AUTOMATED LOADING AND UNLOADING OF THE STRATASYS FDM 1600 RAPID PROTOTYPING SYSTEM

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By

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ABSTRACT

Rapid prototyping systems have advanced significantly with respect to material capabilities, fabrication speed, and surface quality. However, build jobs are still manually activated one at a time. The result is non-productive machine time whenever an operator is not at hand to make a job changeover. A low-cost auxiliary system, named Continuous Layered Manufacturing (CLM), has been developed to automatically load and unload the FDM 1600 rapid prototyping system (Stratasys, Inc.). The modifications made to the FDM 1600 system are minimal. The door to the FDM 1600 build chamber is removed, and the .SML build files that are used to drive the FDM 1600 are modified at both ends to facilitate synchronized operation between the two systems. The CLM system is capable of running three consecutive build jobs without operator intervention. As long as an operator removes finished build jobs, and adds new build trays before at most every three build jobs, the FDM can operate near indefinitely. The impact of the CLM system on the productivity of the FDM 1600 rapid prototyping system is demonstrated by the expected reduction from the customary eight weeks down to a future three and one-half weeks required to complete the typical forty build jobs during a semester in the course ME 4644 Introduction to Rapid Prototyping at Virginia Tech.
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- FDM® is a registered trademark of Stratasys, Inc. of Minneapolis, Minnesota, U.S.A., Reg. No. 1,663,961.
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CHAPTER 1
INTRODUCTION

The American Heritage Dictionary of the English Language defines a prototype as “an original form or model [American92].” Prototyping of parts has been shown to be extremely useful for design verification, improving communication between different groups involved in the product development, and reducing the time to market [3Dsystems99][Stratasys99].

Rapid prototyping is automated part fabrication using computer numerical controlled (CNC) machines whose programs are generated automatically and directly from the computer aided design (CAD) models of the parts. This process is faster and less error prone than part fabrication with CNC programs that have been manually entered based on engineering drawings. The most commonly used computer controlled machines for producing prototypes are wire electrode discharge machines (wire-EDM), CNC mills, and, more recently, layered manufacturing (LM) machines.

Wire-EDM and CNC mills represent subtractive fabrication processes, in which material is removed from a work-piece until the desired shape is attained. LM machines, on the other hand, represent additive fabrication processes, in which material is added layer by layer to create the desired shape. The advantage of additive processes over subtractive processes is that additive processes are not restricted by tool access and hence can produce virtually any shape.

Commercial LM machines were first introduced in 1987 by 3D Systems, Inc. Since then, several other LM systems have arrived on the scene, including Fused Deposition Modeling (FDM) from Stratasys, Inc., Layered Object Manufacturing (LOM) from Helisys, Inc., and Selective Laser Sintering (SLS) from DTM Corp. These systems all build in layers, each on top of the previous, to create the finished part; hence the term layered manufacturing.
The Stereo Lithographic Apparatus (SLA) from 3D Systems, Inc. consists of an ultraviolet laser tracing across each cross-section of the part to be built, on the surface of a vat of liquid photopolymer. When the laser hits the photopolymer it solidifies to create a cross-section of the part in the vat of liquid photopolymer. The cross-section is then submerged in the vat, and the next cross-section is built on top of the previous.

As with any new technology, progress is continually being made to improve the process. Research and development in LM has thus far primarily focused on two aspects; materials and fabrication time. Since the start with photopolymers, several new materials have been introduced with new systems, and new materials for older systems are continually being developed. Hence, commercially available LM systems now support thermoset and thermoplastic polymers, waxes, metals, ceramics, paper, and various other composites [DTM00][Helisys00].

Fabrication time is an important aspect of LM, since the whole idea of rapid prototyping is to quickly produce prototypes parts. Recent improvements in fabrication time can be separated into three areas; hardware, software, and materials. Hardware improvements include hardware capable of building faster without losing accuracy. An example of this is the magnetic suspended extrusion head for Stratasys FDM systems, which reduces vibrations to enable increased build speed without decreased part quality [Stratasys99]. Software improvements include new building strategies that produce hatched or even hollow interiors [Stratasys98]. Another interesting building strategy is adaptive slicing, which optimizes each layer thickness to achieve a constant surface finish and faster build [Tyberg98]. Finally, new materials have been developed to accommodate the faster building procedures.

LM hardware is costly compared to CNC mills and wire-EDM machines. With this relatively high capital and maintenance cost, it is particularly important that their productivity is maximized. The previously noted hardware, software, and materials improvements have increased productivity to some extent. However, they have not
addressed the non-productive machine time encountered between build jobs. The advantages of integrating LM machines with automated build job changeovers have been noted [Burns93][Gibson96], though none have been implemented thus far.

1.1 PROBLEM STATEMENT AND OBJECTIVES

Existing commercial LM systems are set up to run single build jobs. In order to realize maximum productivity of the LM system, an operator must be available at the end of each build job to start the next one. The availability of an operator is often limited, especially during non-working hours at night or on weekends. Without an operator present at the end of a build job, non-productive machine time between build jobs is inevitable.

The objective of this thesis is to improve the productivity of the Stratasys FDM 1600 rapid prototyping system by developing an automated loading and unloading system that minimizes the non-productive machine time between build jobs, and that requires minimal modifications to the existing FDM 1600 rapid prototyping system. The new system should be capable of performing at least two unassisted build job changeovers.

1.2 SOLUTION OVERVIEW

This thesis is concerned with improving the productivity of the Stratasys FDM 1600 rapid prototyping system by minimizing the non-productive machine time between build jobs. In order to minimize this non-productive machine time, a new stand-alone system named Continuous Layered Manufacturing (CLM) has been developed. The CLM system automates the build job changeover procedure: Build jobs are automatically started by inserting a build tray for the part to be built on into the FDM 1600 modeler, and by removing this tray with the part when finished.

The modifications made to the FDM 1600 system are minimal. The door to the FDM 1600 build chamber is removed, and the .SML build files that are used to drive the FDM
1600 are modified at both ends to facilitate synchronized operation between the FDM 1600 and the CLM.

The CLM consists of a rolling table in front of the FDM. It moves empty build trays to the door opening of the FDM, opens the door to the FDM build chamber, pushes the build tray into the FDM, and closes the door. The FDM then takes over and builds a part. When it is done, the CLM opens the door, removes the build tray with the part, closes the door, and then moves the build tray with the part out of the way down the rolling table. The cycle is then repeated.

The CLM is capable of running three consecutive build jobs without operator intervention. Hence, as long as an operator removes finished build jobs and adds new build trays before at most three build jobs, the FDM can operate continuously near indefinitely.

1.3 THESIS OUTLINE

The remainder of this thesis details the development of the continuous layered manufacturing system. It consists of the following:

Chapter 2 details the history of automation in general and in the CNC industry, and provides an in depth review of previous work in the area of automation of LM machines.

Chapter 3 describes the FDM process, the FDM 1600 rapid prototyping system, and the CLM system development.

Chapter 4 describes the testing procedures and presents the test results. It also discusses the expected benefits of the CLM system based on the results.

Chapter 5 concludes the thesis and summarizes its contributions.
CHAPTER 2

LITERATURE REVIEW

This thesis is concerned with the automation of the build job changeover procedure for the Stratasys FDM 1600 rapid prototyping system. The focus of this literature review will therefore be on automation in general, followed by automation in layered manufacturing.

2.1 AUTOMATION

D.S. Harder, an engineering manager at the Ford Motor Company, initially coined the term “automation” in 1946 [Encyclopedia00]. The term was used to describe the use of automatic devices and controls in mechanized production lines.

Automation as it applies to this thesis is concerned with material handling and feeding, and controlling the process with computers. There are several books available on automation, such as “Robots and Manufacturing Automation” [Asfahl92] and “Flexible Manufacturing Systems Handbook” [Draper84]. In addition, there are also many books covering specific aspects within automation, such as material handling [Lindkvist85], computer control [Koren83], and mechanical conveyors [Fayed97].

The classical type of automation from the 40’s, 50’s and 60’s is fixed automation. Fixed automation (also known as hard automation) is designed for a specific process, and not easily adaptable to change. These days fixed automation is mainly used for high volume production at high speed.

With the emergence of computers, flexible automation was born. Flexible automation involves both hardware and software. The term flexible relates to the fact that the system can be re-programmed as needed. Flexible automation systems have the ability to deal with conditions as they arise, and then take the appropriate action. These systems are
controlled by microprocessors or programmable logic controllers. An example of a flexible automation system is the industrial robot [Asfahl92].

Automation is today common with CNC machining and wire-EDM. For instance, machining centers capable of switching cutting tools automatically have been commercially available for decades. This automated tool changing enables a series of different cutting operations without operator intervention. Another example of automation is the automated loading and unloading of work pieces mounted on pallets. This palletizing enables a series of pallets with work pieces mounted to be processed without operator intervention. Hence, both CNC machining and wire-EDM are today readily available with minimal operator dependent downtime during part fabrication and their job changeovers.

2.2 AUTOMATION AND LM MACHINES

The automation of LM build job changeovers has thus far not been a major topic in the LM industry. Instead the focus has been on improving the fabrication processes and their materials. Thus, only a limited amount of research in this area has been published.

Burns [Burns93] briefly discussed combining rapid prototyping machines with robotic devices to remove items as an element in a flexible manufacturing cell. A similar idea was subsequently proposed by Gibson [Gibson96], in which loading, unloading and finishing of LM parts would be done by robots. He anticipated that simply loading and unloading parts would not be financially viable, because of the high cost of robots. However, automating finishing is extremely difficult and thus far only developed the simulation of robot loading and unloading of an SLS machine [Lai99].

While the physical loading and unloading of LM systems has yet to be implemented, the electronic queuing of build jobs is becoming well established. Bailey [Bailey95] demonstrated a network print-queue for LOM machines to facilitate online submission of
build jobs. Today several commercial LM systems, including the new ‘desktop’ machines from Stratasys, Inc. (genisysX) [Stratasys99] and 3D Systems, Inc. (ThermoJet) [3Dsystems99], provide print-queues to organize their build jobs. These editable print-queues may be used to increase productivity by organizing build job sequences such that longer build jobs are run overnight while smaller build jobs are run during working hours. Such organization, while not eliminating, would minimize the likelihood of extended job changeover downtimes due to the unavailability of an operator.

2.3 OBSERVATIONS

LM automation has thus far been limited to speculation and network print-queueing of build jobs. Hence, the productivity of LM systems is still limited by the availability of operators to manually perform build job changeovers. The more mature CNC machining and wire-EDM industries have demonstrated the usefulness of automating the build job turnovers to reduce the dependency on operator availability. This thesis will extend this capability to LM.
CHAPTER 3

AUTOMATED LOADING AND UNLOADING OF FDM SYSTEMS

The FDM 1600 rapid prototyping system uses the fused deposition modeling (FDM) process to fabricate physical parts directly from computer aided design (CAD) models. This allows designers to produce prototypes quicker and more easily than through conventional prototyping methods. To improve productivity of the FDM 1600 rapid prototyping system, an auxiliary loading and unloading system has been developed. This continuous layered manufacturing (CLM) system allows the FDM 1600 rapid prototyping system to operate continuously with minimal operator intervention. This chapter describes the FDM process, the FDM 1600 rapid prototyping system, and the design of the CLM.

3.1 FDM PROCESS

FDM is one of several layered manufacturing (LM) processes that are currently commercially available. It fabricates physical parts by extruding a thin bead of semi-liquefied material, typically a thermoplastic or wax, that is routed back and forth in the horizontal plane to form a physical cross-section of the part as the material solidifies immediately after it is extruded (Figure 3.1). A three-dimensional structure is achieved as the extrudate fuses to the material on the previous layer underneath the current layer [Stratasys92]. Overhang structures are achieved by extruding two materials at each layer; one for the final part and one for temporary support structures. Hence, at the completion of the fabrication, there is no overhang in the union of these two materials. The overhang is revealed when the support structure is removed [Stratasys96].

In their current implementations, most FDM systems today re-extrude a filament feedstock of thermoplastic stored on a spool by pushing it through a ram-extruder that is
moving in the horizontal xy-plane. The vertical motion is achieved by moving the build table, not the extruder.

The machine code that controls the fabrication process is generated directly from a CAD model described in the .STL file format, the de facto LM industry standard [3DSystems89]. This CAD model is mathematically sliced into a stack of horizontal cross-sections corresponding to the fabrication layers. A raster trace pattern is then generated for each cross-section corresponding to the motion of the extruder in the xy-plane.

Reducing the three-dimensional fabrication process into a series of two-dimensional operations greatly simplifies the motion complexity, which facilitates the automated code-generation. Hence, once the operator has oriented the CAD model relative to the build envelope, the code can be automatically fabricated without any human intervention.
other than initiating each major step in the process (Table 3.1). This thesis aims to automate steps 4, 5, and 7 to fully automate the FDM “printing” process.

### 3.2 THE FDM 1600 RAPID PROTOTYPING SYSTEM

The FDM 1600 rapid prototyping system consists of a desktop FDM modeler driven by an external computer, in this case an SGI Octane workstation. The FDM 1600 modeler (Figure 3.2) may be placed on virtually any flat and stable surface, including in an office environment. The following will describe hardware, software, and operation in more detail.

#### 3.2.1 The FDM 1600 Hardware System

The FDM 1600 modeler measures approximately 4×3×4 feet (1.2×0.9×1.2 m). On the front of the modeler there is a polycarbonate door leading to the build chamber. Inside the build chamber (Figure 3.3), the ram extrusion head is positioned at the top where it moves in the horizontal xy-plane. Two metal dies protrude from the bottom of the extrusion head; one for the model material and one for the support material. The support material is used to build support structures to facilitate fabrication of model material parts with overhang features. It is also used to build a base of a few layers that is horizontally aligned with the xy-motion of the extruder. The feedstock material filaments enter the rear of the extruder head where they are pulled into the extruder by a set of rolling wheels.

<table>
<thead>
<tr>
<th>Table 3.1: Current interaction between operator and FDM system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Operator: orient CAD model</td>
</tr>
<tr>
<td>2. Operator: start code generation</td>
</tr>
<tr>
<td>3. Computer: generate code</td>
</tr>
<tr>
<td>4. Operator: send code to FDM system</td>
</tr>
<tr>
<td>5. Operator: initialize FDM system</td>
</tr>
<tr>
<td>6. Computer: fabricate part</td>
</tr>
<tr>
<td>7. Operator: remove part from FDM system</td>
</tr>
</tbody>
</table>
The build chamber also contains a build table in the form of a horizontal aluminum shelf that rides on four lead screws, one in each corner, to move it up and down in the z-direction. An aluminum build tray with shallow walls slides onto the build table. The build tray holds an expendable foam pad which acts as the foundation for the parts, and which is attached to the tray using pins pushed through the tray sidewall and into the foam pad. Several small box-shaped aluminum guides with spring loaded ball plungers protrude from the sides and the front of the build tray. These ball plungers match the indentations of the small fixtures that are attached to the build table, and they ensure, together with a set of side rails on the build table, that the build tray is correctly positioned on the build table.

The FDM 1600 moves the extrusion head relative to an origin, which is typically set manually by the operator. The z-position of this origin is manually set slightly submerged
into the top surface of the foam pad. The first few layers of support material therefore
bonds to the foam pad and creates a model material surface above the foam pad that is
aligned with the xy-motion of the extruder. The xy-position of the origin may be placed
anywhere on the foam pad as long as it does not cause the relative path of the extruder to
exceed its physical xy-limits. The maximum part size that can be fabricated is
10.0×10.0×9.4 inches (250×250×240 mm).

The extruder and build chamber temperatures are not controlled by software, but are set
manually on the front of the FDM 1600. For ABS plastic, the most popular FDM model,
these temperatures are set to 270°C and 70°C, respectively (T_g of ABS is 105°C). This
filament feedstock has a radius of 0.070 inches (1.80 mm), and is typically extruded
through a 0.012 inch (0.30 mm) die to form beads that are 0.010 inch (0.25 mm) thick
and 0.020 inch (0.50 mm) wide at a rate of 0.8 inches per second (20 mm/s).
3.2.2 The FDM 1600 Software System

The software for the FDM 1600 consists of two parts; the program QuickSlice which processes .STL files to produce machine code to control the FDM 1600 modeler, and a series of small utility programs that are used for communication with the FDM 1600 modeler.

The program QuickSlice 6.1 (Stratasys, Inc.) lets the operator orient one or more .STL files within the FDM 1600 build volume, and, if desired, customize the slicing, support structure generation, and tool path generation and process parameters. Its output is an ASCII text file in the .SML file format [Stratasys91] describing the FDM 1600 motion and operating parameters.

The utility programs communicate with the FDM 1600 modeler via an RS-232 serial line at 9600 baud. They include the ability to program the FDM 1600 firmware (e.g., for calibrations), and for sending the .SML file to the FDM 1600. A number of these utility programs were developed at Virginia Tech.

3.2.3 Operating the FDM 1600 Rapid Prototyping System

The Stratasys FDM 1600 rapid prototyping system is designed to run single build jobs initiated by a human operator. The first step in operating the FDM 1600 modeler is to use QuickSlice to generate an .SML file for the part to be built (Figure 3.4, boxes 1-5). Next, the extruder and build chamber must be brought up to temperature (Figure 3.4, box 6). These temperatures are displayed on small LCD screens on the FDM 1600 front panel and may be adjusted with arrow buttons next to each display. Then, the modeler must be loaded with a build tray with a foam board attached (Figure 3.4, box 7). Once the build tray is in place, the operator initiates the transmission of machine code from the workstation to the modeler (Figure 3.4, box 8).
At the start of each .SML file there is first a pause (PS) command followed by an initiation sequence. A pause command requires the operator to press the pause button on the front panel of the FDM 1600 to continue. The first PS command is simply a safety measure to allow the operator to clear the build chamber before any motion. The subsequent initiation sequence homes the extrusion head and the build table, lets the operator set the desired origin, and purges the extruders of old material (Figure 3.4, box 9).

Figure 3.4: Flowchart for operating the FDM 1600.

At the start of each .SML file there is first a pause (PS) command followed by an initiation sequence. A pause command requires the operator to press the pause button on the front panel of the FDM 1600 to continue. The first PS command is simply a safety measure to allow the operator to clear the build chamber before any motion. The subsequent initiation sequence homes the extrusion head and the build table, lets the operator set the desired origin, and purges the extruders of old material (Figure 3.4, box 9).
Homing is the process of moving the extrusion head and the build table to their known positions. The homing of the build table is achieved by moving the build table upwards until a proximity sensor at the top of the build volume is triggered. The table then goes down approximately 0.5 inch (13 mm), and repeats the homing at slower speed for increased accuracy. The homing of the extrusion head is achieved by moving the extrusion head into the front left corner of the build chamber at low speed.

After the homing, a second PS command is executed to let the operator set the desired origin for the build job (Figure 3.4, box 10). To set the desired origin for the build job, the operator moves the extrusion head and build table using arrow buttons on the front panel of the modeler. Once the origin has been reached, the operator presses the pause button again. This records the current locations of the extruder and the build table as the relative origin, and it permits the automated process to continue. Next, the two extruders are purged of old material. This is important to ensure good part quality. After the purge, the part fabrication commences without further delay (Figure 3.4, box 11).

The part fabrication consists of processing the code that was generated by Quickslice. This code ends with a PS command as a safety measure; namely, to allow the operator to remove the finished part before any unintended motion damages the part.

The last step in the build process is for the operator to remove the build tray and part from the build chamber (Figure 3.4, box 12), separate the part from the foam pad, and then separate the model material from the support material (Figure 3.4, box 13). At this point the part is ready for any subsequent finishing operations.

### 3.3 CONTINUOUS LAYERED MANUFACTURING

The FDM 1600 rapid prototyping system completes only one build job at a time without operator intervention. Its design expects an operator to unload any completed parts in the
machine; insert a new, empty build tray; identify the build job start position; and then start the next automated sequence of build operations.

This section describes in detail the design of the continuous layered manufacturing (CLM) system (Figure 3.5) that automates the FDM 1600 build job changeover, such that several build jobs can be completed on an FDM 1600 without operator intervention. Specifically, its subsections will describe the design specifications; the resulting hardware, control, and software systems, respectively; before describing the operation of the composite FDM 1600 / CLM system.

### 3.3.1 The CLM Design Specifications

A number of design specifications were identified at the start of this thesis research. These are summarized in Table 3.2.

An analysis of these requirements and in particular requirement (2), indicates that closely follows the tasks performed by the operator. The CLM hardware must be able to insert and remove build trays, store empty build trays, and store build trays with finished parts. Driving this, the CLM software must synchronize the operations of the FDM 1600 and the CLM, and maintain a print queue to facilitate a series of unattended build job changeovers. The following sections will describe the resulting design solution in detail.

### 3.3.2 The CLM Hardware System

The purpose of the CLM hardware (Figure 3.6) is to perform the physical tasks involved with loading and unloading build trays from the FDM 1600 modeler, and to store the build trays before and after each build job.

The CLM hardware (Figure 3.6) consists of a conveyor table, a set of build tray positioning guides, a linkage, a new door, an attachment frame, and a new build tray. All the CLM hardware was designed to involve minimal modifications to the FDM 1600.
The conveyor table rests on the attachment frame such that it is positioned in front of the FDM 1600 modeler. The linkage is attached in the middle of the conveyor table, with build tray positioning guides on either side. A new powered door attached to the conveyor table replaces the existing door on the FDM 1600. Finally, a set of new build trays with features that facilitate automation replaces the existing build trays which were designed for manual insertion and extraction.

Figure 3.5: The CLM is positioned in front of the FDM 1600 modeler. The operations of the two systems are synchronized, which enables the FDM 1600 modeler to complete three consecutive build jobs without operator intervention.
The loading of the build trays is accomplished by performing the series of tasks shown in Table 3.3. First, the empty build trays, which are stored at the start of the table, move to the middle of the table where they are positioned by the build tray positioning guides such that the current build tray is located in front of the door to the FDM 1600 build chamber. At this point, the build table inside the FDM 1600 build chamber is positioned near its bottom position, where all loading and unloading of the build trays takes place. Next, the powered door opens so the empty build tray can enter the build chamber. Then the linkage pushes the build tray onto the build table. To remove the build tray, the procedure is reversed. First, the door of the FDM 1600 build chamber opens. Then, the linkage moves the build tray from the build table to the conveyor table, and the door closes. Finally, the build tray is moved to the storage area at the end of the conveyor table.

### Table 3.2: CLM design specifications

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The CLM should be able to perform two build job changeovers</td>
</tr>
<tr>
<td></td>
<td>without operator interaction. With asynchronous operator-</td>
</tr>
<tr>
<td></td>
<td>adding of empty build trays and removing of completed parts,</td>
</tr>
<tr>
<td></td>
<td>the CLM should be able to operate near indefinitely.</td>
</tr>
<tr>
<td>2</td>
<td>The modifications of the FDM 1600 should be minimal so the FDM</td>
</tr>
<tr>
<td></td>
<td>quickly can be reconfigured to operate without the CLM.</td>
</tr>
<tr>
<td>3</td>
<td>The cost of the CLM must be less than US$ 5,000.</td>
</tr>
<tr>
<td>4</td>
<td>The footprint of the CLM should be less than six square feet</td>
</tr>
<tr>
<td></td>
<td>(0.6 m²) beyond the FDM 1600. Laboratory storage space is</td>
</tr>
<tr>
<td></td>
<td>limited.</td>
</tr>
<tr>
<td>5</td>
<td>The CLM should be reliable enough to handle the 40 or so build</td>
</tr>
<tr>
<td></td>
<td>jobs each spring semester in the course ME 4644 Introduction to</td>
</tr>
<tr>
<td></td>
<td>Rapid Prototyping.</td>
</tr>
</tbody>
</table>

The loading of the build trays is accomplished by performing the series of tasks shown in Table 3.3. First, the empty build trays, which are stored at the start of the table, move to the middle of the table where they are positioned by the build tray positioning guides such that the current build tray is located in front of the door to the FDM 1600 build chamber. At this point, the build table inside the FDM 1600 build chamber is positioned near its bottom position, where all loading and unloading of the build trays takes place. Next, the powered door opens so the empty build tray can enter the build chamber. Then the linkage pushes the build tray onto the build table. To remove the build tray, the procedure is reversed. First, the door of the FDM 1600 build chamber opens. Then, the linkage moves the build tray from the build table to the conveyor table, and the door closes. Finally, the build tray is moved to the storage area at the end of the conveyor table.
The following subsections will describe in more detail the design of the conveyor table, the position guides, the linkage, the new door, the new build tray, and the attachment frame, respectively.

3.3.2.1 The Conveyor Table

The conveyor table (Figure 3.7) is the central part of the CLM hardware system. All the other CLM hardware parts are attached to the conveyor table. The purpose of the conveyor table is to store empty build trays, transport the build trays, and store the build trays with finished parts. Hence, the conveyor table contains three regions; namely, a storage area for two new build trays, a loading and unloading area, and a storage area for two completed build jobs.

Figure 3.6: The CLM is a stand-alone system, able to load and unload build trays into and from the FDM 1600 modeler on demand.
Table 3.3: CLM load and unload tasks

<table>
<thead>
<tr>
<th>Load Tasks</th>
<th>Unload Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Move a build tray to the load position in front of the FDM 1600 build chamber.</td>
<td>1. Open the door of the FDM 1600.</td>
</tr>
<tr>
<td>2. Open the door of the FDM 1600.</td>
<td>2. Remove the build tray from the FDM 1600 build chamber.</td>
</tr>
<tr>
<td>3. Insert the build tray into the build chamber of the FDM 1600.</td>
<td>3. Close the door of the FDM 1600.</td>
</tr>
<tr>
<td>4. Close the door of the FDM 1600.</td>
<td>4. Move the build tray to the storage area.</td>
</tr>
</tbody>
</table>

The conveyor table consists of 22 steel rollers encased in an aluminum $2 \times 2 \times 0.25$ inch ($51 \times 51 \times 6.4$ mm) L-profile frame. The build trays are moved from one area to the next by rolling on the rollers. Each roller has a diameter of 1.9 inches (48 mm) and a length of 13 inches (330 mm). The spacing of the rollers is such that there are always three rollers underneath each build tray at any time. This ensures that the build trays remain horizontal.

Figure 3.7: The conveyor table transports and stores the build trays before and after the build jobs.
In the middle of the conveyor table frame, cutouts have been made to make room for the linkage. The front L-profile is completely cut, and an aluminum u-bracket bolts the two parts of the front beam together.

Fourteen of the rollers are driven by a reverse drive system, while the remaining eight are idle. The idle rollers are mostly positioned along the storage area for completed build jobs. The rollers in this area do not need to be powered since the final destination for the build trays with the completed parts is the storage area at the end of the conveyor table. The only three other idle rollers are located on either side of the loading and unloading area, and at the very start of the conveyor table. These were made idle because the position of the frame cross-members prevents their access to the drive system.

The reverse drive system (Figure 3.8) consists of grooved rollers connected to a drive shaft running perpendicular to the rollers. Rubber o-rings rest in the grooves of the rollers and wrap around the perpendicular drive shaft. The steel drive shaft is 0.75 inches (19 mm) in diameter, and is supported by bronze bushings attached to two cross members of the conveyor table. A flexible rubber coupling connects the drive shaft to a 12 volt DC gearmotor, rated at 12 rpm and a maximum torque of 45 lbs-in (56 N-m). The motor

![Figure 3.8: The conveyor-table drive-train (viewed from below) consists of a reverse drive system, where the rollers are driven by a perpendicular drive shaft. Each driven roller is grooved, and connected to the driveshaft by rubber o-rings.](image-url)

21
itself is attached to the end piece of the conveyor table frame. At a drive-shaft speed of 12 rpm, the build trays move at a speed of 0.6 in/s (15 mm/s).

A 1.5 inch (38 mm) tall plexi-glass fence attached to the aluminum frame ensures build trays remain in correct orientation for loading and do not fall off the conveyor table. The fence is attached to the conveyor table frame by straight brackets and machine screws.

Finally, there are four aluminum feet protruding below the conveyor table frame. At the end of each foot, there is a 6 inch (150 mm) long, 3/8 inch (9.6 mm) diameter threaded rod attached. The rods match a set of holes in the attachment frame, and the elevation of the conveyor table frame relative to the attachment frame can be adjusted and secured by nuts on the threaded rods.

3.3.2.2 The Position Guides

The position guides (Figure 3.9) serve to position the build trays correctly in the loading and unloading area of the conveyor table, and to control the flow of build trays when the conveyor table is running.

Figure 3.9: The left, middle, and right position guides are placed between the rollers on the conveyor table, and control the flow and position of the build trays. The build trays move from right to left.
There are a total of three position guides; the left and middle position guides are positioned on either side of the loading area, and the right position guide is positioned at the end of the storage area for the empty build trays. The left and middle position guides are placed slightly more than a build tray width apart on opposite sides from the middle of the conveyor table. Their purpose is to provide correct positioning and orientation of the build tray in front of the FDM 1600 build chamber, and to provide guidance when the linkage pushes the build tray off the conveyor table and onto the build table of the FDM 1600 modeler. The right position guide ensures that the next empty build tray in line is kept far enough away so it does not interfere with the insertion of the current build tray onto the build table.

The position guides consist of angled aluminum bars that are attached on one end of the conveyor table frame cross-members by revolute joints with bronze bushings. At the other end, the aluminum bar is prevented from twisting sideways by bronze sleeves attached to the conveyor table.

In non-activated mode the position guides protrude up between the rollers, pushed up by coil springs. There is some preload in the spring caused by a constant length steel wire connected to the aluminum bar and the conveyor table. This wire adjusts how far above the rollers the position guides protrude in non-activated mode. When the position guide is retracted, this wire becomes slack.

The top of the position guide protrudes about 0.125 inches (3 mm) above the rollers, to make contact with the side of the build trays. When the position guide is up, the build trays cannot move when the conveyor table is running. In this position, the rollers slip underneath the build tray so the build tray remains stationary.

Each position guide is activated by a separate 12 volt DC box-style pull-solenoid that pulls it down below the rollers. The solenoids are nonlinear with a pulling force that varies from 1 lb (4.4 N) at the start of the pull to 75 lbs (334 N) at the end (when the
position guides are completely retracted beneath the rollers). The solenoids are attached to the conveyor table by brackets that are attached to conveyor table cross-members. A steel wire connects the solenoid pin to the angled aluminum bar.

### 3.3.2.3 The Linkage

The linkage is a straight-line linkage, and it is used to insert and remove the build trays from the FDM 1600 modeler. Straight-line linkages are a convenient alternative to conventional linear actuators in applications with limited space such as this. Linear devices such as lead screws take up space equal to at least twice the length of the usable path in the line of motion, while straight-line linkages usually do not. In this case, the linkage is positioned beneath the conveyor table, and does not increase the footprint of the hardware like a lead screw would.

The CLM uses a straight-line linkage used is called the Chebyshev Type 1, which is named after the Russian engineer who invented it [Riutort96]. Only one point on the coupler link moves in an approximate straight line, and then for only part of the path. The path (Figure 3.10) has the shape of the letter D, lying on its back. The linkage has been sized such that the length of the straight-line segment of the path is approximately 21 inches (530 mm), with a maximum deviation of 0.035 inches (1 mm) from a straight line.

The Chebyshev Type 1 linkage (Figure 3.11) is a fourbar, where the ground link is a structure protruding beneath the conveyor table. The coupler link has been designed with a bend in it to avoid interference with the conveyor table drive shaft and the conveyor table frame. All the joints are revolute with bronze bushings, and the parts are held together by nuts and shoulder bolts.

A one-inch (25 mm), 12 Volt DC electromagnet has been attached to the straight-line point of the coupler link. This permits the electromagnet to grab onto a small steel plate.
on the build tray with a pull of 32 lbs (140 N), when inserting and removing the build tray.

It is important that the electromagnet maintains a constant orientation parallel to the build tray and the conveyor table. A failure to maintain such an orientation will cause the pull on the build tray to approach zero, which would prevent the removal of the build tray from the FDM 1600 build chamber. This would be the case if the electromagnet was bolted to the coupler link, as its orientation would change from 37 degrees at the start of the motion and 95 degrees at the end. A solution to this problem is to attach the electromagnet to the coupler link via a revolute joint, and then use a parallel wire linkage to control the angular orientation. This parallel linkage (Figure 3.12) is effectively a second fourbar linkage that is offset from the original, and which results in two straight-line points that are offset from each other; one for each linkage. These two straight-line points allow both constant angular orientation and linear motion to be achieved.

Figure 3.10: The path of the Chevyshev Type 1 straight-line linkage resembles the letter “D” rotated 90 degrees counter-clockwise. Only the bottom portion of the path is a straight line and used for inserting and removing build trays into and from the FDM 1600 modeler.
The parallel linkage consists of a steelon wire wrapped around one-inch (25 mm) diameter pulleys on the electromagnet and coupler link, the joint between the rocker and coupler links, and then attached to a grounded pulley. Figure 3.13 shows a schematic of the parallel linkage, and direction vectors at each joint and for the electromagnet.

Figure 3.11: The ground link of the Chebyshev Type 1 linkage is a structure connected to the conveyor table frame. A bend was designed on the coupler link to avoid interference with the conveyor table frame and drive system.
Figure 3.12: A wire running along the coupler and rocker links make up a parallel linkage, which controls the angular orientation of the electromagnet.

shows that the rotation of the direction vector of the electromagnet is independent of link angles, and 0 degrees relative to ground. This means that the electromagnet is always moving along a horizontal line. On the actual linkage, a small steel angle is added at the joint between the coupler and the rocker links to make sure the wire is in constant contact with the joint, which acts as a pulley, in all linkage positions (Figure 3.12). The pulleys
on the coupler link ensure that the wire does not come in contact with the conveyor table drive shaft or frame, which would result in changing the angle of the electromagnet. At the end of the coupler link closest to the electromagnet, a sleeve covers the steelon wire so it does not catch on the conveyor table.

The linkage is driven by a 12 volt DC gearmotor running at 4.5 rpm with a maximum torque of 44 lb-in (5.0 N-m) connected to the crank link with a steel coupling. The non-linear nature of the linkage results in a variation of force output in the direction of motion at the straight-line point from about 9 lbs (40 N) at the start of the load to about 8.75 lbs (39 N) at the end.

Figure 3.13: The schematic of the parallel linkage shows direction vectors at each joint, including the direction vector of the electromagnet.
3.3.2.4 The New Door

In order to achieve full automation of the build job changeover procedure, the CLM must have the ability to open and close the door of the FDM 1600 modeler. A new powered door (Figure 3.14) replaces the original door of the FDM 1600 modeler. The new door is opened and closed by rotating in the plane of the front side of the FDM 1600 modeler.

![Diagram of the new door](image)

**Figure 3.14:** The new door is connected to the conveyor table, and it rotates about an axis parallel to the rollers.
For comparison, the original door swings outwards (Figure 3.15). Thus the closed position remains the same as the original door, but the new door achieves the open position by turning 90 degrees about an axis perpendicular to the door glass.

The new door is an assembly consisting of the door itself, a drive shaft, a motor, two door stoppers, a counterweight, and a weather-strip frame. This section will describe these components in detail.

The new door is connected to the conveyor table frame, unlike the original door which is connected with hinges to the front of the FDM 1600 modeler. Thus, the door changes its elevation relative to the FDM 1600 modeler door opening when the elevation of the conveyor table is adjusted. To ensure the door always covers the entire FDM 1600 modeler door opening over a limited elevation range, the dimensions of the new door are slightly larger than the original door. The new door is 1.5 inches (38 mm) taller and

![Figure 3.15: The original door (top) rotates outwards, while the new door (bottom) rotates about an axis perpendicular to the door glass.](image-url)
wider than the original door, which allows the elevation of the conveyor table to be adjusted 0.75 inch (19 mm) up or down.

Both the original door and the new door are made out of a 0.625 inches (16 mm) thick polycarbonate sheet. Polycarbonate provides good stiffness and thermal properties, but still the polycarbonate has a tendency to deform at the FDM 1600 build chamber's operating temperature. To decrease deformation of the polycarbonate sheet, aluminum side-rails have been added to provide additional stiffness. The side-rails were by experiment shown to reduce the maximum deformation, which occurs at the top of the door, from 0.5 inches (13 mm) to 0.125 inches (3 mm).

The bottom of the door consists of a machined aluminum bracket that is attached to the polycarbonate sheet with machine screws. The purpose of this bracket is to provide a sturdy connection between the polycarbonate sheet and the door shaft.

A set-screw ensures the connection between the bracket and the door shaft. The position of the door can be changed by sliding the door along the door shaft before securing the set-screw. Thus the distance between the front surface of the FDM 1600 and the door may be adjusted up to 0.5 inches (13 mm). This ability to slide the door away from its operational position, facilitates the assembly and disassembly of the CLM.

The remaining parts of the door assembly includes a door shaft, a motor, a counterweight, and a door shaft bushing, and they are hidden beneath the conveyor table. Two aluminum plates are connected to conveyor table frame cross-members, and these are used to mount the 12 volt DC gearmotor powering the door and the door-shaft bronze bushing. The gearmotor is rated at 3.4 rpm and 44 lb-in (55 N-m) of torque. A steel coupling is used to connect the gearmotor with the 0.5 inches (13 mm) diameter door shaft. The door shaft bronze bushing is used to reduce the overhung load on the motor shaft, which is caused by the weight of the bracket and door glass.
The door shaft is connected to the bottom right corner of the bracket. This means that the center of gravity of the door is not directly above the door shaft in neither the closed nor the open position. Thus the weight of the door glass and the bracket creates a moment about the door shaft in both the open and closed positions (Figure 3.16). To balance this moment, a counterweight was added to the door shaft. The counterweight creates a moment in the opposite direction of the moment caused by the door glass and the bracket.

The counterweight consists of a steel bar moment-arm attached to the door shaft between the gearmotor and the bushing with a set-screw. At the end of the moment arm, a 1 inch (25 mm) diameter shaft loaded with 12.5 lbs (5.7 kg) of standard barbells, is press fit onto the steel bar.

Flats have been machined on the door shaft to improve the connections to the shaft. This includes one at each end of the shaft, and one in the center where the counter weight arm is attached.

Moment caused by the door glass and bracket:
4.75 lbs (2.2 kg) × 8 in (200 mm)
= 38 lb-in (4.32 N-m)

Moment caused by counterweight:
12.5 lbs (5.7 kg) × 3 in (76 mm)
= 37.5 lb-in (4.25 N-m)

Figure 3.16: The counterweight balances the door assembly by creating a counter moment about the door shaft.
Two steel door stoppers (Figure 3.17) are attached to the rear of the conveyor table frame (Figure 3.6). These door stoppers prevent the door from sagging or being pushed beyond the open and closed positions. Each door stop is shaped like an L and is made from a strip of steel.

There is a 0.5 inch (13 mm) lip on the FDM 1600 modeler chassis along the outer edge of its front surface. Thus, the door must be at least 0.5 inches (13 mm) from the front surface of the FDM 1600 modeler to clear the lip when opening. This causes a significant air gap between the new door and the FDM 1600 modeler when the door is in its closed position. Such an air gap would cause the temperature inside the build chamber to drop, which could impact the quality of the parts built. A rectangular weather-strip wood-frame is therefore used to seal the gap between the new door and the FDM 1600. The weather-strip frame avoids the need to permanently modify the FDM 1600 modeler by applying weather-stripping directly on its front surface. Thus, the FDM 1600 modeler can easily be configured back to the original setup by removing the weather-strip frame and installing the original door. There is weather-stripping on both sides of the frame. A thin foam strip on the rear seals between the frame and the FDM 1600 modeler, where as a

Figure 3.17: "L" shaped doorstoppers attached to the conveyor table frame, prevent the door from moving beyond its intended range of motion.
tubular rubber strip on the outside seals between the frame and the door. The weatherstrip frame is secured to the FDM 1600 door opening with 4-inch (100 mm) machine screws in each inside corner. These screws tighten against the inside of the FDM 1600 modeler door opening with washers and nuts.

### 3.3.2.5 The New Build Trays

It was necessary to redesign the build trays to facilitate their insertion and removal into and from the FDM 1600 modeler (Figure 3.18). The new build trays were kept as similar to the original ones as possible to eliminate the need for modifications of the FDM 1600 modeler itself. Hence, there are only three changes from the original build tray design. First, the handle used by the operator to pull the build tray out of the FDM 1600 build chamber has been replaced with a steel plate; second, the build trays have been elongated; and third, some exterior edges have been beveled. The new build trays use the original foam boards, which attach in the same manner as on the original build trays, and they use the same ball plunger setup to secure the build trays to the build table.

![Figure 3.18: The new build trays are longer and have been beveled to facilitate loading. Additionally, the handle has been replaced with a steel plate that connects to the electromagnet on the linkage.](image-url)
To enable the electromagnet to grab onto the build tray, the handle was replaced with a steel plate. The steel plate is attached identically to the original handle with machine screws. However, the screw holes in the steel plate are oversized, and a set of small foam inserts have been placed around the screws between the steel plate and the build tray. This allows the steel plate a small degree of freedom to move relative to the build tray, which allows the electromagnet to make proper contact with the steel plate even if the magnet does not approach the steel plate at a perfect angle.

The build trays were elongated by 1.25 inches (32 mm) (Figure 3.18: 2A, 2B) and their corners were beveled (Figure 3.18: 3A, 3C) to ensure that they could successfully navigate the 5-inch (125 mm) gap between the conveyor table and the build table inside the FDM 1600 build chamber. The trays were further beveled (Figure 3.18: 3B) to ensure reliable insertion into the fixture on the build table in the FDM 1600 build chamber. With this design, the build tray will successfully operate even if it is 0.25 inches (6 mm) off the center load position.

3.3.2.6 The Attachment Frame
A frame was designed to attach and position the conveyor table relative to the FDM 1600 modeler. The attachment frame acts as a loaded beam (Figure 3.19) where the weight of the CLM is countered by the weight of the FDM 1600 modeler.

The attachment frame (Figure 3.20) is made from one-inch (25 mm) steel square tubing and a 3/8×1×24 inch (25×10×610 mm) grooved steel bar. An FEA analysis of this attachment frame by SDRC I-DEAS showed a maximum deflection of 0.04 inches (1 mm) when loaded with 200 lbs (890 N). A protruding structural beam on the bottom of the FDM 1600 is matched with the groove in the frame and provides correct position and angular orientation of the attachment frame relative to the FDM 1600 modeler. The attachment frame is still free to move sideways relative to the FDM 1600 modeler, however, bolts protruding from the side of the attachment frame secure side ways positioning by tightening against the feet of the FDM 1600 modeler. This sideways
adjustment by the bolts is limited to 0.25 inches (6 mm). A pair of leveling glides supports the attachment frame against the surface the FDM 1600 modeler sits on.

The connection between the attachment frame and the conveyor table is through 3/8 inch (9.6 mm) threaded rods protruding from the conveyor table feet and into holes in the attachment frame secured with nuts. This allows for the elevation of the CLM to be adjusted relative to the FDM 1600 modeler by turning the nuts (Figure 3.6, Section 3.3.2.1).

### 3.3.3 The CLM Control System

The CLM control system (Figure 3.21) brings together the hardware performing the physical tasks and the software describing the sequence of tasks. The control system itself can only perform basic tasks, such as opening the door, and simple sequences of such basic tasks. The actual automation and coordination of the build job changeovers is left to the workstation software.

Even the simplest task, such as opening the door, requires use and synchronization of several components of the control system. The control system must receive the instruction to perform the task, know which components to use, and know the sequence
Components used in the control system include a microprocessor, sensors, actuator drivers, a serial port, and a keypad. The control system components, except the sensors and the manual door override, are contained on a circuit board housed inside an enclosure attached beneath the start of the conveyor table.

The center of the control system is the microprocessor to which all the other components are directly or indirectly connected. The microprocessor is programmed with the basic procedures, such as opening the door, inserting the linkage, as well as the complete build tray loading and unloading procedures. A keypad and a serial port allow the operator and the computer, respectively, to instruct the microprocessor to perform a task. The microprocessor controls the operation of the all the gearmotors, solenoids, and the electromagnet via h-bridge motor drivers and relays. Feedback is provided by photo-sensors which monitor the position of the hardware, including the linkage, the door, and the build tray positions. A second source of feedback comes from the h-bridge motor drivers, which allow the microprocessor to monitor the amount of current drawn by the gearmotors. These sensors and electrical actuators are connected to the control system enclosure through a wire harness. The control system uses a 5 volt signal internally, as well as 12 volt which it supplies to the electrical actuators.
The following sections will describe the components of the control system. These components include the power supply, the microprocessor, the sensors, the actuator drivers, the keypad, the serial port, the wire harness, and the manual override.

Figure 3.21: Control system schematic. The lightweight arrows represent 5 volt signals, while the heavy weight arrows represent 12 volt signals.
3.3.3.1 The Power Supply
The CLM is powered by an external 12 volt DC linear power-supply with a power switch mounted on the front panel of the control system enclosure. A regulator on the circuit board supplies a 5 volt signal from the 12 volt external linear power supply. The 5 volt signal is used by the control system internally, while the 12 volt supply is used by the electrical actuators.

3.3.3.2 The Microprocessor
At the heart of the control system is a Microchip PIC17C44 microprocessor. This microprocessor was chosen based on the large number of input and output ports it has available. The microprocessor is attached to the circuit board with a zero insertion force socket, unlike the remaining components, which are soldered to the circuit boards. This allows for safe and quick removal and re-programming of the microprocessor in the software development stage. The microprocessor is programmed in assembly language, which is written on a PC and then uploaded to the microprocessor. This program is described in detail in the CLM software section.

3.3.3.3 The Sensors
Sensors are used to provide the microprocessor with information about the position of the hardware. The CLM uses photo proximity sensors, which means that they detect the presence of an object using light. These sensors consist of both a transmitting and a receiving diode. Each sensor uses two simple circuits, and both circuits use a diode in series with a resistor. The transmitting circuit supplies a 5 volt signal from the microprocessor, which enables the diode to transmit infrared light. The intensity of the light can thus be adjusted by changing its resistor value. The receiving circuit on the other hand generates a 5 volt signal when enough infrared light hits the diode, and the sensitivity of the receiving diode can be adjusted by changing its resistor value. With the current resistor values, a metallic object placed within half an inch (13 mm) of the sensor, will reflect enough light from the transmitting diode to trigger the receiving circuit.
Six sensors are used as limit switches and for monitoring the position of the build trays. Their positions are shown in Figures 3.22 and 3.23. These sensors are all positioned using attachments manufactured by the FDM 1600 modeler. The door and table sensor attachments (Figure 3.22) are mounted to the conveyor table, while the linkage sensor attachment (Figure 3.23) is mounted on the linkage gearmotor.

Both the door motor and the linkage motor use two sensors each as limit switches for the start and end positions of their respective ranges of motion. The two remaining sensors are placed between the rollers on the conveyor table 0.25 inches (6 mm) below the top of the rollers to monitor the position of the build trays. The first conveyor table sensor is used to detect the presence of a build tray in the loading area, while the second conveyor table sensor is placed at the start of the storage area for finished build jobs to monitor the available storage space.

Figure 3.22: The door and table sensor attachments are made by the FDM 1600 modeler and attach to the conveyor table frame.
3.3.3.4 The Actuator Drivers

The actuator drivers enable the microprocessor to control the electrical actuators in the system. Three relays and three h-bridge motor drivers make up the hardware drivers, and these are permanently soldered to a circuit board inside the control system enclosure.

The relays are used to switch on and off three solenoids and an electromagnet. One relay drives the left and right position guides in tandem; the second drives the middle position guide; and the third drives the electromagnet. Each relay is connected to the 12 volt supply, a signal from the microprocessor, and an electric actuator (solenoid or electromagnet). When the relay receives a 5 volt signal from the microprocessor it connects the 12 volt supply with the electrical actuator, thereby energizing it.

The three h-bridge motor drivers each control a gearmotor. Like the relays, the h-bridge motor drivers are connected to the 12 volt supply and an electric actuator (i.e., a
gearmotor). However, each h-bridge motor driver needs two signals from the microprocessor. The first signal tells the h-bridge what fraction of the available 12 volt supply to pass on to the gearmotor (though all the motors in this system operate at full power). The second signal tells the h-bridge motor driver whether or not to switch the leads to the gearmotor, and thereby controlling the direction of rotation of the motor shaft. The h-bridge motor driver also monitors the amount of current drawn by the gearmotor. Since the amount of current drawn is proportional to the torque of the gearmotor, the microprocessor can thus detect jamming. This current sense signal is connected to the microprocessor through a potentiometer, which adjusts the relative level of the signal passed on to the microprocessor. The torque value at which the microprocessor detects a current sense signal may therefore be adjusted. Only the linkage and door motors utilize the current sense feature, since jamming is not an issue for the conveyor table drive shaft.

3.3.3.5 The Keypad
The keypad allows the operator to send instructions to the microprocessor. Through the keypad all the motors, the solenoids, and the electromagnet can be controlled. The keypad is composed of twelve numerical buttons, and it is mounted on the front panel of the control system enclosure. When a button is pressed, the action is detected by the microprocessor, which then executes the procedure assigned to that button.

3.3.3.6 The Serial Port
The serial port allows the computer workstation to communicate with the microprocessor. The serial port is composed of the physical serial port positioned on the rear panel of the control enclosure and a serial port transceiver on the circuit board. The serial port transceiver is used to enhance the signal, and it is connected directly to the microprocessor. The serial port is discussed in more detail in Section 3.3.4.
3.3.3.7 The Wire Harness

The wire harness connects the electrical actuators and the sensors to the components inside the control system enclosure. There are two types of wires in the wire harness: sensor wires and actuator wires. The sensor wires use 4-prong wires, composed of a 5 volt input signal, an output signal, and ground for both. The electrical actuators wires are dual prong, providing 12 volt and ground. Connectors at both ends of the wire harness mate with connectors to the sensors and actuators, and to the rear panel of the control system enclosure, respectively. The connectors are all numbered to facilitate assembly.

3.3.3.8 The Manual Door Override

The manual door override (Figure 3.24) is used to open the door without using the microprocessor. The manual door override consists of two separate switches: the main switch and the direction switch. The main switch connects the door motor to the h-bridge motor driver or to the direction switch. During normal operation the main switch will be connect the door motor to the h-bridge. However, if the control system fails, the door can still be opened by setting the main switch to the direction switch position. The direction

![Image of the manual door override](image)

**Figure 3.24:** The manual door override allows the operator to open and close the door without using the microprocessor.
switch is connected directly to the 12 volt DC power supply, and connects the door motor to the power supply to open the door and reverses the leads to close the door. When opening and closing the door with the manual override, then neither the limit switches nor the current sense are operational.

### 3.3.4 Communication

Robust communication between the FDM 1600 modeler and the CLM is important in order to achieve full automation. The computer serves as the central communication hub connecting these subsystems together via RS-232 serial lines (Figure 3.25): The communication between the computer and the FDM 1600 is unidirectional at 9600 baud using XON/XOFF handshake protocol, while the communication between the computer and the CLM is at 9600 baud with no handshaking. In both cases the instructions passed to the subsystems consists of ASCII characters. The instruction set for the FDM 1600 is given in the Stratasys Modeling Language (SML)[Stratasys91], while the instruction set and error messages from the CLM are listed in Table 3.4.

### 3.3.5 CLM Software

The purpose of the CLM software is to control the automation process. There are two separate software programs in the CLM system: the microprocessor software and the workstation software. These are two separate software programs, written in different computer languages, that communicate with each other.

![Communication Diagram for the CLM System.](image)
The microprocessor software is stored in the memory of the microprocessors in the control system and is written in assembly language. Its purpose is to control all the tasks.
needed to load and unload a build tray. There is no connection between this software program and the FDM 1600 modeler, and it has no knowledge of the status of the FDM 1600 modeler.

The workstation software is stored on the workstation hard disk and is written in C++. Its purpose is to control the overall automation process. The software program must incorporate a print-queue (without it there would be no reason to automate the build job changeover process), have the ability to control the FDM 1600 modeler building procedure, have the ability to instruct the CLM control system to perform the tasks, and to synchronize the operation of the FDM 1600 modeler and the CLM. The following two subsections will describe these two software codes in more detail.

3.3.5.1 Microprocessor Software

The microprocessor controls the electrical actuators which power the mechanical devices, which in turn perform the physical tasks involved in the loading and unloading the FDM 1600 modeler. The microprocessor operates by processing input from the serial port, keypad, sensors and the h-bridge motor drivers. Based on these inputs, the microprocessor executes hard-coded instructions, which include driving the actuators, executing delays, and transmitting serial port output.

The microprocessor software (Figure 3.26) is event-driven with a subroutine for every task that are executed on demand. These subroutines include: stop, open door, close door, insert linkage, withdraw linkage, run conveyor table, toggle left and right position guides, toggle middle position guide, toggle electromagnet, load, and unload. The load and unload subroutines are special in that they include the complete build tray load and unload procedures respectively, unlike the other subroutines which each only performs a single task.

Feedback to the subroutines is provided by the current-sense feature on the h-bridge motor drivers for the linkage motor and door motor, and by the photo sensors which are
used as limit switches for the linkage and the door and to detect the position of the build trays.

Figure 3.26: Microprocessor software flowchart. The solid lines represent the flow through the program, while the stippled lines represent the feedback to the functions.
There are two modes of operation: manual and automatic. In manual mode, an operator executes the subroutines by pushing the buttons on the keypad. Every subroutine is assigned to its own button on the keypad (Tables 3.5 and 3.6). In automatic mode, the CLM is synchronized with the FDM 1600 modeler via the computer workstation. However, in this mode, only the load and unload subroutines are available. These instructions are received from the workstation via the serial port. At the completion of these subroutines, the CLM sends a message back to the workstation software to report whether the task was successful or not.

Table 3.5: Manual mode subroutines.

<table>
<thead>
<tr>
<th>The following manual mode subroutines can only be executed through the keypad, and they perform the basic tasks related to each actuator.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stop (Keypad button 1)</strong></td>
</tr>
<tr>
<td>The <em>stop</em> subroutine turns off all the motors.</td>
</tr>
<tr>
<td><strong>Open Door (Keypad button 3).</strong></td>
</tr>
<tr>
<td>The <em>open door</em> subroutine opens the door to the FDM build chamber. The subroutine first checks the open-door limit-switch sensor to see if the door is already in the open position, in which case nothing more happens. Then the door motor is turned on in the clockwise direction. After the motor has been started, the subroutine enters a loop to check for a current-sense or a limit switch signal. In the event of either, the motor is turned off. A current-sense signal indicates that the door jammed, while the limit-switch signal indicates that the door reached its open position.</td>
</tr>
<tr>
<td><strong>Close Door (Keypad button 6)</strong></td>
</tr>
<tr>
<td>The <em>close door</em> subroutine closes the door to the FDM build chamber. The subroutine first checks the close-door limit-switch sensor to see if the door is already in the desired position, in which case nothing more happens. Then the door motor is turned on in the counter-clockwise direction. After the motor has been started, the subroutine enters a</td>
</tr>
</tbody>
</table>
loop to check for a current-sense or a limit switch signal. In the event of either, the motor is turned off. A current-sense signal indicates that the door jammed, while the limit-switch signal indicates that the door reached its closed position.

**Insert Linkage (Keypad button 5)**

The *insert linkage* subroutine inserts the linkage into FDM build chamber. The subroutine first checks the linkage-end-position limit-switch sensor to see if the linkage is already in the target position, in which case nothing more happens. Then the linkage motor is turned on in the clockwise direction. After the motor has been started, the routine loops to check for a current-sense or a limit-switch signal. In the event of either, the motor is turned off. A current-sense signal indicates that the linkage jammed, while the limit-switch signal indicates that the linkage reached the target position.

**Withdraw Linkage (Keypad button 2)**

The *withdraw linkage* subroutine withdraws the linkage from the FDM build chamber. The subroutine first checks the linkage-start-position limit-switch sensor to see if the linkage is already in the target position, in which case nothing more happens. Then the linkage motor is turned on in the counter-clockwise direction. After the motor has been started, the routine loops to check for a current-sense or a limit-switch signal. In the event of either, the motor is turned off. A current-sense signal indicates that the linkage jammed, while the limit-switch signal indicates that the linkage reached the target position.

**Run Conveyor Table (Keypad button 4)**

The *run conveyor table* subroutine turns on the conveyor table motor, which makes the rollers rotate and the build trays move down the conveyor table. The *stop* subroutine must be executed to turn off the conveyor table motor.

**Toggle Left and Right Position Guides (Keypad button 9)**

The *toggle left and right position guides* subroutine turns the left and right solenoids on
and off in tandem, thus retracting and releasing the left and right position guides.

**Toggle Middle Position Guide (Keypad button 7)**

The *toggle middle position guide* subroutine turns the middle solenoid on and off, thus retracting and releasing the middle position guide.

**Toggle Electromagnet (Keypad button 8)**

The *toggle electromagnet* subroutine toggles the electromagnet on and off.

---

**Table 3.6: Automatic mode subroutines.**

The automatic mode subroutines can be executed either through the keypad or through the serial port. The *load* and *unload* subroutines are composite sequences of manual mode subroutines. If an error such as a current-sense signal occurs, then these automatic mode subroutines stop and if the subroutine was started via the serial port, a message is sent to the computer workstation. To stop the automatic mode subroutines the power must be turned off.

**Load (keypad button * or ASCII character “l” via the serial line)**

This subroutine moves a build tray from the storage area at the start of the conveyor table onto the FDM build table. The following procedure describes the operation:

1. Reset the linkage by retracting it to the start position (check limit-switches and current-sense).
2. Retract the position guides to allow the free flow of build trays.
3. Start the conveyor table. Stop and terminate the subroutine after 60 seconds if no build tray has been detected in the load area by the load-area sensor (which would indicate that there are no empty build trays available).
4. When the load-area sensor triggers, release the right and left position guides to position the current empty build tray for loading and to keep the next empty build tray...
at a safe distance. After a ten second delay, the middle position guide is released to restrict the build tray from moving in either direction along the length of the conveyor table. The build tray is now only able to move towards the FDM 1600 modeler.

5. Open the door (check limit-switches and current-sense).
6. Turn on the electromagnet.
7. Insert the linkage to push the build tray onto the build table (check limit-switches and current-sense).
8. Turn off the electromagnet.
9. Withdraw the linkage to the start position (check limit-switches and current-sense).
10. Close the door (check limit-switches and current-sense).
11. If the subroutine was started by the workstation, send a confirmation message.

Unload (Keypad button # or ASCII character “u” via the serial line)
This subroutine removes a build tray from the FDM build table, and stores it at the end of the conveyor table. The following procedure describes this operation:

1. Run the conveyor table for 15 seconds to push the all build trays located in the storage area for finished jobs to the end of the conveyor table.
2. Check the load-area sensor to make sure there are no obstructions in the unload area. If the load-area sensor is triggered, then terminate the subroutine.
3. Check the table-storage sensor at the start of the storage area for finished jobs to make sure there is storage space available. If there is no storage space available, then terminate the subroutine.
4. Retract all the position guides to allow the free flow of build trays.
5. Open the door (check limit-switches and current sense).
6. Insert the linkage (check limit-switches and current sense).
7. Turn on the electromagnet.
8. Withdraw the linkage (check limit-switches and current-sense) to the start position to remove the build tray with the finished part from the FDM machine. Check the load area sensor to make sure the build tray was removed. If the load area sensor did not
trigger, then terminate the subroutine.

9. Turn off the electromagnet.
10. Close the door (check limit switches and current sense).
11. Run the conveyor table for 15 seconds to move the build tray with the finished part from the load area to the storage area for finished jobs. The middle position guide is released after 1 second to stop the flow of empty build trays.
12. Release the left and right position guides.
13. If the subroutine was started by the workstation, send a confirmation message.

3.3.5.2 Workstation Software

The workstation software (Figure 3.27) controls the overall automation by synchronizing the FDM 1600 modeler and the CLM, and by managing a print-queue. The software is called fdmoper5 and is written in C++ for an SGI Octane UNIX workstation running the IRIX 6.5.6m operating system. fdmoper5 replaces the ssend program provided by Stratasys. It sends instructions to the FDM 1600 modeler and instructs the CLM to load and unload the build trays.

fdmoper5 starts by extracting an .SML filename from the print-queue. The format of this file is then verified to be of a recognized version of .SML (version 6.0). Once this has been verified, the serial ports are opened and the first few lines of the .SML file are sent to the FDM 1600 modeler. After this initiation sequence, the CLM is instructed to load a build tray onto the build table. The program waits for a confirmation message from the CLM and then sends the remainder of the .SML file to the FDM 1600 modeler. At the end of this build job, the CLM is instructed to unload the build tray. Once the associated confirmation message from the CLM has been received, the program restarts the process and extracts the next filename from the print-queue. The program continues to run until there are no more files left in the print-queue, or until an error is reported by the CLM. While fdmoper5 is running, the operator is continuously updated on the status of the operations on the workstation screen. If the program terminates early, an error message explains the reason.
Figure 3.27: Workstation software flowchart. The flow is along the arrows without annotation unless the criterion in the annotation is satisfied.
The remainder of this section describes the external files used and the software functions in detail.

**External Files Used**
The workstation software uses three external ASCII text files: the print-queue, a log file, and a temporary data file. The print-queue file contains the .SML filenames to be processed, one filename per line in the order they are to be processed. This print-queue must be generated (if necessary by manual editing) before the program is started. The log file keeps track of the .SML files as they are processed, the times at which the load and unload routines are initiated and completed, and of any errors that occur during loading and unloading. The temporary data file is used to store temporary information during the updating of the print-queue after a file name has been extracted.

**Workstation Software Functions**
Figure 3.27 shows the program flow. At the start of each function except main, a message stating the status of the program is printed to the workstation screen. If an error occurs in one of the functions, a message explaining the error is printed to the workstation screen.

**main**
The *main* function contains the calls to the other functions in order.

**read_printque**
The *read_printque* function opens the print-queue file and extracts the first entry. If the print-queue is non-existent or cannot be opened, the program terminates immediately. Upon extracting the first filename, the remainder of the print-queue is re-written as the new print-queue. After re-writing the print-queue, the file is closed, thus enabling the operator to edit the print-queue while the program continues.
open_sml_file
The *open_sml_file* function opens the file which name was extracted in the *read_printque* function. If the file is non-existent or cannot be opened, then the program returns to the *read_printque* function to extract the next filename.

verify_sml_file
In the *verify_sml_file* function, the .SML file is examined to make sure it conforms to the QuickSlice 6.0 format. To avoid sending bad, and potentially damaging commands to the FDM 1600 modeler, it is important that only .SML files created by QuickSlice 6.0 are accepted.

Two separate file format checks are performed on the .SML file. The first check counts the number of PS commands in the .SML file. If the number of PS commands is not two, which is the number used in Quickslice 6.0 .SML files, then the file is discarded and the program returns to the *read_printque* function to extract the next filename. Check number two compares a sequence of ten commands at the start of the .SML file. If this sequence differs from the standard Quickslice 6.0 sequence, then the file is discarded, and the program returns to the *read_printque* function to extract the next filename. In addition to checking the format of the .SML file, the height of the build job is also calculated. Since the conveyor table elevation is above the lowest possible build table position, a build job ending below the conveyor table level cannot be removed without jamming and/or damaging the FDM part. Thus, build jobs ending below the unload level are not allowed. If the build job is too tall (6.5 inches (170 mm) maximum), the file is discarded and the program returns to the *read_printque* function to extract the next filename.

open_serialport1
This function opens serial port one, which is connected to the FDM 1600 modeler. It is assumed that the correct settings are set by default in the workstation configuration. The default settings for serial port 1 should be 8 bit, 1 stop bit, 9600 baud, and XON/XOFF
handshake protocol. If the function is unsuccessful in opening the serial port, then the program terminates immediately, since the automation process cannot work without communication with the FDM 1600 modeler.

**open_serialport2**
This function opens serial port two, which is connected to the CLM. The settings for serial port two differs from the default settings, so they have to be changed. To change the settings, the function calls the function *set_baud_rate*. Finally, a dummy character is transmitted in order to initialize the serial port. If unable to open the serial port, the program terminates immediately, since the automation process cannot work without communication with the CLM.

**Set_baud_rate**
This function changes the settings for serial port two. Serial port two does not use a handshake protocol, and it is set to 8 bit, 1 stop bit, and 9600 baud.

**run_build_job**
The function *run_build_job* loads the build trays into the FDM 1600 modeler; reads the .SML file, processes it, and passes it onto the FDM 1600 modeler; before unloading the build trays. The processing of the .SML file consists of removing all comments and pause (PS) commands, and setting the relative origin of the build job to a constant position.

In an original .SML file, the operator is expected to manually navigate the extrusion head to the desired relative origin of the build job. With the CLM, this position is hard-coded via additional .SML instructions inserted into the beginning standard sequence of the .SML file as it is passed onto the FDM 1600 modeler. This position is the front-left corner of the foam pad, and slightly into the foam; the exact same position that an operator would typically choose when using a clean new foam pad.
The loading and unloading of the FDM 1600 modeler takes place while the passing on of .SML code to the FDM 1600 modeler is suspended: After the origin has been set, run_build_job calls the load function to insert a build tray into the FDM 1600 build table. Once the loading is complete, the remaining lines from the .SML file is passed on to the FDM 1600 modeler. When the build job is done, marked by the end of the .SML file, a delay is executed in order process any remaining instructions in the serial port buffers and the unload function is called.

**Load**
This function controls the loading of build trays. First, the time, date and name of the .SML file is written to the log file. Next, the build table is moved to the loading level, which has been hard-coded into the program (2.0 inches (54 mm) above bottom of the build chamber). A delay is then executed to allow the build table time to reach the load level. After the delay, a one-character command, consisting of the ASCII character ‘l’, is sent to the CLM to execute the load routine stored in the microprocessor. Finally, the verify_load function is called.

**Verify_load**
This function waits for a message from the CLM and evaluates the message. When the loading is completed, or if an error occurred, the CLM sends a one-character reply. If an error is reported, the program will terminate. The possible error messages are listed in Table 3.7. Finally, the status of the load, time, and date is written to the log file. The status is also printed to the workstation screen.

**Unload**
This function controls the unloading of build trays. First, the time and date is written to the log file. Next, the build table is moved to the unloading level, which has been hard coded in the program (2.0 inches (54 mm) above bottom of the build chamber). A delay is then executed to allow the build table time to reach the unload level. After the delay, a one-character command, consisting of the ASCII character ‘u’, is sent to the CLM to
execute the unload routine stored in the microprocessor. Finally, the `verify_unload` function is called.

**Verify_unload**
This function waits for a message from the CLM and evaluates the message. When the loading is completed, or if an error occurred, the CLM sends a one-character reply. If an error is reported, the program will terminate. The possible error messages are listed in Table 3.8. Finally, the status of the load, time, and date is written to the log file. The status is also printed to the workstation screen.

**close_all_files**
In the `close_all_files` function the function `reset_baud_rate` is called, and then all the external files and serial ports are closed.

<p>| Table 3.7: Error messages for the loading process. |</p>
<table>
<thead>
<tr>
<th>Message</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
<td>The loading completed successfully.</td>
</tr>
<tr>
<td>n</td>
<td>No available build trays.</td>
</tr>
<tr>
<td>p</td>
<td>The linkage jammed.</td>
</tr>
<tr>
<td>d</td>
<td>The door jammed.</td>
</tr>
</tbody>
</table>

<p>| Table 3.8: Error messages for the unload process. |</p>
<table>
<thead>
<tr>
<th>Message</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
<td>The unload completed successfully.</td>
</tr>
<tr>
<td>p</td>
<td>The linkage jammed.</td>
</tr>
<tr>
<td>d</td>
<td>The door jammed.</td>
</tr>
<tr>
<td>o</td>
<td>Could not remove build tray from the build table.</td>
</tr>
<tr>
<td>f</td>
<td>No storage space available.</td>
</tr>
<tr>
<td>i</td>
<td>The unload area on the conveyor table is obstructed.</td>
</tr>
</tbody>
</table>
Reset baud rate
This function resets serial port two back to the default settings.

3.3.6 Operating the CLM System

The CLM system has three operating modes: manual mode, automatic mode, and emergency mode. During normal operation, the system is in automatic mode and completely controlled by the computer workstation. Manual mode is used for setup and resetting the system after an error occurs. Manual mode allows the operator to control each actuator in the CLM system independently, as well as running the load and unload procedures without using the computer workstation. Finally, there is the emergency mode, which allows the operator to open and close the door to the FDM build chamber even if the control system malfunctions.

Parts may be built in any of the three operating modes; however, only the automatic mode will provide continuous manufacturing with automated loading and unloading of build trays. In manual or emergency mode, parts can be built by using the procedure for building single build jobs with the original FDM 1600 system (Section 3.2.3, Figure 3.4). The only functions the CLM will provide in these modes, is to open and close the door to the FDM build chamber. The following will describe these modes in more detail.

3.3.6.1 Manual Mode
The manual mode allows the operator to control the motors, solenoids and the electromagnet using the buttons on the keypad. Each button executes one of the subroutines stored in the microprocessor (Table 3.9). There is in general no need to manually operate the system, other than for: opening and closing the door when running single build jobs without using the CLM; resetting the system after an error in one of the automation routines; or checking the hardware during installation.
3.3.6.2 Emergency Mode

The emergency mode allows the operator to open and close the door of the FDM build chamber even if the control system malfunctions. To operate the CLM in emergency mode, the main switch on the manual door override must be set to “manual”. The door can then be opened and closed by using the direction switch. The CLM should only be operated in emergency mode as a last resort since neither the limit switches nor the current-sense features will then be operational to prevent the door motor from operating once the target door position has been reached or after the door otherwise jams.

3.3.6.3 Automatic Mode

In automatic mode, the automation process is controlled by the workstation software. For normal operation of the CLM system only the automatic mode should be used. The CLM system can perform 2.5 build job changeovers without operator intervention. This means that 3 consecutive build jobs may be performed before intervention from an operator is

---

**Table 3.9: Keypad button assignments.**

<table>
<thead>
<tr>
<th>Number</th>
<th>Button Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stop</td>
</tr>
<tr>
<td>2</td>
<td>Withdraw Linkage</td>
</tr>
<tr>
<td>3</td>
<td>Open Door</td>
</tr>
<tr>
<td>4</td>
<td>Start Conveyor Table</td>
</tr>
<tr>
<td>5</td>
<td>Insert Linkage</td>
</tr>
<tr>
<td>6</td>
<td>Close Door</td>
</tr>
<tr>
<td>7</td>
<td>Toggle Middle Position Guide</td>
</tr>
<tr>
<td>8</td>
<td>Toggle Electromagnet</td>
</tr>
<tr>
<td>9</td>
<td>Toggle left and right Position Guides</td>
</tr>
<tr>
<td>*</td>
<td>Start Load Routine</td>
</tr>
<tr>
<td>#</td>
<td>Start Unload Routine</td>
</tr>
</tbody>
</table>

---
required. If the storage area for completed build jobs is full, the next build job will be loaded, but cannot be unloaded until an operator removes at least one of the build trays in the storage area for completed build jobs (hence the 2.5 and not 3 complete changeovers).

The operating procedure for the CLM in automatic mode (Figure 3.28) is trivial. First, the .SML files must be generated. This process is detailed in Section 3.2.3 and illustrated in Figure 3.4 (boxes1-5). Next, the print-queue must be edited. The print-queue should list the names of all the .SML files to be built, one on each line, in the desired order. Then, one or two build trays with foam pads must be placed onto the start of the conveyor table. Additional build trays may be added whenever there is room to the right of the position guides. Next, the FDM extrusion head has to be heated to the specified temperatures, but the temperature of the build chamber should be limited the to 55°C, to avoid jamming problems when the build table is lowered to the load and unload position.

Figure 3.28: CLM operation flowchart
This jamming problem occurs with the particular FDM 1600 modeler in the Virginia Tech Rapid Prototyping Laboratory and not necessarily with other FDM 1600 modelers. Finally, the automated process is started by running the executable ‘fdmoper5’ on the workstation. The finished build jobs will be stored at the end of the conveyor table, and may be removed at any time for finishing operations. Once the automation process is running, the print-queue file can be modified at any time, except during loading. The automation will continue until the print-queue is empty or a loading or unloading error occurs.
CHAPTER 4

RESULTS

The CLM system was extensively tested to evaluate the performance and reliability of the system. Since this thesis does not modify the existing FDM 1600 modeler substantially, testing concentrated on loading and unloading the build trays.

The test consisted of operating the CLM separately from the FDM 1600 system. A small C++ computer code was written to simulate the system operation for two build job changeovers. The code sends a load instruction to the CLM, waits for a response from the CLM, and then repeats these instructions once. Two build trays were placed at the start of the conveyor table before the program was started. When the two test cycles were completed, the build trays in the storage area for finished jobs were moved back to the start of the conveyor table, and the program was started again. This process was repeated 167 times for a total of 334 test cycles over a period of three days. A log file kept track of the time of the initiation, completion, and the status of every load and unload operation. The CLM was inspected and adjusted at the start of the test to make sure it was setup correctly. In addition, the system was disassembled and assembled twice, and periodically shut down during the test to simulate normal operating conditions; specifically after test cycles 79 and 172.

Four failures were recorded in the 334 test cycles, which gives the CLM a 97.3 to 99.6 percent reliability based on an F-distribution with a 95 percent confidence interval. The mean time between failures (MTBF) was 84.5 test cycles, and the mean time to repair (MTTR) was 5 minutes and 30 seconds. Table 4.1 shows the results of the test. The cause of the three first failures involved the transport of the build tray along the conveyor table. The problem always occurred near an idle roller: It seems that the idle rollers were positioned slightly higher than the neighboring driven rollers. This caused the build trays to occasionally hesitate and briefly stop as they passed over the idle rollers, and, in the
worst case, completely stop. To remedy this, the elevations of the idle rollers were lowered slightly after the test.

The first failure occurred as a build tray was unloaded. The previously unloaded build tray stopped at the start of the storage area for completed jobs instead of moving to the end of the storage area. This caused the storage sensor to trigger, which told the control system that the storage area was full and that build tray should not be unloaded.

Table 4.1: CLM load and unload test results.

<table>
<thead>
<tr>
<th>Test Cycle</th>
<th>Operation</th>
<th>Cause of Error</th>
<th>Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>Unload</td>
<td>The previously unloaded build tray got stuck at the start of the storage area, which caused the “storage area full” sensor to trigger.</td>
<td>30 Seconds. Reset system.</td>
</tr>
<tr>
<td>45</td>
<td>Load</td>
<td>The linkage jammed, because the build tray did not fully reach the load position.</td>
<td>1 Minute. Reset system.</td>
</tr>
<tr>
<td>134</td>
<td>Load</td>
<td>The build tray got stuck, and never reached the load position. Operation timed out.</td>
<td>30 Seconds. Reset system.</td>
</tr>
<tr>
<td>276</td>
<td>Load</td>
<td>The linkage jammed, because the build tray did not completely reach the load position after an o-ring snapped.</td>
<td>20 Minutes. Replaced all the worn o-rings.</td>
</tr>
</tbody>
</table>
The second failure occurred while loading a build tray. The build tray reached the start of the loading area and triggered the load sensor. This triggered the left and right position guides. However, shortly after triggering, the build tray stopped and thus did not completely reach the proper load position. This caused the linkage to jam as the electromagnet started pushing on the corner of the build tray to jam the build tray between the front of the FDM 1600 modeler and the electromagnet.

The third failure also occurred while loading a build tray. This time, the build tray stopped before it reached the loading area, and the control system erroneously concluded that there were no available empty build trays.

The last failure was caused by an o-ring that snapped. This stopped the build tray in the loading area. Like the second failure, the build tray was jammed between the electromagnet and the front of the FDM 1600 modeler. All the o-rings were promptly replaced as most of them showed superficial cracking. These o-rings had been installed six months earlier, and should be replaced more often to avoid this type of failure in the future.

In actual use, the complete load and unload operation also includes moving the FDM 1600 build table. This adds a substantial amount of time to each operation. Loading a build tray takes nearly seven minutes, mainly because of the large amount of time required for the build table to move to the conveyor table level. Unloading is faster, but depends on the position of the build table at the end of the build; the closer it is to the conveyor table level, the faster the unloading is completed.

As a result of a jamming problem with the build table of the FDM 1600 modeler in the Virginia Tech Rapid Prototyping Laboratory, the ambient build chamber temperature must be kept below 55° C. At higher temperatures the build table tends to get stuck at the load and unload elevation.
The new door does not seal as tightly as the original door, and a gap of 0.125 inches (3 mm) between the door and the weather-strip frame appears when the door is completely warmed up by the warm air in the build chamber. However, there is not a pressure differential across the door and the gap does not cause the ambient temperature in the build chamber to drop.

Assembling and setting up the CLM takes about three hours, while disassembly requires takes less than 45 minutes to complete. Both assembly and disassembly requires two people to handle the conveyor table, but a single person can handle the rest of the procedures.

A separate design and operation document is available on the SGI workstation. This document includes installation and operating instructions, all the software codes, the engineering drawings, the bill of materials, and the test log.

It is estimated that significant time savings can be achieved through the use of the CLM when fabricating parts for the course ME4644 Introduction to Rapid Prototyping at Virginia Tech. Currently it takes 8 weeks to complete these 40 build jobs. This includes an average of 10 non-productive hours per day and non-productive weekends. With the CLM this non-productive machine time should be removed to enable completion in less than 3.5 weeks.

The productivity increase will vary with the print-queue management. For instance, building three short jobs overnight will still result in non-productive machine time. However, by optimizing the print-queue, and in particular making certain that no more than 2.5 build job changeovers will occur while an operator is unavailable, it should be possible to effectively eliminate non-productive machine time.

The cost of materials, supplies, and services to manufacture the CLM system has been approximately US$ 4,000.
CHAPTER 5

CONCLUSIONS AND CONTRIBUTIONS

This thesis has presented an automated loading and unloading system for the Stratasys FDM 1600 rapid prototyping system. This continuous layered manufacturing (CLM) system requires minimum operator intervention by automatically inserting build trays into the build chamber, running the build job, removing the finished part, and storing the finished part.

The CLM has a footprint of approximately six square feet, and is suspended in front of the FDM 1600. There is storage space for two empty build trays and two build trays with finished jobs. Only minimal modification to the FDM 1600 is needed, and it involves the removal of the existing door. The cost of materials, supplies, and services to fabricate the CLM is approximately US$ 4,000, which is significantly less than the cost of adding an additional FDM machine.

The CLM system has the capacity to perform 2.5 build job changeovers without operator intervention. This means that three consecutive build jobs can be completed. Finished parts can be removed from the storage area at any time; new build trays can be added any time there is room for more trays; and new build jobs can be added to the print-queue any time other than when a tray is being loaded. Hence, as long as there is storage room, new build trays available, build jobs in the print-queue, and material available in the FDM 1600 modeler, the process can run near indefinitely, with minimal non-productive machine time. As an example of expected productivity gains, the total fabrication time for the 40 build jobs each semester in ME 4644 Introduction to Rapid Prototyping at Virginia Tech could be reduced from 8 weeks to 3.5 weeks by utilizing the CLM. The CLM can thus increase the productivity of the FDM 1600 machine significantly.
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VITA

I was born in Kristiansund, Norway, to Dutch and Norwegian parents. My early childhood was spent in Bergen, Norway, until my family moved to the capitol of Norway, Oslo.

In high school, I chose science-oriented classes, and after high school, engineering was the obvious career path. In 1993 I arrived in Ames, IA, where I spent four and a half years completing a bachelor degree in Mechanical Engineering at Iowa State University of Science and Technology. Wanting to pursue the academic path further, I chose to continue with graduate studies in Mechanical Engineering at Virginia Polytechnic Institute and State University, in Blacksburg, VA. During my graduate studies I quickly gained interest in CAD/CAM and Rapid Prototyping, which I chose as the subject for my research.

After Graduate School, I started working in the automotive industry in Detroit, MI developing CAD/CAE and KBE software for Mechatronics, Inc.

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