Automated Loading and Unloading of FDM Systems

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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 wasted idle time whenever an operator is not at hand to make a job change. A low-cost auxiliary system has been developed and implemented to automatically load and unload FDM 1600 (and FDM 1650 / FDM 2000) rapid prototyping systems. The modifications to the FDM 1600 system are minimal. The door to the FDM 1600 build chamber has been removed, a new build tray has been developed, and the .SML build files have been slightly modified at both ends to facilitate synchronized operation between the FDM 1600 and the automated loading and unloading systems.

1 Introduction

Layered manufacturing was commercially introduced by 3D Systems, Inc. in 1987. Since then, several more systems and advancements to existing systems have been commercialized, and research has primarily been concerned with increasing the build speed, improving part quality, and developing new fabrication materials. Hence, today the utility of layered manufacturing spans the range from rapid physical visualization to low volume manufacture. Unfortunately, layered manufacturing systems remain relative expensive compared to equivalent build-volume size computer numerical control (CNC) machining systems and most other computer peripherals. It is therefore important that layered manufacturing systems are used efficiently to justify their high capital cost.

The efficiency of layered manufacturing systems has thus far been addressed by increasing the material deposition rate and by making it easier to "print a part." Examples of advances to increase the material deposition rate include adaptive build layer thicknesses, slanted build layer contours, adaptive material area deposition, parallel material deposition, and faster motion systems. The ease of use has been facilitated by more intuitive and less complex user interfaces, and by the implementation of print queues to ease the movement of customer build files to the fabrication unit. An example of the latter includes the network print queue for a laminated object manufacturing (LOM) system (Helisys, Inc.) that was demonstrated by Bailey in 1995 [1]. Today print queues are increasingly more common. For instance, the Genisys X (Stratasys, Inc.) [2] and the ThermoJet (3D Systems, Inc.) [3] have print queues to help users submit build jobs and administrators order these jobs for optimal utilization of their respective fabrication systems.

Being able to optimize the order of the build jobs is essential for the effective utilization of most layered manufacturing systems. Today's systems require an operator to manually change build jobs, and most systems are installed in an environment where an operator is available only during regular working hours on weekdays. Hence, to maximize system throughput over time and to maximize the number of hours over which to share fixed costs (e.g., capital depreciation and maintenance contracts), operators will attempt to schedule long build jobs over night and over weekends, and short build jobs during the time operators are available to manually change build jobs. Too often this strategy is insufficient to ensure continuous operation, and a choice must be made between letting the system stand idle for hours at a time or absorbing the additional expense of having an operator come in after hours to make a build job change.

For instance, in the course *ME 4644 Introduction to Rapid Prototyping* at Virginia Tech, 20 student teams each have an FDM 1600 (Stratasys, Inc.) reserved for 24 hours twice during the semester, with each build job taking on average about 15 hours to complete. Hence the system stands idle for about 360 of the 960 reserved hours (63% system utilization). With continuous operation, these 40 build jobs could be completed in 25 days instead of the current 8 weeks.

Burns [4] argued in 1993 the need for automating the loading and unloading of layered manufacturing system to make them true automated fabrication systems, similar to many CNC machining and EDM systems [5]. Gibson [6] discussed the use of robots for loading, unloading, and finishing operations, and is currently working to simulate robot loading and unloading of selective laser sintering (SLS) systems (DTM Corp.) [7].

This paper presents the complete implementation of a fully automated loading and unloading system for FDM 1600 rapid prototyping systems. With minimal modification it should also work with FDM 1650 and FDM 2000 rapid prototyping systems. The following sections discuss the characteristics of FDM systems and the design and implementation of this auxiliary loading and unloading system.

2 Fused Deposition Modeling

Fused deposition modeling (FDM) systems fabricate parts by extruding a thermoplastic material (typically ABS plastic) through a small die to produce a thin bead that, when routed back and forth across a horizontal plane, combines to produce a horizontal cross-sectional build layer, bonded to the build layer below (Figure 1). The instructions for this fully automated motion are contained in a text file that is uploaded from a host computer to the FDM unit. This text file is often referred to as an .SML build job file. However, currently, both before and after this automation, an operator must perform a series of trivial, though manual, tasks for each build job:

1. Bring system up to temperature;
2. Open door;
3. Place new build tray on build table;
4. Close door;
5. Upload build job file;
6. Position relative start point;
7. Continue build job;
8. Open door;
9. Remove build tray with part; and
10. Close door.

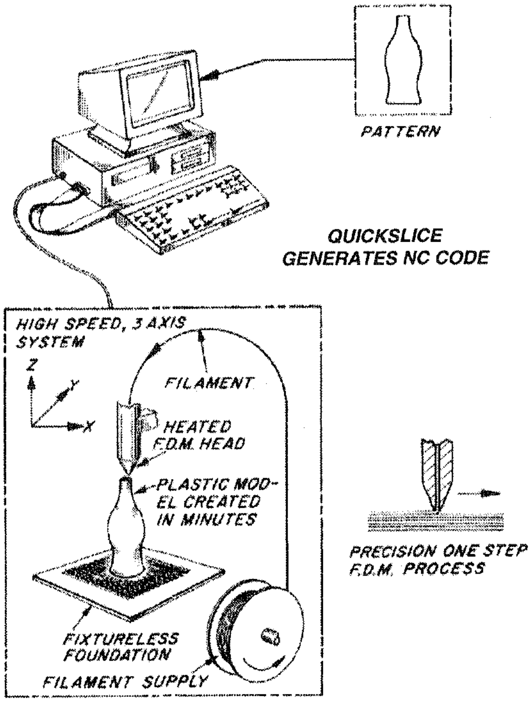

Figure 1 Fused deposition modeling (FDM).

Hence, in order to fully automate FDM rapid prototyping systems, so they can operate unassisted across multiple build jobs, analogous to how a laser printer is loaded with a ream of paper, it is necessary to automate the above loading and unloading process. The following section will describe one such solution.

3 Continuous Layered Manufacturing

A low-cost auxiliary loading and unloading system has been developed to enable continuous layered manufacturing (CLM) with FDM 1600 and similar rapid prototyping systems (e.g., FDM 1650 and FDM 2000 systems). The CLM system attaches to the front of the FDM system on a steel frame that slides beneath the FDM system (Figure 2) and requires only three minor modifications to the FDM system: First, the front door on the FDM system is removed and replaced by a slender frame holding a weather strip seal. Second, a redesigned build tray is used in place of the original build tray. The redesigned tray features several guides that enable it to reliably go into and come out of the fixture on the FDM build table (no modification is made to the FDM system). Finally, custom software is used to automatically modify the .SML build files at the time of job submission, and to coordinate the operations of the CLM and FDM systems across two independent RS232 serial lines. Hence, setting up the CLM—or resetting the FDM back to its original state—takes less than 10 minutes.

The following describes in more detail the CLM's mechanical and electrical systems and the software used to coordinate the CLM and FDM operations.

3.1 Mechanical System

The mechanical system for the CLM consists of four parts; a roller conveyor table, a new rotating door, a loading and unloading linkage, and a new build tray that actually forms the only physical interface between the CLM and FDM systems.

The conveyor table, which consists of several driven and idle rollers in a frame, has three zones over which it can store five build trays: The first zone is where up to two unused build trays rest prior to fabrication; the second zone is where the active build tray is moved into and out of the FDM build chamber; and the third zone is where up to two build trays with parts rest after fabrication. The driven rollers are connected by o-rings to, and powered by, a driveshaft that runs perpendicular to the rollers below the conveyor table. Three spring-loaded position guides are placed in between the rollers to control the flow and positioning of the build shelves along the conveyor table.

The original door to the FDM build chamber was removed because it swings outward and would interfere with the CLM. A new door was put in its placed. This door is attached to and driven by the CLM such that it rotates in its plane. Finally, a slender frame with weather stripping was attached to the FDM to provide a seal between the FDM and the new door.

The build shelves are moved between the CLM and FDM by an electromagnet attached to a Chebyshev Type One four-bar linkage [8] with a parallel wire linkage (Figure 3). This linkage combination ensures that the electromagnet travels in a straight line without rotation.

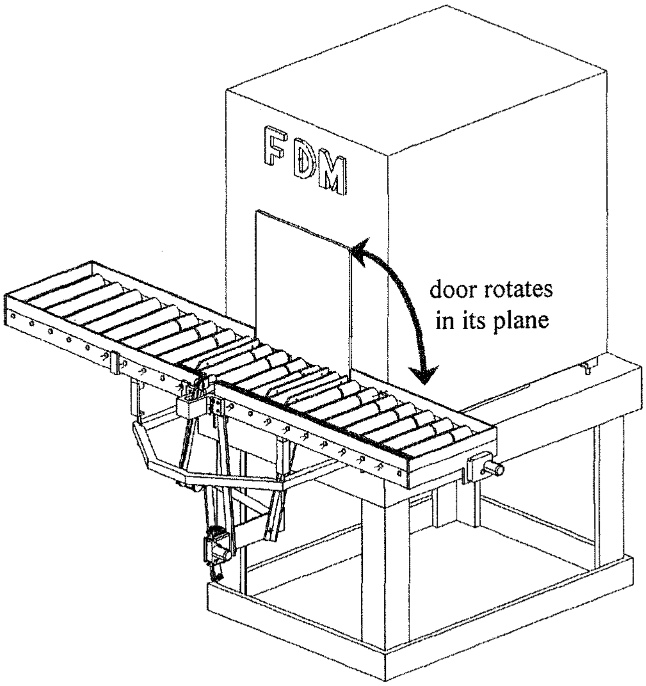

Figure 2 Continuous layered manufacturing (CLM) system positioned relative to FDM system.

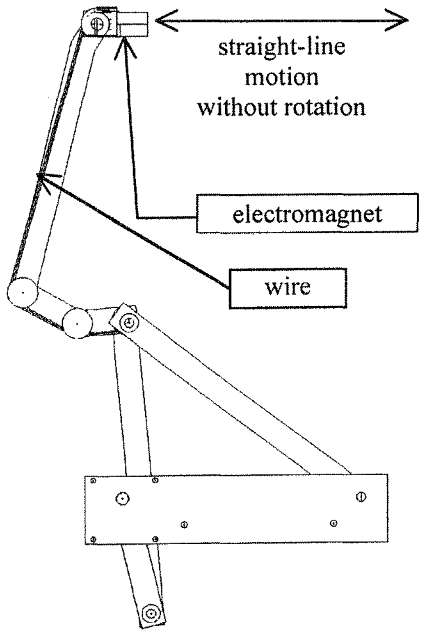

Figure 3 The Chebyshev Type One four-bar linkage with a parallel wire linkage is used to insert and remove the build shelves into and out of the FDM build chamber.

The original FDM build shelves were designed for manual operation. Two modifications were therefore made to these build shelves to enable their use with the CLM: First, the handle was replaced by an iron plate to enable the use of an electromagnet. Second, the bottom plate and the guides on the sides were elongated and heavily beveled to ensure that the tray easily guides itself into and out of position without jamming. These changes are shown in Figure 4.

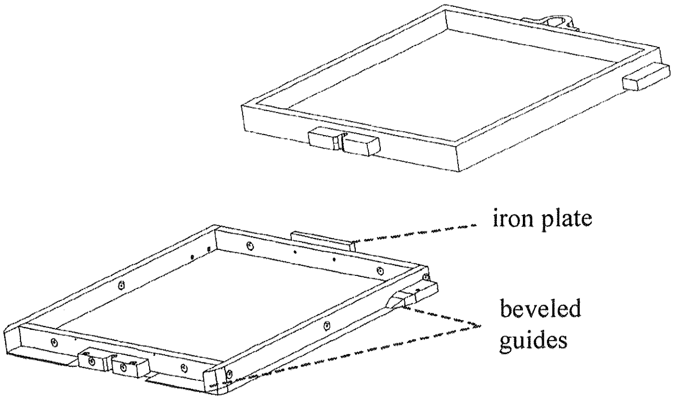

Figure 4 The new elongated build shelf (lower left) has guides to facilitate reliable loading and unloading. The original build shelf (top right) is shown for comparison.

3.2 Electrical System

Seven electrical devices actuate the CLM system: three solenoids, three DC gear motors, and an electromagnet. The three spring-loaded position guides between the rollers are actuated by separate pull-style solenoids. When a solenoid is energized, the corresponding guide retracts beneath the rollers, which allows build shelves to pass. The DC gear motors open and close the door, drive the conveyor table, and move the linkage. Lastly, the electromagnet is used to connect the build shelf to the linkage during loading and unloading.

Six infrared proximity sensors provide feedback to control the CLM system. Four of these sensors act as limit switches; two for the door, and two for the linkage. The remaining two are positioned between the rollers of the conveyor table: One sensor is placed close to the linkage to senses when the build shelf reaches the load/unload position; the other is placed at the start of the storage zone for finished parts to sense if this zone is full.

The CLM control system is located on a circuit board inside an enclosure attached below the conveyor table. A microprocessor controls the CLM electrical devices via motor drivers and relays, and receives input from the six proximity sensors, a numerical keypad, and a serial port connected to the host computer driving the FDM system. The electrical devices can therefore be activated manually via the keypad or by a program over the serial line. This includes the *load* and *unload* sequences, which, for convenience, have been programmed directly into the microprocessor memory. A brief overview of these two predefined sequences follows:

Load Sequence

1. Retract linkage (moves the linkage out of the way)
2. Retract position guides (allows the free flow of build shelves)
3. Run conveyor table until the first build shelf reaches the loading position
4. Release position guides (positions the build shelf for loading)
5. Open door

6. Turn on electromagnet (grabs onto the build shelf)
7. Extend linkage (pushes the build shelf into the FDM machine)
8. Turn off electromagnet (lets go of the build shelf)
9. Retract linkage
10. Close Door

Unload Sequence

1. Check storage sensor (make sure there is storage space available)
2. Retract position guides (allows free flow of build shelves)
3. Open door
4. Extend linkage
5. Turn on electromagnet (grabs onto the build shelf)
6. Retract linkage (removes build shelf with finished part from the FDM machine)
7. Turn off electromagnet (lets go of the build shelf)
8. Close door
9. Run conveyor table for 15 seconds (moves build shelf with finished part to the storage zone)

3.3 Software

The software for controlling and coordinating the CLM and FDM systems has been designed to take the place of the program *ssend* that is shipped with the FDM systems. It assumes that the CLM and FDM systems are connected to the same host computer via two independent RS232 serial lines operating at 9600 baud. The new program incorporates a basic print queue. For each file it attempts to "print", it verifies the file; modifies its beginning and end; and then sends it to the FDM system while coordinating with the CLM system.

Since modifications are made to the original .SML file that is fed to the FDM system, it is important that the format of the .SML file is well understood to avoid sending the FDM system instructions that might cause damage. This is achieved by verifying the version of the .SML file and by checking the file for certain constant characteristics (e.g., the standard instruction preamble sequence). Once the version and integrity of a file has been verified, the beginning and end of this file are modified to accommodate synchronous operation between the CLM and FDM systems. These modifications are made in memory (RAM) as the FDM fabrication instructions are read from the disk and resent to the serial port; they do not affect the actual file on disk itself.

The coordinated operations of the CLM and FDM systems assume that the FDM system temperatures are set appropriately for the materials to be used; that the FDM has been loaded with material; and that build trays with new foam have been loaded onto the CLM unused build tray storage zone. Once these one-time manual operations have been completed, the coordinated operations under program control are repeated for each file in the print queue as follows:

FDM system

1. Lower build table (avoid collision during Find (0,0) operation)
2. Find (0,0) in XY build plane (enable moving to safe position)
3. Move head to safe position (avoid collision during subsequent Find Z=0 operation)
4. Find Z=0 level (enable moving to CLM loading/unloading level)
5. Lower table to CLM loading/unloading level

CLM system

6. Execute the preprogrammed CLM loading sequence (see Section 3.2)

FDM system

7. Move to standard start position (left front corner with tip slightly submerged in foam)
8. Continue with actual build instructions — stop before entering final standard FDM sequence
9. Lower table to CLM loading/unloading level

CLM system

10. Execute the preprogrammed CLM unloading sequence (see Section 3.2)

4 Results

A fully operational prototype of the CLM has been built and installed with an FDM 1600 rapid prototyping system, with both systems controlled concurrently by an SGI Octane workstation running IRIX 6.5.4. The control program was written in C++ and should easily port to other systems. The estimated construction cost was less than US$5,000.

The CLM system has the capacity to complete three build jobs before operator intervention is required. However, completed build jobs can be removed from the CLM, new ready-to-use build trays can be added to the CLM, and build jobs can be added to the print queue—all at any time. Hence, sustained continuous automated FDM fabrication is feasible.

It takes close to seven minutes to load a new build shelf. The vast majority of this time is for the build table to find the Z=0 level and then move to the CLM loading/unloading position, which is towards the bottom of the FDM build chamber. Unloading is faster and depends on the position of the build table at the end of the build; the closer it is to the CLM loading/unloading level, the faster the unloading is completed.

The FDM productivity increase with the CLM system will still vary with build times. For instance, a series of three short build jobs overnight or over the weekend will still cause significant down time. However, in most cases a series of three build jobs will continue through the night or over the weekend, which will reduce the downtime between build jobs to less than 15 minutes. Alternatively, the CLM can easily be extended in both directions to accommodate more build jobs without operator intervention.

5 Conclusion

This paper has presented a low-cost auxiliary system for automated loading and unloading of build trays for FDM 1600 systems (and, with minimal modification, FDM 1650 and FDM 2000 systems). The new system has the potential to provide continuous FDM operation with only occasional operator attendance at his or her convenience. For instance, it is expected that the 40 build jobs during a semester in the course *ME 4644 Introduction to Rapid Prototyping* at Virginia Tech will now take 25 days to complete instead of the customary 8 weeks.

Acknowledgment

FDM® is a registered trademark of Stratasys, Inc. of Minneapolis, Minnesota, U.S.A., Reg. No. 1,663,961.

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