DEVELOPMENT OF AN AUTOMATED MULTIPLE MATERIAL STEREOLITHOGRAPHY MACHINE

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Abstract

An automated Multiple Material Stereolithography (MMSL) machine was developed by integrating components of a 3D Systems 250/50 stereolithography (SL) machine in a separate stand-alone system and adapting them to function with additional components required for MMSL operation. We previously reported retrofitting a 250/50 SL machine with multiple vats to accommodate multiple material fabrication for building a wide variety of multi-material models (Wicker *et al.*, 2004). In the MMSL retrofit, spatial constraints limited the multiple vats located circumferentially on a vertical rotating vat carousel to cross-sectional areas of approximately 4.5-inches by 4.5-inches. The limited build size of the retrofitted 250/50 motivated the full development of a new system with multiple material build capabilities comparable to the build envelope of the original 250/50 machine. The new MMSL machine required fabrication of a large system frame, incorporating various 250/50 components and software, and adding a variety of new components and software. By using many existing components and software, the previous engineering development of 3D Systems could be directly applied to this new technology. Components that were transferred from an existing 250/50 to the MMSL machine included the complete optical system (including the optics plate with laser, mirrors, beam expander, scanning mirrors, and focusing lens), the rim assembly (including the laser beam profilers), the associated controllers (computer system, scanning mirror controller, power supply-vat controller) and the wiring harness. In addition to the new frame, the MMSL machine required the development of a new rotating vat carousel system, platform assembly, multi-pump filling/leveling system, and a custom LabVIEW® control system to provide automated control over the MMSL process. The overall operation of the MMSL system was managed using the LabVIEW® program, which also included controlling a new vat leveling system and new linear and rotational stages, while the 3D Systems software (Buildstation 4.0) was retained for controlling the laser scanning process. As a demonstration of MMSL technology, simple multi material parts were fabricated with vertically and horizontally oriented interfaces. The fully functional MMSL system offers enormous potential for fabricating a wide variety of multiple material functional devices.

Keywords: rapid prototyping; stereolithography; functional devices; functional integrated layered manufacturing; multiple material stereolithography;

1. Introduction

Conventional rapid prototyping (RP) or layered manufacturing (LM) technologies are flexible in manufacturing complex three-dimensional (3D) freeform objects, although these technologies typically have access to only a single build material during fabrication. As RP technologies have evolved, the materials available for use in RP have advanced considerably where these new materials are enabling LM to be used in rapid manufacturing of end-use products instead of simply producing prototypes. The first commercialized RP technology, stereolithography (SL), continues to be one of the most widely used LM processes for manufacturing prototypes. In SL, an ultraviolet laser beam is used to scan the surface of a photo-curable polymer that builds 3D parts by selectively solidifying thin layers of the polymer and stacking these layers together. The number of resins available for use in SL has steadily been increasing with several functional high temperature and high strength resin options today. As a result of these new materials, we believe a market exists for using multiple materials in SL during the same build (including, for example, embedding different colors in medical models or depositing conductive media within mechanical structures to manufacture unique 3D electronic devices). Our particular motivation for this new technology is in the area of tissue engineering where we are using multiple polymers to tailor the bioactive and mechanical properties for particular tissue engineering applications (see Arcaute *et al.*, 2005a, 2005b, 2006 as examples).

Our group embarked on developing a multiple material SL machine by first retrofitting an existing 3D Systems 250/50 SL machine with multiple vats positioned on a rotating vat carousel (Wicker *et al.*, 2004). To build out of multiple materials, the process proceeds as follows. First, the platform is submerged in one of the build vats where building proceeds normally. Different materials are used by simply raising the platform out of the current vat and rotating a different vat underneath the platform providing access to a second material. The process also includes a cleaning step where the platform is submerged and cleaned in a cleaning vat prior to being submerged in subsequent material vats. The process can proceed indefinitely to build a wide variety of multiple material parts.

MMSL technology is one aspect of a concept we refer to as Functional Integrated Layered Manufacturing (FILM), where access to virtually any subtractive or additive manufacturing technology, materials, and software is provided in an automated building environment for manufacturing unique functional devices. In addition to MMSL, our group has integrated a direct write (DW) fluid dispensing system with SL for automated dispensing of conductive media combined with SL-fabricated structures (see Palmer *et al.* 2004; Medina *et al.*, 2005; Lopes *et al.*, 2006 as examples). This automated machine demonstrates the ability of SL to be combined with non-SL technologies (i.e., using/combining non-UV curable media) for fabricating functional devices, where we have used this machine to fabricate 3D, high density circuitry with integrated embedded electronics. The concept of combining different materials in the same build is not new and many researchers are exploring ways to exploit the advantages of additive manufacturing in producing multi-material parts. For example, Valerio *et al.* (2005) demonstrated a multi material and multi process deposition method to produce parts with specific requirements that could not be met by a single material, such as with graded composition and locally controlled properties. Kumar *et al.* (2004) presented a concept for multi-material solid freeform fabrication of heterogeneous components using selective laser sintering. Jafari *et al.* (2000) demonstrated fused deposition of multiple ceramics for fabrication of advanced functional ceramic and composite components. In the end, many of these technologies may be combined in the integrated FILM environment to fully capitalize on individual strengths afforded by each LM technology for producing useful products.

We previously demonstrated multi-material fabrication of PEG hydrogel multi-lumen nerve regeneration conduits and functional devices with embedded electronics applying the MMSL concept. However, in the MMSL retrofit, spatial constraints limited the multiple vats located circumferentially on a vertical rotating vat carousel to cross-sectional areas of approximately 4.5-inches by 4.5-inches. The limited build size of the retrofit motivated the development of a new stand-alone system with multiple material build capabilities comparable to the build envelope of the original 250/50 machine. This new machine, described here, required fabrication of a large frame to house the system, incorporating various 250/50 components and software, and adding new components and software as required for the MMSL machine to function. The 3D Systems components integrated in the new system were all associated with the beam scanning system and its operation. Additional components and software were required for MMSL operation, where an overall process control software management system was developed using LabVIEW. The following sections describe the MMSL hardware and software systems followed by demonstrations of MMSL operation where simple multiple materials parts with vertically and horizontally oriented interfaces were fabricated.

2. Multiple material stereolithography machine design

The new MMSL machine, as shown in Figure 1, consists of a control center and manufacturing center. The manufacturing center includes the scanning mirror system, laser, and the rim assembly retained from the 250/50 system and a newly developed rotating platform, rotating vat carousel consisting of four vats, vat cover, and rotary stages. The control center includes a multi-pump filling/leveling system, 3D Systems software, overall process control software management system, scanning mirror controller, and signal conditioning module. The new MMSL machine is comprised of hardware that deals with the fundamental component design (including MMSL machine frame, rotating vat carousel system, platform assembly, multi-pump filling/leveling system, and optical system) and software (including 3D Systems software, and a custom LabVIEW® program) to function as a separate stand-alone manufacturing setup. The following section describes the hardware of the new MMSL machine in greater detail.

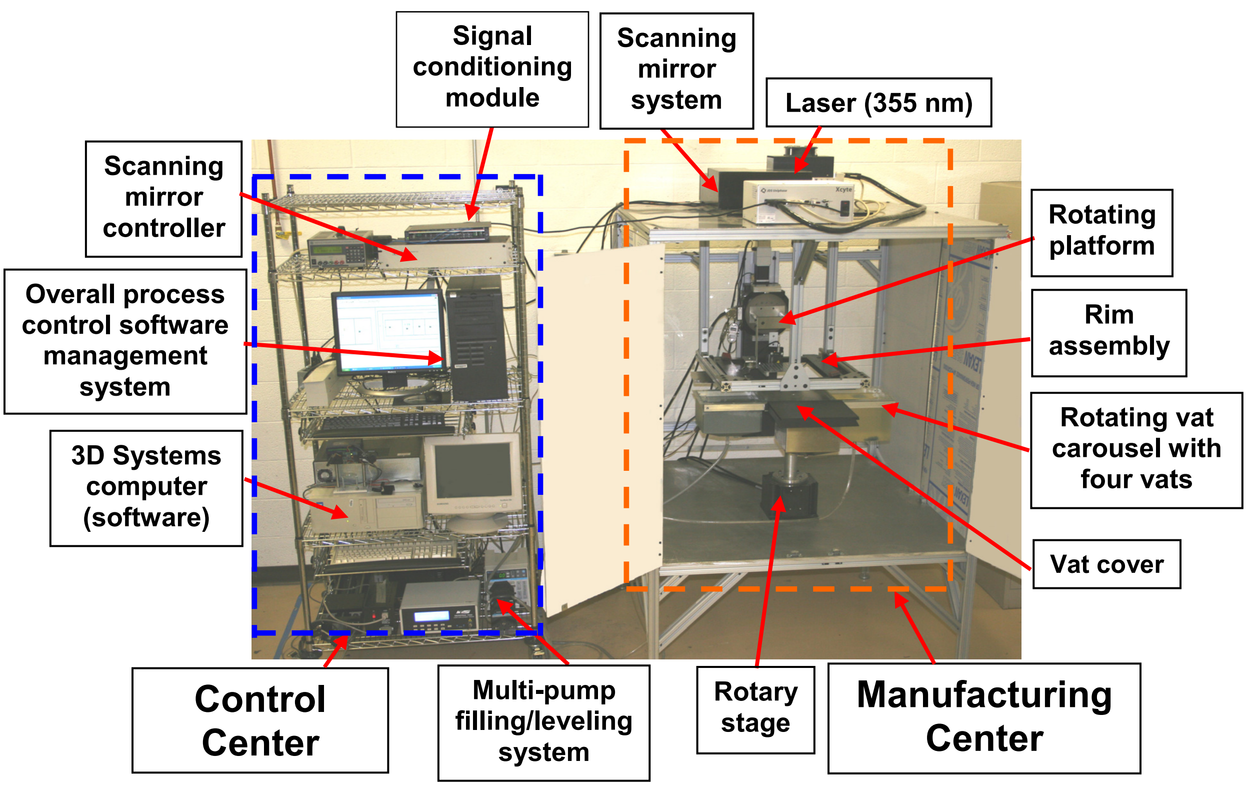


Figure 1. Multiple material stereolithography (MMSL) machine.

2.1 MMSL machine frame

A 6105-T5 aluminum fractional (1.5 square inches) T-slotted framing system (Part # 47065T122, McMaster-Carr Supply Company, Chicago, Illinois) was used to create the overall machine frame due to its ease of assembly and disassembly, and the ability to be easily reconfigured. The vat cross-section (8-inches by 9-inches) was limited by the load carrying capabilities of the rotary stage used for the vat carousel system which in turn constrained the MMSL machine frame to a 4-ft square cross-section. The aluminum extrusions available in 8-ft sections (maximum available length) are utilized to form the MMSL machine frame (4-ft by 4-ft cross-section) while providing the most compact design for the MMSL machine. This square machine setup offers scalability by integrating with other non-SL technologies, as presented by Wicker *et al.* (2004). A structural analysis of the MMSL machine frame was performed considering the entire load (including laser head and laser power supply, optical system, rim assembly, rotary and linear stages, vat carousel assembly including vats filled with resin, and platform assembly), yielding a maximum deflection of 0.006 inches. In order to accommodate this deflection and ensure the rigidity of the frame, tee connectors and 45º support brackets were used in each corner as additional support members. The frame was enclosed with transparent, ultra violet (UV) protective Lexan® doors (GE Structured Products Department, Mt. Vernon, Indiana) on three sides and another UV-protective Lexan® sheet on the back for easy access to all the components of the new MMSL machine and to protect from the UV radiation of the laser. A 6061 aluminum plate (0.5-inches thick) was used as a base of the manufacturing center to accommodate the rotating vat carousel system. The optical system retained from the original 250/50 machine was placed on another aluminum plate (0.25-inches thick) located on top of the MMSL machine.

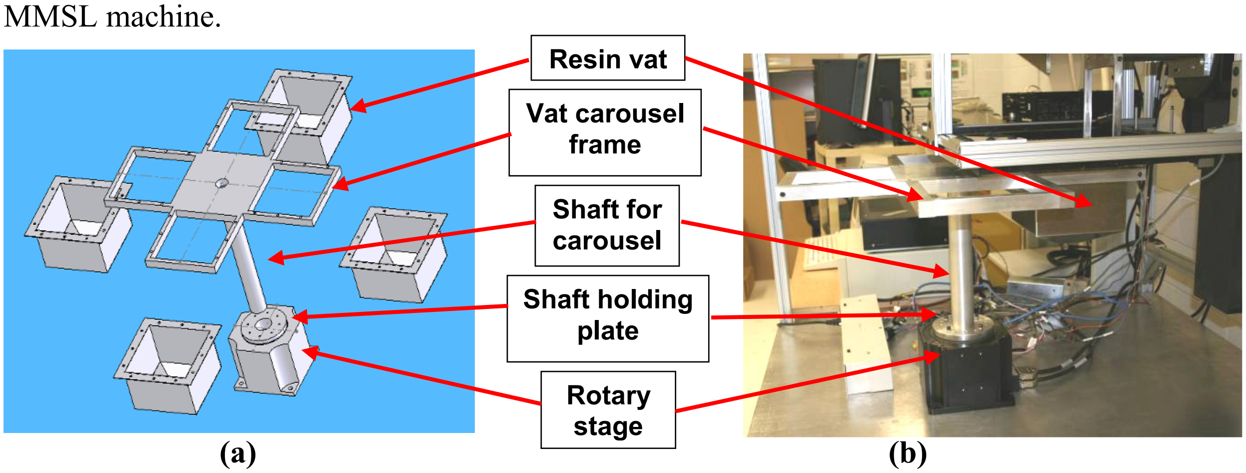


Figure 2. (a) Vat carousel assembly exploded view, (b) Vat carousel assembly.

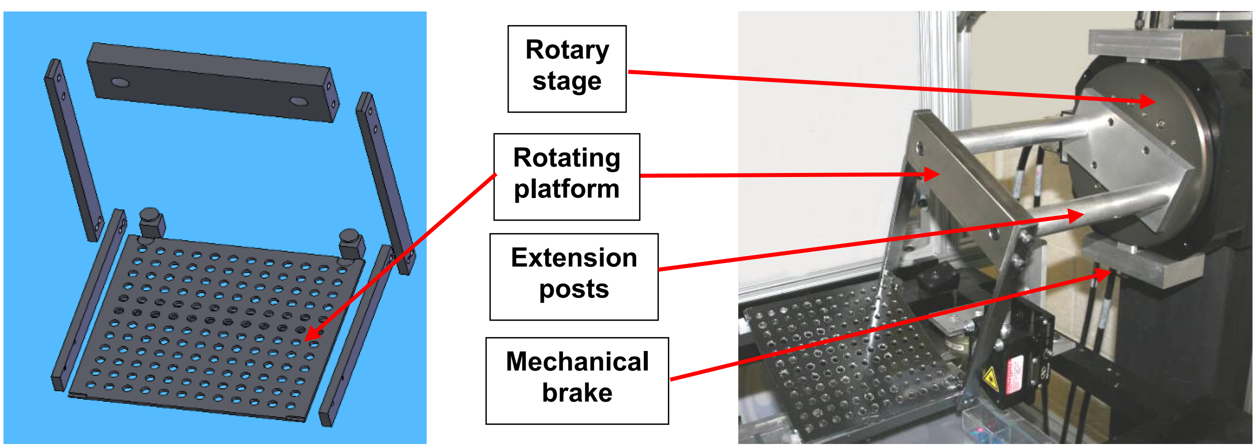
2.2 Rotating vat carousel system

The rotating vat carousel system includes four stainless steel vats (8-inches by 9-inches), located circumferentially, as shown in Figure 2. The maximum build envelope of the MMSL machine based on the vat design was 6.5-inches by 6.5-inches by 4.75-inches. The vertical build was limited to 4.75-inches due to the platform supporting plates, the slope provided to the resin vats, the positioning and the travel (500 mm) of the linear stage (Z-stage). The maximum vat cross-section of the MMSL machine was limited, as compared to the original 250/50 system vats (approximately 11.5-inches by 14.5-inches), by the torque output of the Aerotech rotary stage (425N-m, which is the highest capacity within the Aerotech range of stages). The volume of the

MMSL resin vats was 9 liters as compared to the 32.21 liters volume of the original 250/50 machine vats. The vats were rotated about a vertical axis (the axis of a 2-inch diameter aluminum shaft) in order to position a specific vat below the build platform. ADRT-200 direct drive rotary stage (Aerotech Inc., Pittsburg, Pennsylvania) was selected for the vat carousel system due to its high accuracy (±30 arc-sec) and high torque output (with in the Aerotech range of stages), along with superior angular positioning, velocity control, and load capacities (30-173 kg). Finite element analysis, using COSMOSWorks®, available from SolidWorks® Education Edition 2005-2006, was performed on each vat to calculate the vat deflection under static loading conditions. Considering maximum volumetric capacity condition, fully restrained flange bottom faces, and hydrostatic pressure, the analysis resulted in a maximum deflection of 0.0014-inches for each vat. Stainless steel (0.0625-inches) vats were fabricated to accommodate the resulting deflection and to store different resins for multi-material fabrication. A vat cover (ABS plastic) fabricated using the FDM machine was designed to avoid external resin contamination and also protect the resin in other vats from laser scattering and adverse environmental effects. The vat carousel frame was composed of a 6061 aluminum plate at the center and a series of aluminum support columns (1 square inch cross-section) attached to it, in order to accommodate the multiple vats filled with resin.

2.3 Platform assembly

A stainless steel build platform (6.5-inches by 6.5-inches in cross-section), as shown in Figure 3, was designed to fit into the vats while maintaining the same spacing between the platform and the sides of the vat as in the original 250/50 system. The build platform also provides space within the vat for the level sensing floating device. The platform assembly was mounted on the ADRS-200 direct drive rotary stage (Aerotech Inc., Pittsburg, Pennsylvania) in order to provide for angled part building, as well as washing and drying of multiple material parts. The rotary stage was further secured to a high precision Z-stage (Model # ATS10050, Aerotech Inc., Pittsburg, Pennsylvania) with high accuracy (±20µm) and repeatability (±1µm), as compared to the original 250/50 machine (accuracy of ±50µm and repeatability of ±7.6µm) while controlling the build layer thickness of the part. Thus, the platform can be manipulated vertically as well as at any given angle about a horizontal axis for customized part fabrication.



(a) **(b)**

Figure 3. (a) Platform assembly exploded view, (b) Platform assembly.

To maintain the position of the platform during part building, a pair of mechanical brakes was designed and attached to the rotary stage as shown in Figure 3b. A custom-made mechanical brake consisting of a pair of small aluminum plates was manufactured to accommodate the shape of the circular disc of the rotary stage placed in a milled slot in the rectangular aluminum plates (5-inches by 2.5-inches in cross-section). The rotary stage was locked in position when the brake was activated. A pair of 9.5-inches aluminum extension posts (1-inch diameter) was attached to the rotary stage via a rectangular plate to allow the laser incidence center to be coincident to the center of the platform and to position the platform in the scanning range of the optical system. In addition, recoating technologies can also be employed in this machine by incorporating them individually in each vat or a conventional recoating system for multiple vats. Although the stratified part fabrication and the space constraints due to integration of a new rotating vat carousel assembly eliminated the use of a Zephyr™ blade (sweeping during part build), a dip coating approach with 0.008-inches layer thickness was used to demonstrate MMSL fabrication. The Zephyr™ blade in the 250/50 system allows for resin surface uniform coating with 0.004-inches thick layers as compared to resin leveling by surface wetting alone. The elimination of the Zephyr™ blade required the use of dip coating approach that limited the vertical resolution of the MMSL system. However, research is ongoing to incorporate a new recoating system that will allow building with higher resolution.

2.4 Multi-pump filling/leveling system

The auto leveling system of the existing 250/50 machine was replaced by an automatic multi-pump filling/leveling system (including laser displacement sensor, peristaltic pump, pump heads, and flexible tubing) to regulate the resin level in the vat. The multi pump filling/leveling system provided high accuracy (±5μm) control for maintaining resin levels in the multiple vats of the MMSL machine. A Masterflex® L/S peristaltic pump (±13μm resolution), as depicted in Figure 4, facilitated adding and removing desired quantities of resin to and from each vat and allowed isolation of the resin from the moving parts of the pump. The most significant advantage of the peristaltic pump is the use of flexible tubing (MasterFlex® Tygon® L/S 18) for the multi-pump system, as the resin being pumped remains inside the tubing at all times. This feature greatly reduced the risk of contamination by offering complete control over the content and purity of the resin along with the integrity of the process. This resulted in minimizing the maintenance, cleanup, and resin changeover times while enabling the pump to deliver various fluids simply by changing the tubing within the pump heads. Four pump heads (Model # 77201-60, L/S Easy-Load® II, Cole-Parmer Instrument Company) were used to facilitate the fabrication of the functional devices with multiple materials. A sensing head (including a solid state laser and a position sensitive detector) mounted on the rim assembly is utilized to determine the resin surface level using a non-contact laser triangulation measurement system.

Figure 4. Multi pump filling/leveling system.

One of the issues encountered by Wicker *et al.* (2004) with the retrofit design was the re-registration of the part to maintain a uniform level of resin on the build layer in multiple vats to produce multi-material parts. This was addressed using a wet film coating thickness gauge (Elcometer®) to manually check the resin level on the build layer of the part as demonstrated by Sandoval *et al*. (2005). The multi pump filling/leveling system of the new MMSL machine addressed this issue by employing a laser displacement sensor (Microtrak™ 7000**)** and a sensing head coupled to a floating device calibrated for the various fluids' buoyancy parameters. A rubber cellulose floating device (3/64 inches thickness) was essential due to the difference in viscosities (Watershed™: 260 cps at 30ºC, and Nanoform™: 570 cps at 30ºC) (DSM Somos®, New Castle, Delaware) and the appearance (Watershed™: Optically clear, and Nanoform™: Opaque gray) of the resins used in SL. The calibrated values (Watershed™: 0.012-inches and Nanoform™: 0.018-inches above resin level) were accommodated in the LabVIEW® program for automatic leveling of various resins, by calculating the error and adjusting the resin level surface to a calibrated (zero) value. A PID (Proportional Integral Derivative) control was used for automatic resin leveling, due to its functional simplicity and robust performance in a broad range of operating conditions. A preliminary experiment using varying PID readings aided in determining the values for Watershed™ and Nanoform™ resins to automatically maintain uniform levels in multiple vats.

2.5 Transferred technologies

Several components of the existing 250/50 system were retained (including the optical system, rim assembly, the associated controllers and the wiring harness) in the new MMSL machine. The components required for controlling the laser scanning process in the original 3D Systems machine and any components required to allow the scanning system to function were retained. The optical system (including the optics plate with laser, mirrors, beam expander, scanning mirrors, and focusing lens) was transferred to utilize the advantages of the existing technology and thus maintain the original SL operation functional. The rim assembly (including the laser beam profilers), and the associated controllers (computer system, scanning mirror controller, power supply-vat controller) were used to achieve the functionality of the laser scanning process. The MMSL machine used a 355 nm solid state laser (Lightwave® Electronics, Mountain View, California) due to its high resolution and small beam diameter (0.004-inches). The wiring harness was utilized to initialize the 3D Systems software and achieve successful interface with the custom LabVIEW® control system by acquiring the analog signal from the stepper motor of the recoating system of the 250/50 machine. The software (including 3D Systems software, and a custom LabVIEW® program) required to provide automated control over the hardware is described in the following section.

3. Multiple material machine operation overview

This section highlights the software system of the new MMSL machine. The development of an overall process management and control software to control the MMSL operation is the most significant element of this research. A generalized multiple material fabrication process is depicted in Figure 5. The process is initialized by submerging the build platform in the vat containing the first resin material (Watershed™). Normal SL build is performed to fabricate the desired part with first resin. When finished, the platform is raised, and a cleaning vat is rotated underneath the platform so that the platform and part can be cleaned. Once cleaned and dried, the platform is raised out of the cleaning vat and the second material vat is rotated underneath the platform (Nanoform™). The SL build continues with the second material until completion, and the process continues indefinitely to fabricate fully functional multiple material parts. The entire MMSL process is managed by the overall process management and control software using a LabVIEW® program. The software controls the rotating vat carousel system, new linear and rotational stages, the filling/leveling system, and communicates directly with the 3D Systems software (Buildstation 4.0) for controlling the laser scanning process.

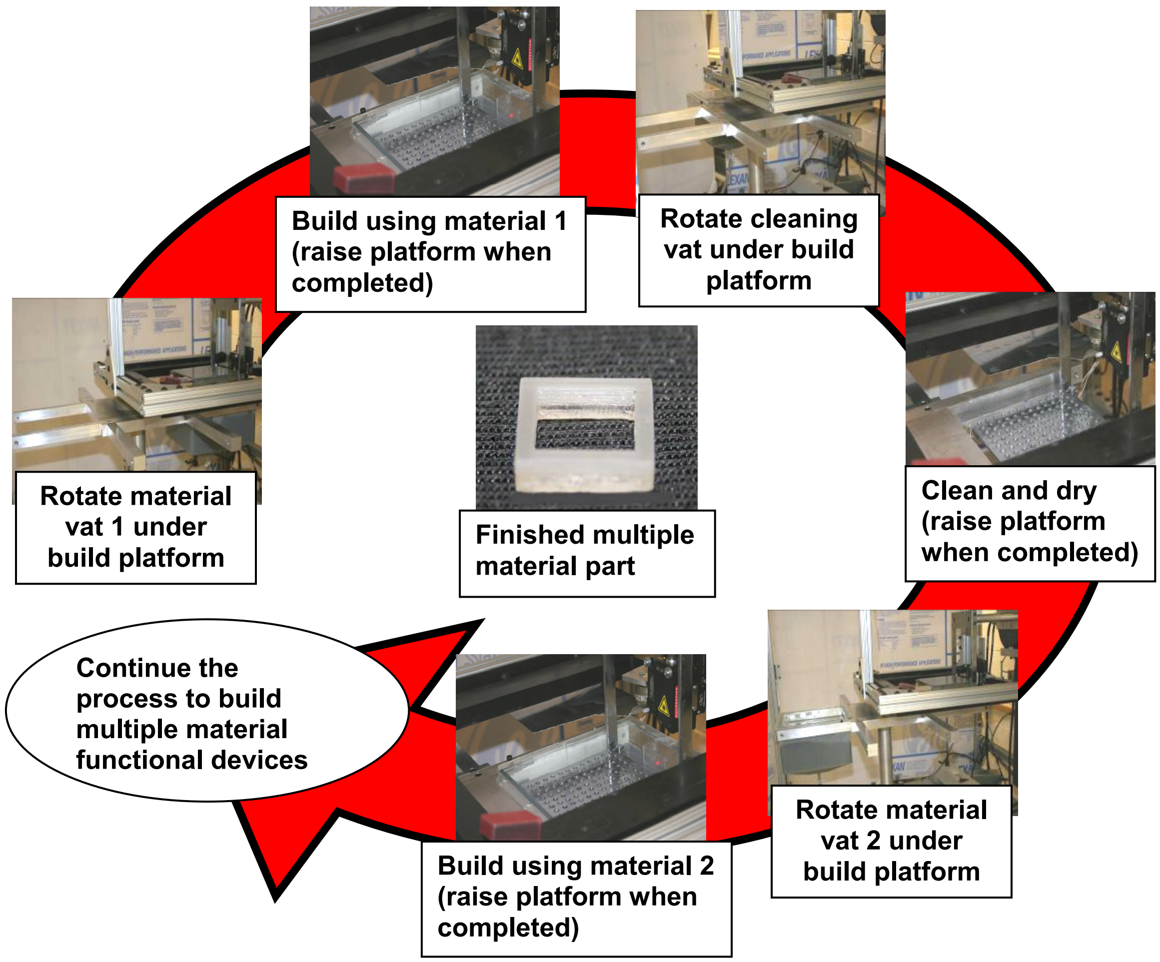


Figure 5. Multiple material stereolithography (MMSL) operation.

The key elements for successful operation include being able to communicate between these two systems. A signal conditioning module (SC-2345 carrier with configurable connectors, National Instruments, Austin, Texas) is used to acquire the analog signal (change in voltage) from the stepper motor of the recoating system used in the 250/50 machine after laser scanning of each part layer. The custom LabVIEW® program uses this change in voltage and opens an interlock switch (a part of the wiring harness retained from the 3D Systems machine) thereby momentarily stopping the 3D Systems program to perform the dip coating operation. The sequence continues as shown in Figure 6 for successful MMSL fabrication.

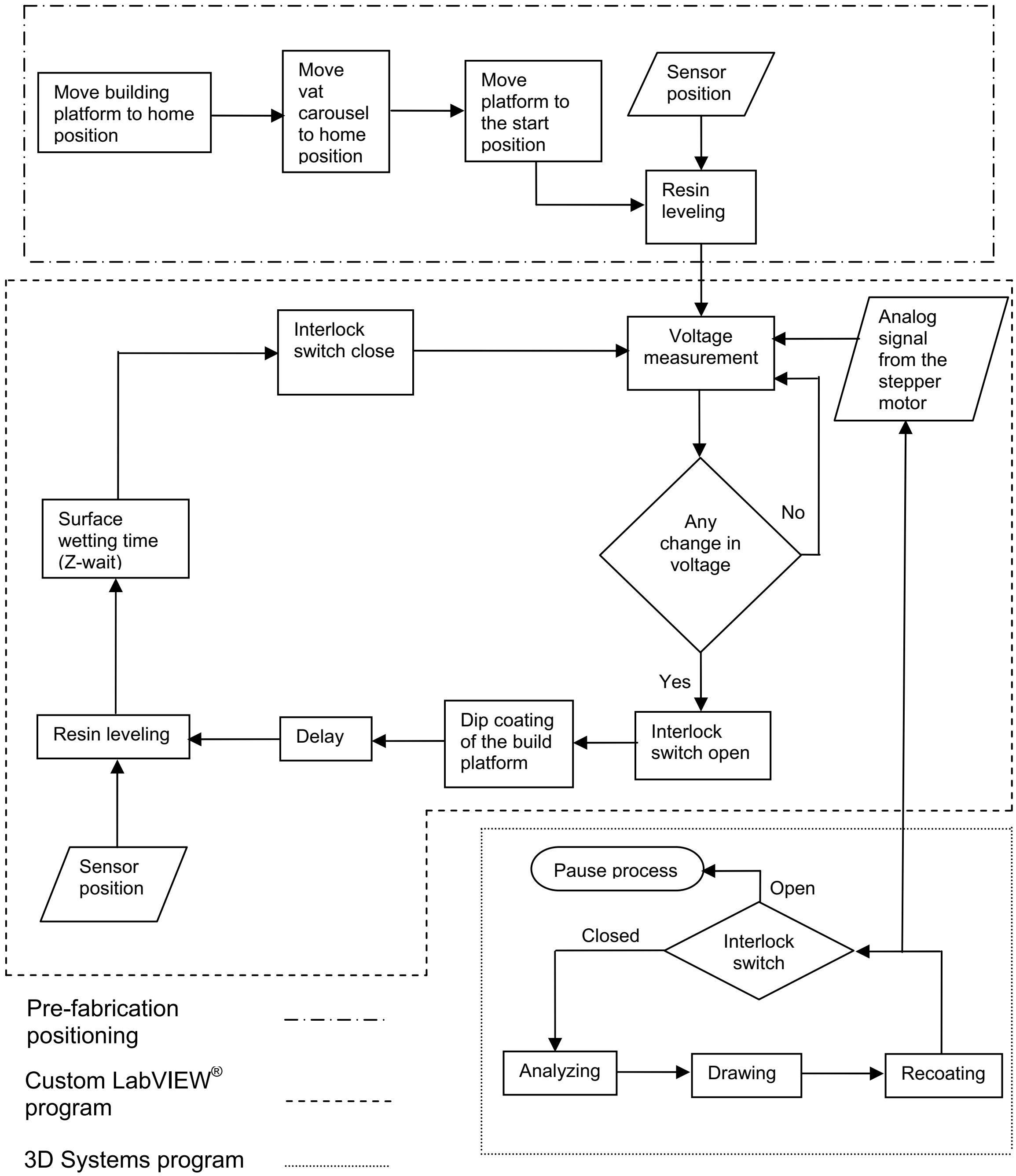
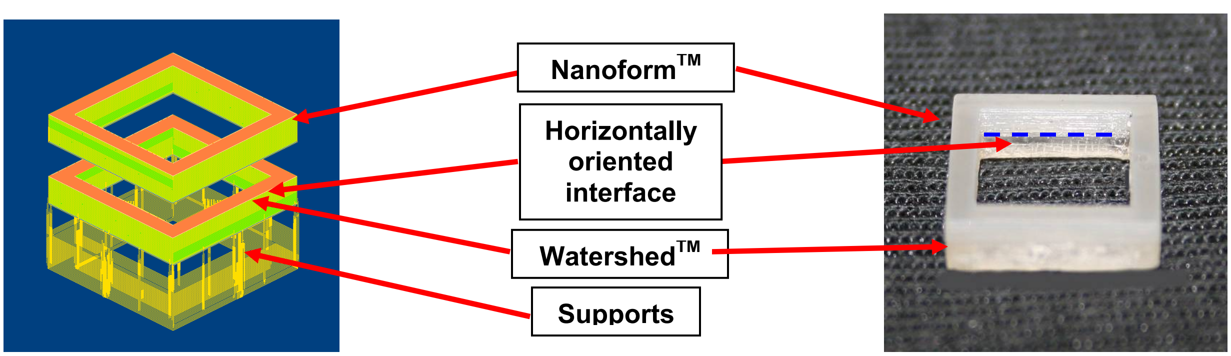


Figure 6. Process flowchart of custom LabVIEW® program.

Any CAD package (such as SolidWorks®) can be used to design the individual parts and export them into STL file format. 3D Systems proprietary slicing software (3D Lightyear™ 1.4) was used to convert the STL files generated during the part preparation and design stages into the build file format required for the operation of the MMSL machine. A process management and control software (described above) was developed using LabVIEW® and its process flowchart is depicted in Figure 6. MMSL operation is divided into three distinct sections (including pre-fabrication positioning, LabVIEW® program, and 3D Systems program). The pre-fabrication positioning starts with initializing the new platform assembly (secured to the Z-stage) and the rotating vat carousel assembly (representing the X-stage) to attain respective home positions. The platform is lowered to the start position and a Masterflex® L/S peristaltic pump is activated to level the resin surface with the platform. After the pre-fabrication positioning is complete, the 3D Systems program is commenced to scan the first layer of the desired part. The LabVIEW® program opens an interlock switch, after the laser beam scans a layer, to pause the 3D Systems program and commands the build platform to traverse vertically downward by a distance equal to the build layer thickness using a dip coating approach. The multi-pump filling/leveling system is then activated to maintain 0.008-inches of the resin on the build layer of the desired part. The LabVIEW® program then closes the interlock switch to commence the laser scanning process. The traditional SL part building is performed layer by layer by integrating the LabVIEW® program with the 3D Systems software to produce desired part with the first resin. Once the part using the first resin is completed, the platform is raised out of the vat and the LabVIEW® program is used to command the vat carousel to rotate to the cleaning and drying vat for cleaning. After desired cleaning of the part and the platform is completed, it is immersed in the next resin vat to continue MMSL fabrication. The process is repeated indefinitely to produce multiple material functional devices. The LabVIEW® program thus controls the interlock switch that acts as an interface between the new MMSL system and the original 250/50 system facilitating successful MMSL operation. The following section demonstrates the manufacturing capabilities of the new MMSL system as compared to the existing 250/50 system.

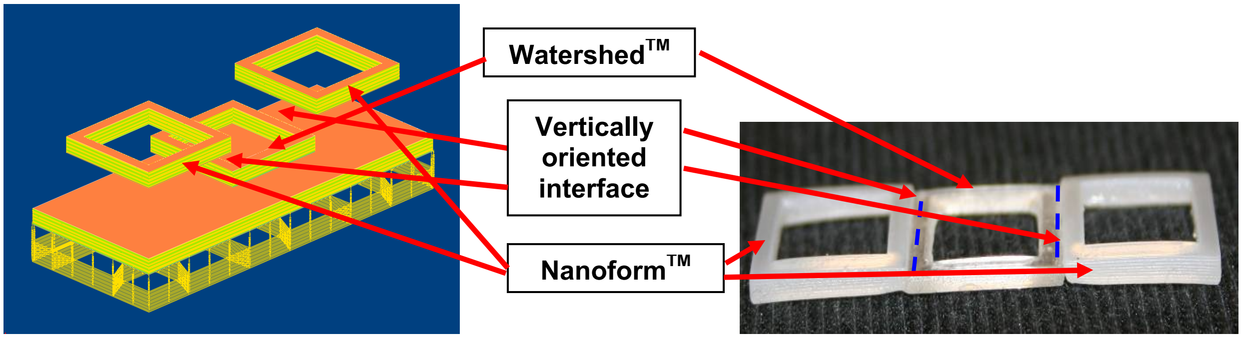
4. Fabrication demonstration

Simple parts with a horizontally oriented interface (a vertical stratified build) and vertically oriented interfaces (a horizontal stratified build) were manufactured using DSM Somos® Watershed™ and Nanoform™ resins due to their considerably different SL resin properties. The part with the horizontally oriented interface is shown in Figure 7 while the part with the vertically oriented interfaces is shown in Figure 8. Watershed™ is the most popular resin and was selected due to its low viscosity while producing strong, tough, water-resistant parts. Nanoform™ (a nanoparticle filled material) was selected due to its ability to withstand high temperatures and fabricate strong, rigid parts. Studies can be conducted to investigate the interfacial bonding between these two resins and various other resins could be included for future research. As shown in Figures 7 and 8, the MMSL machine successfully fabricates multiple material parts with horizontal or vertical material stratification. Some of the important aspects to be studied are interfacial bonding between different SL materials which could expand the scope of MMSL technology into various engineering fields.



(a) **(b)**

Figure 7. (a) Vector file demonstrating vertical stratified build, (b) Finished vertical stratified part



(a) **(b)**

Figure 8. (a) Vector file demonstrating horizontal stratified build, (b) Finished horizontal stratified part

5. Conclusions

A novel MMSL setup was developed to fabricate multiple material functional devices. The new MMSL setup operates similarly to the existing 250/50 system, although a custom LabVIEW® management and control system was used to manage the overall process. The 3D Systems software was retained for controlling the laser scanning process. The new MMSL machine was composed of two basic systems: a hardware system (including machine frame, rotating vat carousel assembly, platform assembly, multi-pump filling/leveling system, and scanning system) and a software system (including 3D Systems software and custom LabVIEW® program). Several components were retained from the existing 250/50 system required for laser scanning and new components and software were developed to add MMSL functionality.

The new MMSL setup was successfully used to manufacture simple multiple material parts featuring vertically as well as horizontally oriented interfaces. This MMSL system offers enormous potential for fabricating a wide variety of multiple material functional structures and research is ongoing to both improve the functionality of the MMSL system and to use the system for exploiting these new MMSL capabilities. We believe a market exists for using multiple materials in SL and our group is exploring a variety of possible opportunities, including multiple colored SL models, embedded electronics and 3D circuitry, and tissue engineering.

Acknowledgments

The research presented here was performed at UTEP in the W.M. Keck Border Biomedical Manufacturing and Engineering Laboratory (W.M. Keck BBMEL) using equipment purchased through Grant #11804 from the W.M. Keck Foundation. This material is based in part upon work supported by the Texas Advanced Research (Advanced Technology/Technology Development and Transfer) Program under Grant Number 003661-0020-2003. Support was also provided through the Mr. and Mrs. MacIntosh Murchison Chair I in Engineering and through research contract 54004 from Sandia National Laboratories in the Laboratory Directed Research and Development (LDRD) program. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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