Multi-Material, Multi-Technology FDM System

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Abstract

A multi-material, multi-technology FDM system was developed and constructed to enable the production of novel thermoplastic parts. Two legacy FDM systems were modified and installed onto a single manufacturing system to allow the strategic, spatially controlled thermoplastic deposition of multiple materials during the same build. Additionally, a build process variation utilizing more than two extrusions tips was employed to deposit thermoplastic materials using variable layer thicknesses and road widths. The hardware and control software is discussed as well as the potential applications of multi-material polymeric parts. Benefits of multiple material FDM include: 1) achieving aesthetic requirements by using polymers of different colors, and 2) attaining desired properties (e.g., bulk tensile/compressive/flexural strength, weight, thermal conductivity) by strategically combining layers and regions within layers of polymers that display different properties. Parts produced using the build process variation exhibited internal road with 1200 ± 39µm road width and 497 ± 11µm layer height while the contours measured 269 ± 18µm road width and 133 ± 3µm layer thickness. Additionally, for a 50.8mm by 50.8mm square section (25.4mm tall), the build process variation required 4.0 hours to build while the original strategy required 6.2 hours constituting a 35% reduction in build time.

1. Introduction

The use of discrete multi-materials within single components may be viewed as a technically challenging and economically favorable manufacturing method that can enable unprecedented levels of functionality and adaptability.[1] By utilizing multi-material components, economic and lightweight designs may be achieved via the reduction of required assembly processes and parts. The automotive industry has already begun taking advantage of multi-material designs in numerous applications (e.g., multi-colored taillights, components with compliant hinges).

Polymers and fiber reinforced polymers are widely used because they exhibit such characteristics as low density, reduced manufacturing cost, ease of manufacturing, high specific strength, and exceptional resistance to corrosion.[2-4] Similarly, these same attributes have attracted much attention in the area of additive manufacturing (AM) in which geometrically complex parts are built in a layer-by-layer fashion directly from computer-aided design (CAD) data. AM technologies that produce polymer parts include fused deposition modeling, stereolithography, laser sintering, laminated object manufacturing, and photopolymer 3D printing. Previous work has demonstrated the use of AM technologies in conjunction with multi-materials to produce a variety of functional components including electroactive polymer actuators[5] and biomedical scaffolds[6]. However, there is no indication in literature that fused deposition modeling (FDM) has been explored for discrete multi-material fabrication even though production-grade thermoplastics (e.g., polycarbonate, acrylonitrile butadiene styrene) are already commercially available for FDM, which may generate greater functionality.

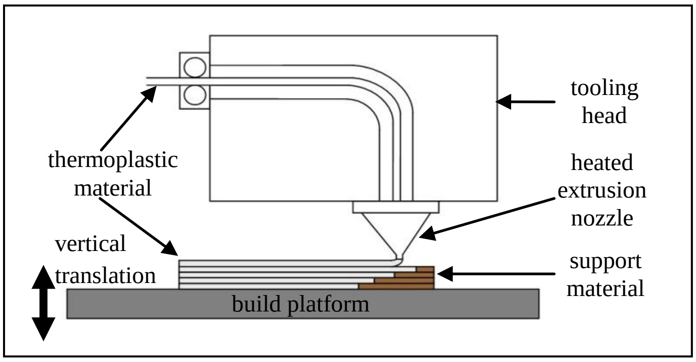

Figure 1: Schematic of FDM process for legacy systems.

An FDM machine builds parts by driving a thermoplastic filament (Ø = 1.59mm) into a heated liquefier and extruding a semi-molten polymer fiber through a small-diameter nozzle (Ø = 0.127, 0.118, 0.254, or 0.330mm). The liquefier is fixed on a tooling head that traverses parallel to the *XY* plane and over a build platform (Figure 1). The tooling head is equipped with two liquefiers that work in concert to deposit both a model and sacrificial support material required for the fabrication of overhanging features and complex geometries. A typical layer of model material consists of a contour that delineates the perimeter of the part's cross section (external region) and rasters that fill the internal region contained by the contour. Additionally, both the contours and rasters are of the same layer thickness. After the layer is completed, the build platform lowers along the *Z* direction a predetermined distance equivalent to the layer thickness to allow for the deposition of the next layer. In this manner, a part is fabricated from bottom to top and is composed of concatenated layers. Moreover, this layered manufacturing process is carried out in a temperature controlled envelope that aids in controlling the shrinkage and development of internal stresses.

Recently, some efforts have been devoted to reducing the build time of AM technologies by using adaptive slicing – a slicing method that assigns variable layer thicknesses based on a part's geometry to better approximate the outer surface.[7-8] Other work that used an FDM machine equipped with two extrusion tips was focused on depositing regular thin layers for exterior regions while using thick layers for interior regions to reduce the build time up to 80% while preserving the surface quality.[9] This approach has demonstrated remarkable improvements to FDM build times and it is hypothesized that having access to more than two extrusion tips can further reduce build times while improving surface quality and part accuracy. The access to four extrusion tips with different orifice diameters can allow more variability in layer thicknesses and road widths as well as the ability to deposit support material for the fabrication of complex geometries. Additionally, discrete multi-material fabrication of geometrically-complex parts using dissimilar materials can be carried out with the use of more than two extrusion tips. As such, the work presented here describes the design and construction of a multi-material, multi-technology FDM system and demonstrates the variable layer thickness and road width deposition method.

2. Multi-Material, Multi-Technology FDM System

Commercial FDM systems make use of two extrusion tips working in concert to deposit a support and model material. In this work, two legacy FDM systems were integrated into a single manufacturing system to provide four extrusion tips and enable the variable layer thickness and road width deposition method. The following sections describe the hardware and software for the multi-material, multi-technology (MMMT) FDM system.

2.1 Hardware

The MMMT FDM system was constructed using two legacy FDM machines, a pneumatic slide, a programmable automation controller, and a central PC. The legacy FDM machines (models FDM 3000 and 2000, Stratasys Inc., Eden Prairie, MN) were used because the standard operations of these machines allow the user to specify model, support, and envelope temperatures. This is particularly beneficial in the sense that non-commercial FDM polymers may be processed, as demonstrated with composite materials[4] and polymethylmethacrylate[10], in contrast to the current FDM machines (e.g., Fortus 400mc or 900mc), which use material-specific microchip canisters that lock-in the machine build parameters. Moreover, each legacy FDM machine communicates using an Automove® Control Language (ACL) that is relatively easy to modify for accommodating non-commercial FDM polymers and interrupting the fabrication process.

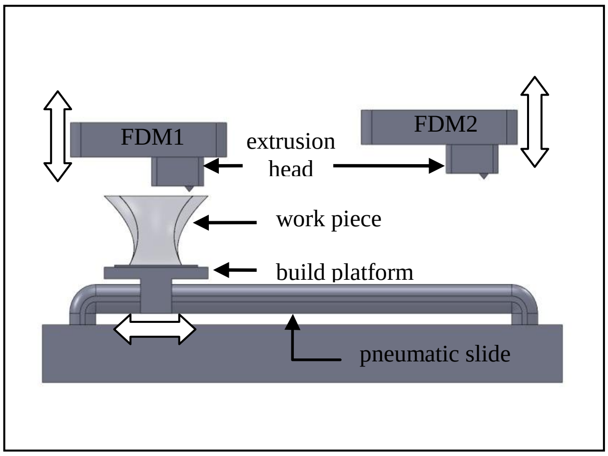

Figure 2: Schematic of multi-material, multi-technology FDM system

The two legacy FDM machines were modified so that the *XY* traversing tooling head was installed on the *Z* stage. The design for this modification was developed in previous work.[11] The non-modified FDM machine consists of an independent *XY* traversing tooling head and a *Z* stage. Installing the *XY* traversing tooling head on the *Z* stage allowed the FDM system to mimic a gantry and enabled the transport of the work piece between the first FDM machine (FDM1) and the second FDM machine (FDM2) on a moveable build platform attached to a pneumatic slide. This layout is illustrated in Figure 2 while Figure 3 shows images of the actual system. Additional space was left vacant between both FDM machines

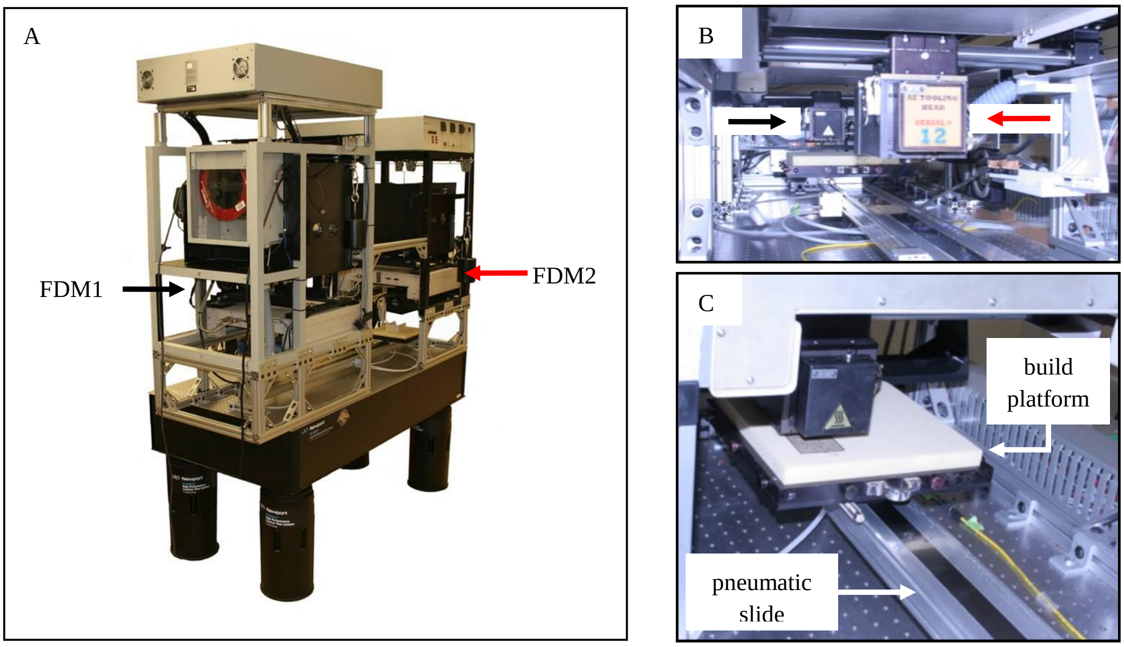

Figure 3: Multi-material, multi-technology FDM system. A) overview of entire system. B) inside view of build envelope (note that FDM1 and FDM2 are highlighted by a black and red arrow, respectively). C) close-up view of FDM1 building on the platform that is attached to a pneumatic slide.

Table 1: Control system hardware for multi-material, multi-technology FDM system

Product	Model	Function
reconfigurable real-time controller	National Instruments cRIO-9074	communicate with control software and individual modules
digital output module	National Instruments 9472	provide voltage signals to pneumatic valves and switches
digital input module	National Instruments 9411	detect logic levels from pneumatic switches and FDM pause indicator
solid-state relay outputs	National Instruments 9485	emulate the pressing of front panel buttons on FDM system

for future incorporations of additional technologies. Direct-write technology is to be incorporated in the future to allow the automated fabrication of 3D electronics such as UAV wings with embedded health monitoring electronics.

The modular, multiple position pneumatic slide (series SFM, PHD, Inc., Fort Wayne, Indiana) was used to transport the work piece between the two FDM machines. The pneumatic slide was configured with two adjustable end stops at each FDM machine and a mid-position actuator as well as corresponding magnetic, solid-state switches at each stop – the voltage output generated by the switches allowed for monitoring the build platform position and coordinated the overall programming logic as will be described below.

The two modified FDM systems and the pneumatic slide were controlled through the use of an overall control system. Table 1 provides a brief description of noteworthy components that constituted the control system as well as the component functions for the MMMT FDM system.

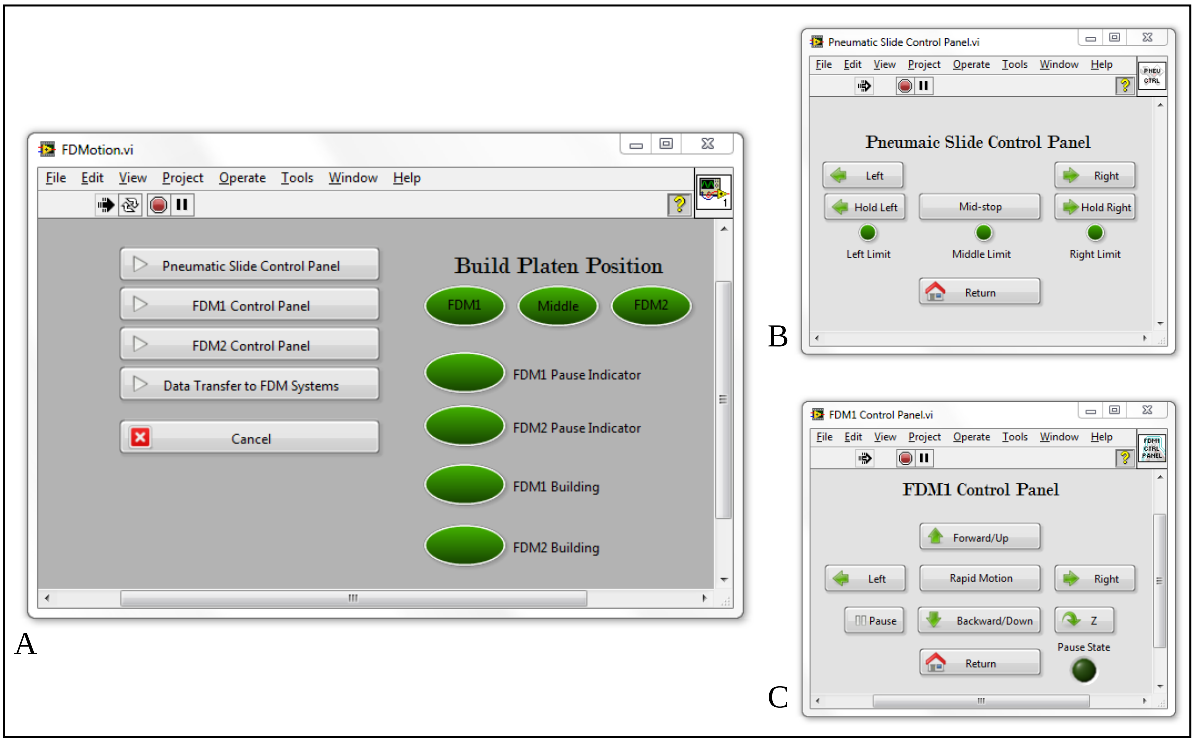

Figure 4: Graphic user interface for FDMotion software. A) main control panel for FDMotion. B) control panel for pneumatic slide. C) control panel for FDM1 system.

2.2 Software

A software program and graphic user interface (GUI) was developed using LabVIEW 2011 (National Instruments Corporation, Austin, TX) to control the fabrication process within the MMMT FDM system. The custom-made software program was named FDMotion for convenience and the GUI for FDMotion is presented in Figure 4. Through this interface, the user is able to control the pneumatic slide (Figure 4B), each of the two tooling heads (FDM1 control panel is shown in Figure 4C), and send the toolpath commands to the MMMT FDM system. The block diagram in Figure 5 illustrates the sequence of actions that are performed by FDMotion.

The programming architecture consisted of a state machine in which a decision making algorithm was developed and employed to direct the hardware operations. The state

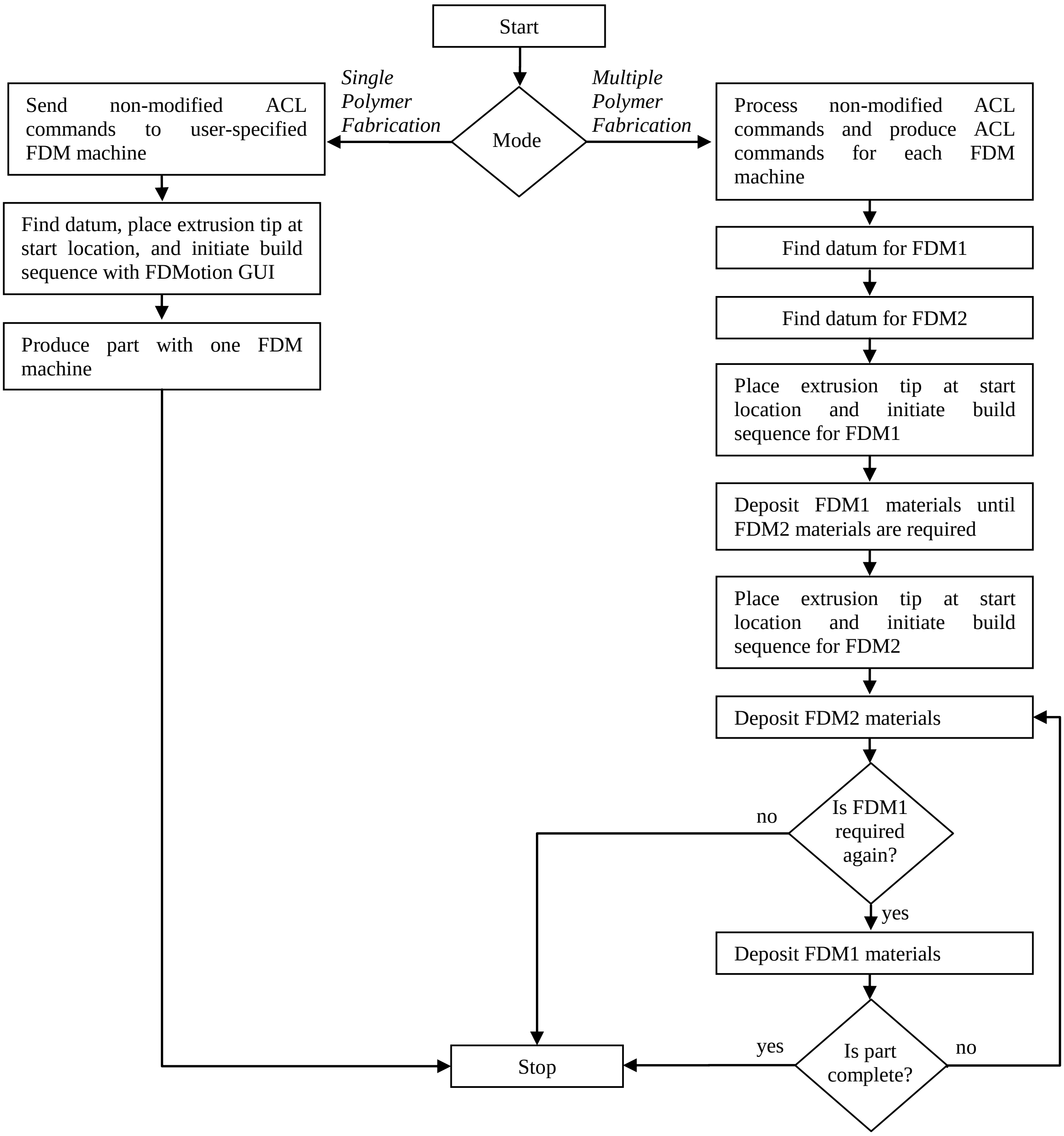

Figure 5: Block diagram for sequence of actions performed by FDMotion.

machine architecture allowed the manufacturing process to enter states as well as transition from one state to another when initiated by triggering events or conditions. Examples of states include "FDM1 building" and "move platform to FDM2", and triggering events where produced by solid-state switches, for example. Note that the system can operate in one of two modes: single polymer fabrication or multiple polymer fabrication.

3. Methods

Simple square prisms were fabricated with a non-modified FDM 3000 and the MMMT FDM system to compare build times. The square prisms were 50.8mm by 50.8mm in square section (25.4mm tall) and made from acrylonitrile butadiene styrene (ABS) thermoplastic. Prisms built with the non-modified FDM 3000 contained layers with a uniform thickness (0.254mm) that consisted of two contours as well as rasters that were parallel to the *Y* axis. Conversely, prisms built with the MMMT FDM system were made using thin layers (0.127mm) and narrow roads (0.254mm) for the exterior regions while the interior regions were filled with thick layers (0.508mm) and wide roads (1.27mm). The rasters were also deposited parallel to the *Y* axis and two contours were used for the exterior regions. These layer thicknesses were chosen as such so that a contour-to-raster thickness ratio of 4:1 would result and enable the proper height alignments of the rasters and contours.

Optical images were captured with a stereomicroscope (model: MZ 16, Leica Microsystems Inc., Buffalo Gove, Illinois) equiped with a digital CCD camera (model: Retiga-2000R, QImaging, Surrey, British Columbia) to confirm the dimensions of the deposited roads within the interior and exterior regions. Specimens were polished with a metallurgical polishing machine equipped with a water coolant sprayer to expose the prism's cross section while prohibiting the thermoplastic from melting. Initial attempts at imaging the exterior regions resulted in undecipherable contours. That is, accurate measurement of layer thickness and road width could not be acquired because it was difficult to distinguish the beginning and end of a contour. Therefore, a separate prism was fabricated using only one contour for the purposes of measuring the contour's dimensions.

4. Results and discussion

Images produced by polishing and optical microscopy are presented in Figure 6. For the fill pattern roads (rasters), measurements ($\mu \pm \sigma$) indicated a 1200 ± 39μm road width and

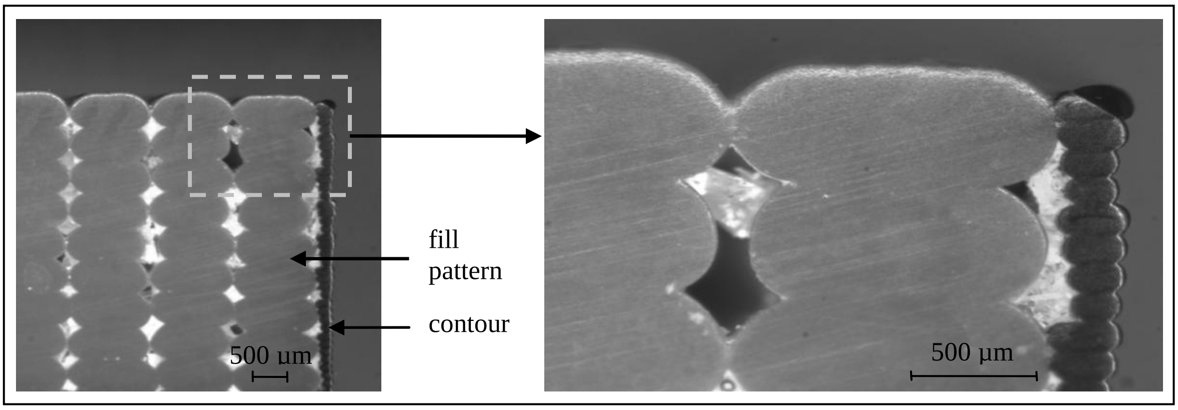

Figure 6: Cross section of square prism obtained with optical microscopy (overview on left and close-up on right). Note the fill pattern is made with a large layer thickness and road width while the contour is made with thinner layer thickness and road width.

497 ± 11μm layer thickness. Contour measurements demonstrated a 269 ± 18μm road width and 133 ± 3μm layer thickness. The layer thicknesses were intended to result in a contour-to-raster thickness ratio of 4:1, and the measured dimensions approximated the ratio within reason (~3.7:1). For the 50.8mm by 50.8mm square section (25.4mm tall), the modified deposition approach required 4.0 hours to build while the original strategy required 6.2 hours constituting a 35% reduction in build time.

To demonstrate the manufacturing capabilities of the MMMT FDM system, other geometries were fabricated using the variable layer thickness and road width approach. Figure 7A shows a dome structure with an outer surface that exhibits much curvature. This type of surface is expected to take advantage of the variable layer thickness and road width approach since contours made using thinner layers will approximate the periphery more accurately than thicker layers.[9] Additional parts were built to demonstrate the capabilities of the MMMT FDM system and are shown in Figure 7B. These parts, in particular, show the use of thermoplastics with different colors that can aid in meeting aesthetic requirements.

5. Conclusions

The MMMT FDM system was successfully constructed using two legacy FDM systems and a custom-made GUI (FDMotion). This system will enable basic and applied research as it pertains to FDM. In particular, this study demonstrated the successful fabrication of parts using three extrusion tips while employing a variable layer thickness and road width approach that reduced the build time of simple square prisms by ~35%.

Although this study successfully demonstrated the fabrication of discrete ABS-ABS parts, much work is required to fabricate using four extrusion tips. An assessment of meeting requirements in terms of aesthetics (color), surface quality, processing time, and part accuracy should also be carried out. In terms of applied/basic research, the developed MMMT FDM system has enabled ongoing research efforts in the area of FDM of dissimilar materials, micromaching of FDM-manufactured substrates, and 3D structural electronics using FDM.

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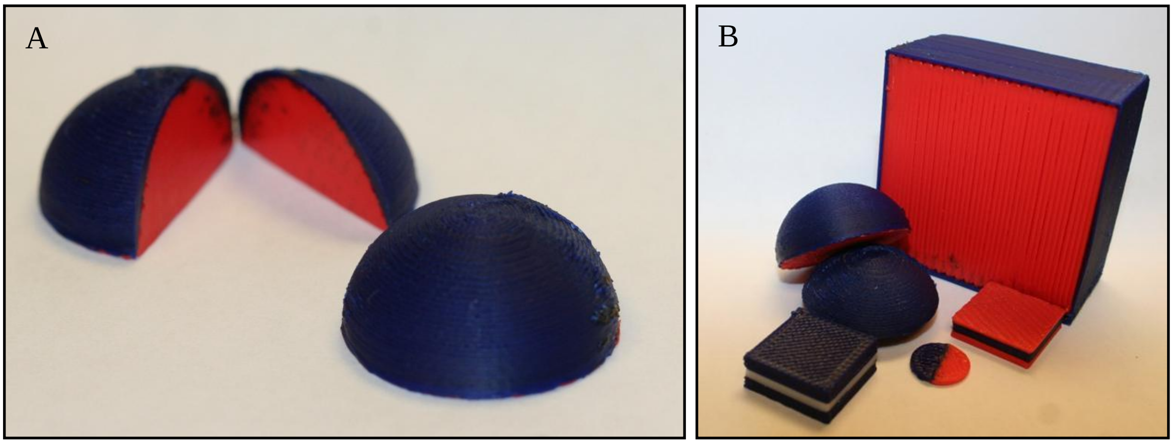

Figure 7: ABS parts demonstrating the variable layer thickness and road width approach. A) dome structures (structure in background was bisected after being fabricated). B) additional parts demonstrating the use of different colored polymers to achieve aesthetic requirements.

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