass Centering Assembly

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultem 1000 Epoxy Resin</td>
<td>General Electric</td>
<td>McMaster-Carr</td>
<td>Magnet mounts.</td>
</tr>
<tr>
<td>Aluminum 6061</td>
<td>Irrelevant</td>
<td>Machine Shop, MSC, McMaster-Carr, etc.</td>
<td>Mounting arm for moving magnet.</td>
</tr>
<tr>
<td>Aluminum 6061 .0625 in. Sheet</td>
<td>Irrelevant</td>
<td>Machine Shop, MSC, McMaster-Carr, etc.</td>
<td>Eddy current damping strip.</td>
</tr>
<tr>
<td>3 Magnets (Crumax D04727 Blend, 1 in. square x 0.25 in. thick)</td>
<td>Crucible Magnetics, Inc.</td>
<td>Manufacturer Direct</td>
<td>Providing the magnetic field</td>
</tr>
<tr>
<td>12 M3×10 mm Socket Head Screws (Stainless Steel)</td>
<td>Irrelevant</td>
<td>McMaster-Carr, etc.</td>
<td>Attaching magnet mounts</td>
</tr>
<tr>
<td>4 M6×15 mm Low-Profile Socket Head Screws (Stainless Steel)</td>
<td>Irrelevant</td>
<td>McMaster-Carr, etc.</td>
<td>Attaching moving magnet mounting arm</td>
</tr>
<tr>
<td>4 M2.5×5 mm Flathead socket screws (Stainless Steel)</td>
<td>Irrelevant</td>
<td>McMaster-Carr, etc.</td>
<td>Attaching damping strip to Countermass Motor Armature</td>
</tr>
</tbody>
</table>

End of Countermass Centering Assembly Materials List
B.3.2 Drawings

Five sets of drawings are given:

- Fixed Stationary Magnet Mount
- Adjustable Stationary Magnet Mount
- Adjustable Moving Magnet Mount
- Adjustable Moving Magnet Mounting Arm
- Eddy Current Damping Strip

B.3.3 Process Plan

The process plan for putting the Centering System together is quite simple. Safety goggles and gloves should be worn when handling the magnets since they are quite strong and will happily fly around and shatter without regard to any fingers or other body parts in the way. No complicated instructions are necessary. Simply attach the damping strip to the top of the Countermass Motor Armature and put the magnets together as per the diagram in Figure B-5. Note in the figure that the relative strength of the Centering System can be changed by moving the adjustable magnets. Some 5-minute epoxy should be used to hold the magnets in place, and some tape as well wouldn't be a bad idea. Take care to align the polarity of the magnets correctly according to the arrows shown in the Figure. Which side

Figure B-5: Countermass Centering System Assembly
is North and which side is South is irrelevant—what is important is that the center moving magnet attached to the Countermass is opposed by both of the stationary magnets. The stationary magnets then attach to the bottom of the Countermass Motor field assembly and the moving magnet attaches to the Countermass spring block via the Aluminum mounting arm.
SECTION A-A

Holes marked 'B' may be sized and spaced as appropriate for mounting during machining process.

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CMLM BOBBIN - PRE-WINDING

Dimensions are in mm, tolerances are ±0.1 mm.
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2XØ3.10 THRU

7.50

15

35

82

7.50

7.50

7.50

15

7.50

7.50

55

82

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CMLM BOBBIN MOUNT ETCHED

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM.
TOLERANCES ARE ±1MM.

CAD-GENERATED DRAWING.
DO NOT MANUALLY UPDATE.

APPROVALS

DATE

DC ABLES
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APPROVED

MATERIAL
COPPER CLAD G10 GLASS RESIN

FINISH

REV.

SIZE
A

DWG. NO.

SCALE

CAD FILE

SHEET OF
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Dimensions are in mm. Tolerances are ±.1 mm.

Material: Ultem-1000
Finish: --

CMLM Coil Spacer

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DO NOT SCALE DRAWING

 APPROVALS | DATE
 DC ABLES | 12/27/99

CMLM COIL SPACER
SECTION A-A
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN MM.
TOLERANCES ARE ± .1 MM.

MATERIAL: ULTEM-1000
FINISH: --

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CMCA 1

A

DRAWING
DC ABLES 12/27/99
APPROVED

APPROVALS DATE

CAD GENERATED DRAWING, DO NOT MANUALLY UPDATE

REVISION

SIZE

SCALE CAD FILE SHEET OF
The information contained in this drawing is the sole property of MIT. Any reproduction in part or whole without the written permission of MIT is prohibited.

Dimensions are in mm. Tolerances are ±0.1 mm. MATERIAL: ULTEM-1000 FINISH: -

DO NOT SCALE DRAWING

CMCA 2

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3DP project

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DIMENSIONS ARE IN MM

TOLERANCES ARE ±0.1 MM

SCALE CAD FILE:

DRAWING SHEET OF 4

REVISION

SIZE ORG. NO. REV

A

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SECTION A-A

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CMCA 4

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MM
TOLERANCES ARE ±.1MM

CAD GENERATED DRAWING
DO NOT MANUALLY UPDATE

DRAWN
DC ABELES 12/27/99
APPROVED

MATERIAL
AL6061

FINISH

SCALE

DWG. NO.

REV.

SHEET OF

DO NOT SCALE DRAWING
Appendix C

LFS Driver Software HOWTO

An effort was made in early 2001 to document the current state of the TDK/MIT slurry 3DPrinter [14]. This Appendix is taken largely from the part of the documentation detailing the driver for the Layer Forming Station. For the latest information regarding any portion of the TDK/MIT machine you should check there. For its part, this Appendix will detail the state of the machine at the time this thesis was written.

The software is split into different interface layers as shown in Figure C-1. The layered design insulates the operation of the Win32 control application from the PMAC motion.
control board running its own control program, called “lfs.main.” Layering the interfaces allows us to make changes to one portion of the software without affecting the operation of any of the other components.

C.1 PMAC Program

The PLC code running on the PMAC is organized according to the diagram in Figure C-2. All interaction with the PMAC occurs through the lfs.main PLC. Commands and queries are processed via the driver DLL, defined with an Application Programming Interface.

C.2 Windows Driver API

C.2.1 Overview

This section describes the operation of the driver for the MIT Layer Forming Station, which is contained in the library mitctrl.dll and which uses the source/header files mitctrl.c
and mitctrl.h. The source is found in the \mitctrl directory of 3dpsrc. In addition, it uses a settings file called mitctrl.ini and a log file called mitctrl.log, both of which are located in c:\3dpsys at the time of this writing.

The logic and operation of the LFS is encapsulated primarily within the Turbo PMAC that controls the 5 axes of the LFS. (Powderbed, carriage, countermass, galvo, and piezoregulator.) The driver DLL is only responsible for communicating with the PMAC. All commands to the PMAC are given “asynchronously,” which means that a command is merely sent – no acknowledgement of success or failure is required. Communication errors are detected, but other routines within the overall 3dpproc.exe program must be responsible for determining when an LFS command has been successfully completed.

Commands to the PMAC are sent over the ISA bus in the form of ASCII text. The format of these commands is identical to what would be manually typed in the PMAC Console program, pewin32.exe. Care must be taken to include newline and carriage return characters at the end of a command so that the PMAC will know when to interpret and execute the command in its buffer. In C, these appear as the control characters '\n' and '\r', respectively.

C.2.2 Function Overview

There are 14 total global, or external, functions that are visible to other parts of the 3dpproc.exe program. Of these, only 10–12 would be considered to be in “active” use, the others being there for compatibility’s sake or due to legacy code.

In addition to the external functions, there are four “helper” functions used only within the LFS driver to handle the nuts and bolts of communication across the ISA bus with the PMAC. The details here aren’t as important since they have been demonstrated to work effectively. They deal primarily with controlling communication over the ISA bus.

Descriptions of each function and its argument(s) will be given here. For in-depth programming notes on the “mechanics” of the functions, it is better to reference the actual comments in the code itself, as those will be changed as the code itself is modified. Or at least, they better be. A description of the mitctrl.ini file is given following function descriptions.

MITCTRL_Init
Returns: a WORD (integer) representing an error code

Arguments: none

Description: Init() readies the PMAC for communication and performs a few initialization steps on the hardware. No motion commands are sent, however. It follows this procedure:

1. Open Log file and Initialize
2. Initialize ISA Bus Interface
3. Open the driver for PMAC communication
4. Load the functions needed to setup PMAC communication
5. Reset the PMAC (pause briefly afterwards)
6. Get number of PMAC code files to download
7. Allocate memory for filename string buffers
8. Read downloaded file list from settings file (mitctrl.ini)
9. Log number of files requested/attempted to download
10. Open communication with the PMAC
11. Configure the interface for ASCII communication
12. Verify that communication is established
13. Download PMAC Code files, logging each one
14. Close communication and release the PMAC driver (all communication from this point is now done by sending ASCII commands to a specific bus address)
15. Initialize the DACs to zero and initialize position
16. Enable PLC operation
17. Set the initial operating state to LFS_OFF
18. Close the server loop on the powderbed axis
19. Run the lfs.main PLC that manages the LFS
20. Pause a bit before exiting the function
MITCTRL_BACK (Legacy Function)

Returns: a WORD (integer) representing an error code

Arguments: none

Description: This function is no longer needed. It is included so that functions which call it will not break, but it doesn’t actually do anything anymore. It could be used as part of the zero-return operation to first move the powderbed axis before homing, but that shouldn’t be necessary.

MITCTRL_OReturn

Returns: a WORD (integer) representing an error code

Arguments: none

Description: OReturn() is used to zero the entire LFS. The carriage home position is determined, as is the zero position for the powderbed. All that is needed is to tell the lfs_main PLC on the PMAC to enter “home” mode. A status variable is also set so that other functions in the LFS driver know that we are homing. This is needed for MITCTRL_CheckDone.

MITCTRL_Stop

Returns: a WORD (integer) representing an error code

Arguments: none

Description: Stop() tells the lfs_main PLC on the PMAC to enter “stop” mode, which should halt the powderbed axis and stop the carriage from moving.

MITCTRL_Setup

Returns: a WORD (integer) representing an error code
Description: Setup() downloads all information needed by the PMAC to process a layer build. At the time of this writing, however, only certain of these values are actually used and downloaded to the PMAC, as noted above.

MITCTRL_Idling (Legacy Function)

Returns: a WORD (integer) representing an error code

Arguments: a DWORD (big integer) representing the speed

Description: Originally, this function started the carriage running separate from the powderbed axis. This is now all handled internally by the lfs_main PLC on the PMAC, so this function is no longer needed. Keeping it here but empty will allow older parts of the 3dpproc.exe program to work without hurting anything.

MITCTRL_Build

Returns: a WORD (integer) representing an error code

Arguments: none

Description: Build() initiates a layer building process. It first puts the lfs_main PLC into initialization mode, pauses briefly for the command to “stick,” and then commands the lfs_main PLC to build a layer. It then pauses for a few seconds while the build begins just so there is no bad overlap in commands.
MITCTRL_JOG

Returns: a WORD (integer) representing an error code

WORD wStSt  - Start or Stop Jogging (0 = stop)

Arguments: WORD wDir  - Direction (0 = positive)
            WORD wSpCd - Jog Speed (0 = Pulse, 1 = Slow, other = fast)

Description: JOG() simply moves the powderbed axis. Depending on the arguments, an
indefinite jog can be called or halted or a brief “pulse” move can be requested.

MITCTRL_GetPos

Returns: a LONG (integer) representing the current position

Arguments: WORD wAxsNo - Axis for which position is requested

Description: GetPos() only makes sense for the powderbed axis or the galvo. Calling
GetPos with wAxsNo = 1 returns the powderbed axis position. Calling with anything
else returns the galvo position. The values are requested from the PMAC and then
converted back into binary values, which is bizarrely what is wanted. Not a very
commonly-used function, most likely.

MITCTRL_CheckDone

Returns: a WORD (integer): 1 = not complete, 0 = complete, other = error code

Arguments: none

Description: CheckDone() acts differently depending on the current state of the LFS. If
we’re currently building a layer according to the driver’s internal status variable, then
we poll the Lfs_main PLC to see what state we’re in. If it’s LFS_READY, then we’ve
finished a layer build. If we’re zeroing the LFS, then we examine a status variable
in the Lfs.main PLC to see if the zero command has completed. If we’re executing a
point-to-point move, then we check some motor status variables see if we’re done.

MITCTRL_CheckSpeed (Legacy Function)

Returns: a WORD (integer): 1 = not complete, 0 = complete, other = error code
Arguments: none

Description: Used to indicate whether or not the carriage had reached the desired speed as a result of the MITCTRL_Idle() function. This is no longer needed since the lfs_main PLC on board the PMAC handles all of the startup procedure.

MITCTRL_PTP

Returns: a WORD (integer) representing an error code

Arguments:  
- XPos - The destination position
- wWait - Wait for move to complete? (0 = yes)

Description: PTP() commands the powderbed axis to move to the position indicated in lXPos, given in encoder units. wWait is supposed to indicate whether or not the function should return immediately or wait until the move is done. However, the code as done will not make this happen. Since nothing seems to break as is, this is a low-priority bug.

MITCTRL_PTP_Spd

Returns: a WORD (integer) representing an error code

Arguments:  
- LONG lXPos - The estimation position
- DWORD dwSpeed - The speed at which to move

Description: Moves the powderbed axis to the given position at the given speed. Returns immediately after sending the commands to the PMAC.

MITCTRL_SetGain

Returns: a WORD (integer) representing an error code

Arguments:  
- WORD wMode - Set gain to high or low (0 = low)

Description: Changes the P-gain for the powderbed axis. wMode = 0 sets it to the low setting (see code for actual value). Anything else sets it to the high setting. A rarely-used function.
MITCTRL_Send_Command

**Returns:** a WORD (integer) representing an error code

- LPSTR lpcCmd - String representing the command

**Arguments:**
- LPSTR lpcRes - String buffer for PMAC response
- WORD wMode - unused

**Description:** Send_Command() simply sends the lpcCmd string to the PMAC directly as a command and places the PMAC's response in lpcRes. At this point we do all communication with the PMAC via the external functions all listed above, so this shouldn't ever actually be needed.

### C.2.3 Settings File: MITCTRL.INI

The LFS driver looks for this settings file in c:\3dpsys. Changing this location would require recompiling the driver source code. At the time of this writing only one section is used, DownloadedFiles. The file looks something like this:

```plaintext
; Comment describing something and documenting how to change the file

[DownloadedFiles]
NumFiles=7
File1="c:\path\to\file.plc"
File2="c:\path\to\other\file.plc"
File3="d:\test\file\thing.plc"
File4="c:\unchanged\file.plc"
File5="a:\floppy\disk.plc"
File6="c:\this\is\alot\of\files.plc"
File7="c:\if\you\can\read\this\youre\driving\too\close.plc"
```

You get the idea. The files can actually be listed in any order, but if you specify N files in NumFiles=N, then only the first N files will be downloaded according to the index M ≤ N in FileM="c:\file\path\in\quotes.plc".

To read these settings the GetPrivateProfileString() and GetPrivateProfileInteger() Win32 functions are used. Basically you give it the config file, section name and variable name (e.g. "DownloadedFiles" and "File4", respectively), plus default values and the buffer size for strings and it will look up the proper information for you.
C.3 Modifications

These modifications outline general philosophies for modifying the PMAC code. For changes involving the Win32 Application see the documentation [14].

First we must understand how the PMAC code is organized. The PMAC code at the time of this writing is divided up into 12 files:

- **macros** - Constant definitions, variable renamings, etc.
- **lfs.pmac.cfg** - The config file for M-variables, etc.
- **clear.plc** - Kills everything and erases any running PLCs
- **lfs_main.plc** - The lfs_main PLC
- **meas_stat.plc** - PLCs for variable and status measurement
- **timers.plc** - The timer PLCs
- **ca_man.plc** - Carriage manager
- **cm_man.plc** - Countermass manager
- **gv_man.plc** - Galvo manager
- **sa_man.plc** - Slow Axis manager
- **bld_sch.plc** - Build scheduler
- **motion.plc** - Motion programs

To make changes, you can simply work on a (copy!) of the original file and then update the mitctrl.ini file to reflect the new code to be downloaded. Extra PLCs can be downloaded in addition to these, or PLCs can be replaced. Whatever floats your boat. One scheme might be to work on a development version copy until the kinks are worked out and then re-integrate the changes back into the original code. Or whatever. In summary,

1. Copy the proper .plc file to a new name/create a new PLC.

2. Make changes to the new PLC.

3. Update mitctrl.ini to download the new PLC.
Appendix D

Raster Fluid System HOWTO

This Appendix describes the fabrication, assembly and operation necessary to replicate the improved on-board clamshell-based fluid-handling system for raster-based 3DP™ systems. The purpose of the system is to provide constant flow rate for fluids deposited from a rastering nozzle/printhead. (See schematic in Figure D-1.) The drawings and schematics here reflect the system as it currently exists. Before using any of this information to build a new system you should first reference the electronic copy stored on the 3DP™ server for any updates or changes.

Figure D-1: Schematic of Fluid System (Reprint of Figure 8-3)
D.1 Parts Lists

There are lots of parts for this thing. We'll give separate parts list for each major subsystem: pump, electronics, clamshell, and reservoir.

D.1.1 Pump Parts

The materials needed to integrate the pump into the fluid system are given in Table D.1.

Table D.1: Materials List for Fluid System Pump

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masterflex LS-7523-30 Peristaltic Pump</td>
<td>Masterflex</td>
<td>Cole-Parmer</td>
<td>Supplying fluid to the clamshell</td>
</tr>
<tr>
<td>Masterflex 77201-60 Quick-Load Pump Head</td>
<td>Masterflex</td>
<td>Cole-Parmer</td>
<td>Actually does the pumping action when attached to the drive</td>
</tr>
<tr>
<td>Masterflex #14 Tubing</td>
<td>Masterflex</td>
<td>Cole-Parmer</td>
<td>Tubing for use in the pumphead</td>
</tr>
<tr>
<td>1/8 in. Hose Barb Male Leur Fittings</td>
<td>Value Plastics</td>
<td>Manufacturer Direct</td>
<td>Connecting supply lines to the pump</td>
</tr>
</tbody>
</table>

End of Fluid Pump Materials List

D.1.2 Control Electronics Parts

The control electronics of course have a very extensive parts list. Commodities like wire aren't listed, but basically everything else is found in Table D.2.

Table D.2: Materials List for Fluid Control Electronics

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>±12V 1A Power Supply</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Powering this whole foolish thing</td>
</tr>
<tr>
<td>7BL05 5V Voltage Regulator</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Providing a 5V source for some of our components from our 12V supply</td>
</tr>
<tr>
<td>GLC555 Oscillator</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Timing signal for sensor square wave drive signal (any generic '555 is okay)</td>
</tr>
</tbody>
</table>

continued on next page
<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD4013B CMOS D-type Flip-Flop</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Creating 50% duty cycle square wave from timing signal.</td>
</tr>
<tr>
<td>BS170 n-channel MOSFET</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Driving the sensor LED with the carrier signal.</td>
</tr>
<tr>
<td>EE-SF5 IR Photosensor</td>
<td>Omron</td>
<td>Digikey</td>
<td>Measuring the membrane position.</td>
</tr>
<tr>
<td>TL047C Quad FET-input Op-Amp</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Building block for the isolation, filter, calibration, and control circuit stages.</td>
</tr>
<tr>
<td>AD630 Balanced Demodulator</td>
<td>Analog Devices</td>
<td>Newark, Digikey, etc.</td>
<td>Demodulating our sensor signal to remove DC offset from the signal.</td>
</tr>
<tr>
<td>±1 mA Needle Display</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Display for membrane position.</td>
</tr>
<tr>
<td>1N419 Diode</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Clamping pump control signal to -1–12V range.</td>
</tr>
<tr>
<td>2 10k 10-turn Potentiometers</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Providing offsets for controller and signal calibration.</td>
</tr>
<tr>
<td>100k 10-turn Potentiometer</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Providing gain adjustment for signal calibration.</td>
</tr>
<tr>
<td>3 locking dial indicator covers</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Giving a reading for the potentiometer settings.</td>
</tr>
<tr>
<td>9 1 μF Electrolytic Capacitors</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Bypass capacitors for power supplies to ICs.</td>
</tr>
<tr>
<td>3 0.1 μF Bi-polar Capacitors</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>Building blocks for Oscillator and Filter circuits.</td>
</tr>
<tr>
<td>Various and Sundry 5% 1/4 W Resistors:</td>
<td>Irrelevant</td>
<td>Digikey, Newark, etc.</td>
<td>See Schematic</td>
</tr>
<tr>
<td>1 x 1k</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 x 3k</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 x 5.1k</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 x 10k</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 x 12k</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 x 100k</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 x 200k</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

continued on next page
D.1.3 Clamshell Parts

The materials needed to build the clamshell are given in Table D.3.

Table D.3: Materials List for Fluid Clamshell

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Acrylic</td>
<td>Irrelevant</td>
<td>Machine Shop, MSC, McMaster-Carr, etc.</td>
<td>Material for the clamshell pieces</td>
</tr>
<tr>
<td>3 x 10-32 Female Leur Fittings</td>
<td>Value Plastics</td>
<td>Manufacturer Direct</td>
<td>Attaching input/output lines to clamshell</td>
</tr>
<tr>
<td>1 x 1/4-28 Female Leur Fittings</td>
<td>Value Plastics</td>
<td>Manufacturer</td>
<td>Attaching air supply to clamshell</td>
</tr>
<tr>
<td>.020 in. 50 Durometer Red Silicone Rubber</td>
<td>Bisco Silicones</td>
<td>Stockwell Rubber</td>
<td>Flexible membrane for clamshell</td>
</tr>
</tbody>
</table>

End of Fluid Clamshell Materials List

D.1.4 Reservoir Parts

The materials needed for building the air reservoir are given in Table D.4.

Table D.4: Materials List for Air Reservoir

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Supplier</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 in. PVC Pipe</td>
<td>Irrelevant</td>
<td>Hardware Store</td>
<td>Body of reservoir</td>
</tr>
<tr>
<td>2 in. PVC End Caps</td>
<td>Irrelevant</td>
<td>Hardware Store</td>
<td>Ends of reservoir</td>
</tr>
<tr>
<td>1/4 in. NPT to 1/8 in. Hose Barbs</td>
<td>Value Plastics</td>
<td>Manufacturer Direct</td>
<td>Connecting air and clamshell to reservoir</td>
</tr>
<tr>
<td>3/32 in. Thin-Wall Flexible Tubing</td>
<td>Small Parts</td>
<td>Small Parts</td>
<td>Connecting clamshell to reservoir</td>
</tr>
</tbody>
</table>

End of Air Reservoir Materials List

D.2 Assembling the System

Now that we have all the parts we need we're ready to put the whole thing together. We'll in order of degree of difficulty for putting the different pieces together, starting with the
Air Reservoir, then building the Clamshell, and finally taking care of the Electronics.

D.2.1 Making the Reservoir

The reservoir should be built and mounted as shown in Figure D-2 from the PVC pipe parts listed in Table D.4. The following steps should be used to build the Air Reservoir.

1. Drill and tap two 1/4 in. NPT holes for the 1/8 in. hose barbs. The spacing isn’t important so long as the barbs will fit when the caps are put on the pipe.

2. Clean and glue the end caps on to the PVC pipe.

3. Install the 1/4 in. NPT-1/8 in. hose barb fittings with some Teflon tape for sealing.

4. Attach 1 fitting to the air regulator and the other end to the clamshell air inlet with the 3/32 in. ID thin-wall tubing.

Figure D-2: Air Reservoir Schematic & Location on Alpha Machine
D.2.2 Making the Clamshell

Figure D-3 shows the Clamshell split up for assembly. When putting the Clamshell together remember that the dull side of the membrane must be abraded with 600 grit sandpaper and that the abraded side must face the sensor in the dry half as shown. Any pre-stretch should be applied to the membrane before putting the clamshell together. The fluid and air connections should be made as shown in Figures D-4 and D-5. The air inlet on the dry half uses female leur to 1/4-28 UNF thread fitting, while the fluid inlet, fluid outlet, and air vent on the wet half use female leur to 10-32 UNF thread fittings. Note which side

![Diagram](image)

Figure D-3: Assembly Diagram for the Clamshell

![Diagram](image)

Figure D-4: Front Exploded View of the Clamshell
of the Clamshell assembly should face the front and back of the printer when mounting on the printhead carriage. Drawings for both the wet and dry halves of the clamshell, as well as the mounting plate for attaching the Clamshell to the carriage, are included at the end of this Appendix.

D.3 Making the Control Electronics

The schematic diagram for the control electronics is given at the end of this section. The only things to note are that the TL074C operational amplifiers are contained within a single DIP package which should receive \( \pm 12 \) V supplies. Also not shown are the 1 \( \mu F \) bypass capacitors which should be placed on the supply lines for each IC, as well as at the power supply itself.

D.4 System Manual

This section serves as a brief “Owners Manual” for the fluid control system. It covers the basics of setup, operation, and troubleshooting. It is not meant to be a comprehensive treatment of every situation you may encounter, but it should hopefully serve as a good starting point for working with the system.
D.4.1 Calibration

Calibrating the system involves counteracting the steady-state offset voltage inherent in the sensor response and adjusting the gain so that our controller has a known sensor transfer function. This is done using the sensor offset pot, sensor gain pot, and the membrane position display.

1. Start with an empty clamshell, the pump turned off, and no air pressure with the air vent open and the air inlet disconnected.

2. Verify through the viewing window that the membrane is flat and in the center position. If it isn’t, connect a 10 cc syringe to the air inlet and add or remove air until the membrane is flat.

3. Turn up the sensor gain to its maximum position.

4. Adjust the sensor offset until the membrane position needle points to zero.

5. Use the syringe to add 5 cc of air to the dry half. This will deflect the membrane by 0.25 in. to the edge of the cavity.

6. Adjust the sensor gain until the needle points to the -1 mark on the display.

At this point the system is ready to be used. The sensor has an approximate gain of 16V/in over the “negative side” of the Clamshell. The gain in the other direction will be somewhat higher due to the non-linear nature of the sensor response, but we only actively control on the negative side, so that’s what we really care about.

D.4.2 Startup Procedure

Filling and starting up flow with the Clamshell is very simple.

1. Turn off the pump.

2. Open the air vent and point it someplace where fluid can drain.

3. Turn on the air pressure to the dry half.

4. Turn on the pump.
5. Wait until fluid starts flowing from the air vent. Let it flush for a bit to clean everything out.

6. Close the air vent.

7. Wait for the system to reach steady state. This should be approximately 20 s.

8. There will probably be some steady state error in the membrane position as indicated on the display. Adjust the pump offset until the needle points at zero. There will be a considerable time-lag between offset adjustments and needle movements, so be patient.

D.4.3 Troubleshooting

There are three primary problem conditions identified at this point that we can address.

**Display Drift** A noticeable change in the steady-state position could results from one of two different possibilities: a change in the fluid flow rate or a change in the sensor/membrane characteristics. First visually verify the membrane position. Assuming they agree, check for leaks, clogs, or any other irregularities with the fluid and/or air lines.

**Meter ≠ Membrane** If the meter and the membrane no longer seem to agree then the calibration is off. This could be due to drift in the electronics, which is unlikely, or because the membrane is responding differently. If the change is sudden and you notice a sudden change in the pump rate the problem may result from too much ambient light. (The modulated scheme cannot compensate for light above a certain threshold.) Barring any obvious problem it may be necessary just to recalibrate the system. If the calibration continues to not hold then the membrane should be replaced.

**Wobbly Drops** This situation refers to the droplet stream being noticeably unsteady upon visual inspection with the camera. The air reservoir should take care of any problems with the regulator and/or air supply, so the first area to check is the air supply line. Failing that, the membrane should be inspected through the viewing window. If it has become wrinkled then the pressure will not remain as constant. A wrinkled membrane should be removed and replaced if it is found to have a permanent deflection. If this is a recurring problem then additional pre-stretch should be applied to the membrane.
MINI CLAM SHELL

4X ø .137 THRU
ø .400 ± .150
R .063

ø .100 ± .025 (NEAREST DRILL OKAY)
ø .525 ± .025
1/4-28 UNF x .200

.275
.108
.375
.258
.400

258
.400

.650

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CLEAR ACRYLIC

DO NOT SCALE DRAWING

UPDATE CS 3/5

EQD. IDWG. NO.

REF. CLS. NO.

COPY NO.

PRINT NO.

PRINT SIZE

SCALE

PART OF
Bibliography


