

Design and Development of a Multi-Tool Additive Manufacturing System

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Abstract

Additive manufacturing (AM) makes complex parts with a single class of material. Each AM technology encompasses specific techniques and requires diverse components to selectively form each layer, which has segregated AM research by respective technologies. Multimaterial AM exists, but it is the same class of material with the same deposition tool. To fully benefit from AM, researchers must explore the combination of multiple AM modalities and materials such that a multifunctional part may be fabricated using strengths of multiple technologies. While the methods for fabricating each layer differ, all of the AM technologies share the fundamental layer-based approach. By recognizing this universal similarity coupled with the desire to make multifunctional parts, a single system has been created to combine five different AM modalities. In this paper, the authors discuss the design and development of a multi-tool AM system that includes binder jetting, material jetting, vat photopolymerization, paste extrusion, and filament extrusion. Examples of multifunctional, multimaterial parts fabricated by multiple AM processes in a single integrated process are demonstrated.

1. Introduction

1.1 Functional organization of AM

Additive Manufacturing (AM), also commonly known as 3D printing, is the process of fabricating parts layer-by-layer. While there are several different types of AM technologies, all share a common process flow of turning a computer aided design (CAD) model into a 3D object. As shown in Figure 1, the CAD model is first converted to a standard tessellation (STL) file, which creates sets of stored triangle vertices and normal vectors. Software slices the file into cross-sectional 2D layers and develops a tool path to manufacture these slices. The AM system then sequentially follows these toolpaths layer-by-layer to fabricate each part. Functionally, the only difference among all AM technologies is how each layer is fabricated [1].

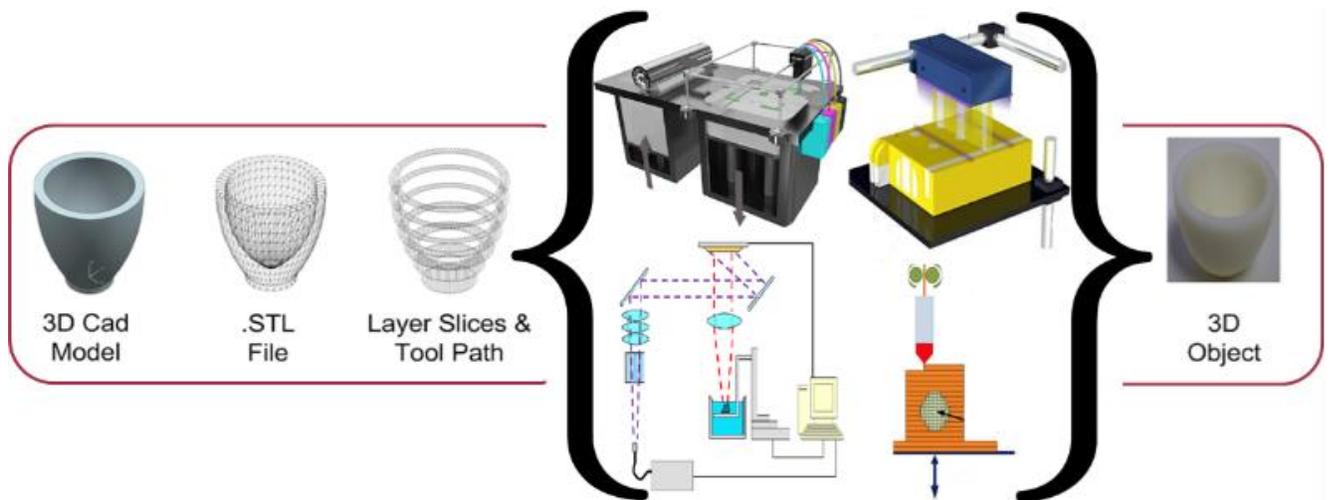


Figure 1. Process flow for AM technologies showing commonality between different modalities.

Each additive technology creates parts in different ways because they use different classes of materials. Vat photopolymerization uses a UV light source to selectively cure regions of a liquid photopolymer resin vat. Binder jetting uses an inkjet printhead to jet binder into a powder bed of either a metal, ceramic, polymer, or plaster powder. Material jetting jets liquid photopolymer droplets onto a substrate and cures it with an overhead UV light source. Filament extrusion heats a thermoplastic beyond its glass transition temperature before selectively creating primitives. Paste extrusion forces viscous pastes through a nozzle with a mechanism such as applied high pressure compressed air.

AM can be an advantageous alternative to traditional manufacturing methods due to its ability to create complex, multimaterial geometries efficiently and economically; however, one of the greatest challenges facing AM is the lack of printable multimaterial parts due to the fact that a single toolhead can only manufacture a single class of materials. With the ability to utilize multiple classes of materials in a single print, engineers can design for a part to serve multiple functions. Each AM technology utilizes different fundamental physics to selectively create building blocks of material, which results in certain materials only being able to be printed with a certain AM technology [1].

1.2 Multimaterial and multi-modality AM systems

Recognizing that the process flow for creating a part with a layer-based method is consistent across all AM technologies, there exists an opportunity to develop an AM system featuring tools of multiple AM technologies within one machine. A multi-tool AM system would allow users to create multi-functional products by using multiple AM technologies in a single print to fabricate multi-material parts. For example, the system could fabricate “smart” products that feature integrated sensing and actuation by extruding conductive pastes into a part with a

photopolymer exterior. This machine would also be able to create functionally-gradient materials by placing ductile materials beside hard materials.

There has been an increase in development of systems combining AM and traditional machining, which can be considered a hybrid manufacturing process, containing both additive and subtractive methods. Arnold and authors have designed a machine integrating material extrusion, milling, and turning in a modular approach [2], and Keating and Oxman combined extrusion, milling, and sculpting through the use of a six-axis robotic arm positioning the workpiece to fixed tool mounts [3]. Zmorph has fabricated a system that has a single tool head slot with attachment options of various extrusion nozzles, a laser for engraving, or a CNC tool. A tool can be manually changed out during a print and replaced with a new tool to continue fabrication with the new attachment [4]. Hyrel 3D has created a three-axis gantry with swappable tools within a common interface. The modular platform allows multiple extrusion heads that handle materials of different viscosities to simultaneously manufacture multiple parts. Additionally, extrusion nozzles may be interchanged with lasers and routers for engraving, cutting, or routing purposes [5]. nScript has developed a high-precision nozzle to handle pastes and filaments, and assembling multiple nozzles onto a gantry combined with a “pick-and-place” tool has been shown to be advantageous for applications such as bioprinting, antennae, and circuit components [6]. These resources were used in the design phase to better understand how machines have integrated diverse manufacturing technologies within a common work space.

Multi-material AM has been typically accomplished within a single technology. The PolyJet process, commercialized by Stratasys, was the first to adapt multi-material printing in material jetting by simultaneously inkjetting two materials in dropwise deposition patterns [7]. This strategy allowed for flexible polymers to be printed directly adjacent to rigid polymers expanding the Design for AM (DFAM) possibilities. Sitthi-Amorn and authors have expanded the material jetting capabilities by developing a machine-vision-assisted platform for multi-material AM that can support up to ten materials simultaneously. The system provides multi-material design and fabrication capabilities to the computer graphics community, and it creates the ability to fabricate complex materials including fiber optic bundles, fabrics, privacy screens, and LED lenses [8]. More recently, multi-material printing has been achieved with vat photopolymerization. One such example is the system developed by Inamdar and authors who used a rotating carousel to house four vats, which expands AM applications in colored printing, embedded electronics, and tissue engineering [9]. Multiple material capability can also be seen with material extrusion technologies. Malone and Lipson created a multi-material extrusion fabrication system featuring extrusion of liquids, gels, and pastes as well as thermoplastics through an open-source extruder design [10]. Wang and Liu used a nozzle with varied pneumatic parameters to extrude both metal and nonmetal inks [11]. Espalin and authors combined two filament extrusion printers onto one platform to enable the production of novel, multi-material thermoplastic parts. Multiple extrusion tips provided the opportunity to vary layer thickness and width to fabricate parts attaining desired tailored properties such as color, mechanical strength, weight, and thermal conductivity [12].

Multi-material AM has recently been expanded to integrate multiple technologies together in one build thus combining strengths from different technologies. Lopes and co-authors have designed a machine to combine vat photopolymerization and extrusion, which was used to conduct research in printed integrated circuits [13]. A system that combines vat photopolymerization and extrusion has also been developed by the Diyouware Initiative in Spain. Instead of keeping all inherent functional components of each AM technology, the system was designed with an extrusion nozzle to deposit low-viscous resins and a laser diode to selectively UV cure the material [14]. Rize has developed a printer that combines extrusion and material jetting to fabricate end-use parts. An extrusion nozzle and a print head are mounted to the printer, and each can be activated in a voxel-wise deposition strategy to create functional thermoplastic and ink combinations [15]. Raza and authors have developed a system capable of depositing low-melting-point alloys, elastomers, and UV-curable resins. The printer features two different jetting nozzles and one paste extrusion nozzle, and a test part included UV cure adhesive, rubber, and solder all on one composite object [16]. While these approaches work towards the goal of multifunctional parts, there have been no previous systems designed combining more than two AM technologies as summarized in Table 1. This multi-tool AM system incorporating five AM technologies will expand the scope of multi-material applications by providing the opportunity to combine several classes of materials.

Table 1. Summary of current systems that utilize multiple, different AM technologies. The system presented in this paper, shown in the bottommost row, is expanding the capabilities of multi-material printing across multiple technologies. For simplicity, extrusion of liquids, gels, and other inks and resins are combined within the “Material Extrusion: Paste” category.

First Author or Company	Material Extrusion: Filament	Material Extrusion: Paste	Vat Photopolymerization	Material Jetting	Binder Jetting
Zmorph	X	X			
Hyrel 3D	X	X			
nScript	X	X			
Malone	X	X			
Lopes		X	X		
Diyouware		X	X		
Rize	X			X	
Raza		X		X	
Wagner	X	X	X	X	X

1.3 Goal and context

The overarching goal was to design, build, and evaluate a single AM system that allows users to print with a combination of five additive technologies: binder jetting, material jetting, vat photopolymerization, filament extrusion, and paste extrusion. As a research printer for AM

materials discovery, an open-architecture approach has been employed to provide users with full control to adjust printing parameters. A multi-tool AM system has been manufactured to incorporate all of the technologies in one toolhead assembly with an adaptable platform for layer fabrication. One main LabVIEW interface was created to access controls for each of the technologies. The authors followed a systematic design process, and the highlights will be discussed in this paper. Section 2 outlines the design goals and specifications that influenced design decisions. Section 3 presents the system overview and key components of the detailed design of the multi-tool AM system. Results and discussion are shown in Section 4, and a summary is provided in Section 5.

2. Design Goals and Target Specifications

Although the five technologies are present on the system, they are not necessarily all compatible. Figure 2 displays the compatibility chart developed during the conceptual design. The black lines between technologies indicate a compatible link, i.e. that the two technologies can be used together for successful fabrication. For example, binder jetting will be incompatible with many technologies. A powder bed for binder jetting and resin vat for vat photopolymerization cannot keep materials separate. Filament extrusion and material jetting would likely not work with binder jetting because the deposited material would have difficulty adhering to loose powder. Paste extrusion, on the other hand, is compatible with all of the other technologies.

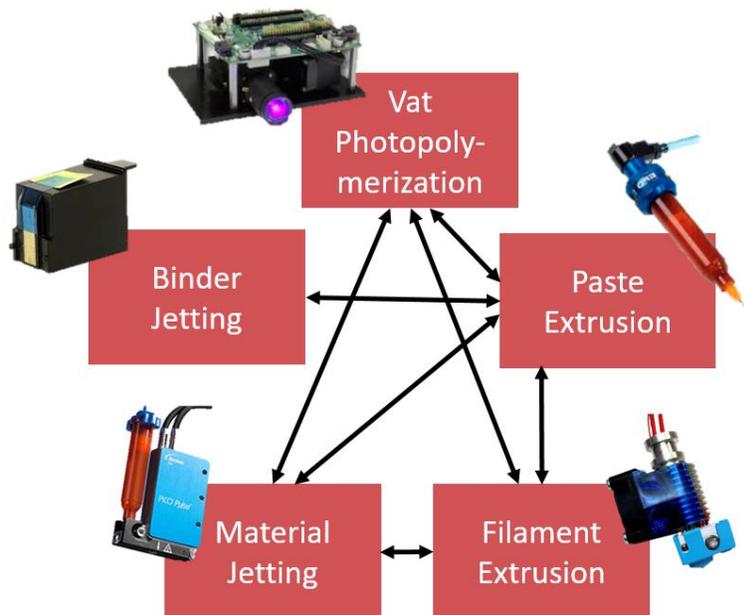


Figure 2. Compatibility chart for the five technologies encompassed in the multi-tool AM system.

With material compatibility kept in mind, a list of requirements and specifications to encompass both the general and technology-specific performance needs of the system. While some requirements were more straightforward, such as the capability of printing in each technology and switching between them quickly, other requirements, such as providing reconfigurable build volumes to enable processing low and high volumes of raw material, arose from demonstrated weaknesses of other AM systems. At a system level, the machine was required to:

- Encompass multiple additive technologies (binder jetting, material jetting, vat photopolymerization, paste extrusion and filament extrusion)
- Allow for fast reconfiguration among technologies (<180 s)
- Be able to print both high and low volume parts (reconfigurable build volume from 50 mm x 50 mm x 50 mm to 200 mm x 200 mm x 125 mm)
- Be stable when printing (<2 m/s² vibrations)

In addition, each technology has specific, individual requirements because final parts depend on the unique parameters and capabilities of each separate technology. These requirements include:

- Operate with variable parameters
- Manufacture small features
- Produce small layer thicknesses

System level target specifications are summarized in Table 2. All of these requirements and specifications influenced key design decisions and testing results which will be discussed in the subsequent sections.

Table 2. Engineering characteristics and target specifications.

Requirement/Engineering Characteristic	Units	Marginal Value	Optimal Value
Prints using material jetting	Y/N	Yes	Yes
Prints using binder jetting	Y/N	Yes	Yes
Prints using vat photopolymerization	Y/N	Yes	Yes
Prints using paste extrusion	Y/N	Yes	Yes
Prints using filament extrusion	Y/N	Yes	Yes
Time to switch between technologies	sec	180	5
Build volume dimensions	mm	50x50x50	200x200x200
Vibrations when printing	m/s ²	2.0	0.1

3. System Overview and Detailed Design

3.1 System Overview

A detailed CAD design of the system and the fully-built system is presented in Figure 3. The main frame was manufactured out of 80/20 aluminum extrusions with diagonal braces at the corners for rigidity. Since the build volume will hold liquid resins, it was designed to be stationary to avoid sloshing while the toolhead moves along X and Y high load, high precision linear stages (Zaber A-LST-E series) that are bolted to cross beams of the main frame. The build plate is actuated in the Z direction to avoid axis collisions while maximizing build size and minimizing additional overall system size. The frame and build platform were bolted to a modified wooden table that allowed linear actuators to control Z motion of the build and feed chambers. A large sheet of high density polypropylene was bolted to the tabletop to serve as the main work surface, which would be compatible with any of the powders, resins, or other liquids used. To accommodate wires and electronics, a shelf was attached to the back of the machine where most of the electronic boards could be protected from harmful materials. Wire looms and cable carriers were also added to reduce the risk of wire tangles with all of the moving components. The authors then decided that the toolhead and build platform operate independently, which allowed them to be treated as separate subsystems.

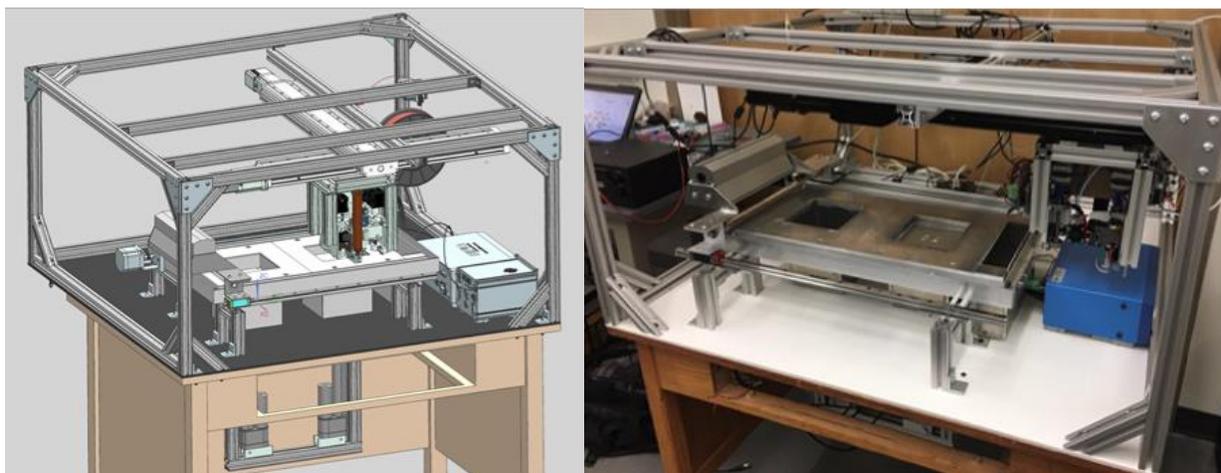


Figure 3. (a) Detailed design of the multi-tool AM system in CAD. (b) Manufactured version of multi-tool AM system.

3.2 Toolhead Design

A toolhead configuration had to be selected that allowed all five technologies to be incorporated, as well as fast reconfiguration between them. A secondary objective was a modular design that allows for integration of additional, new tools. To fulfill these requirements, a toolhead was designed featuring all individual technologies mounted on one rigid frame due to simplicity of machine integration, as seen in Figure 4. Each individual toolhead mounts to a lead screw actuated by a stepper motor which allows lowering into optimal printing position and retracting when finished, as shown in Figure 5, to avoid interference with printed parts. Future

development can easily be implemented by creating a new bracket to the leadscrew if a new toolhead is to be included.

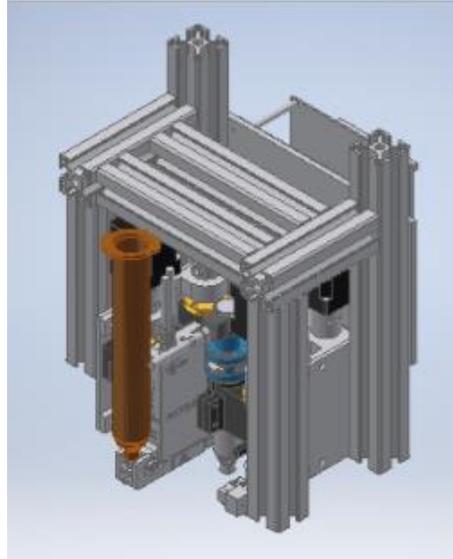


Figure 4. CAD model of the toolhead with unique all-in-one design.

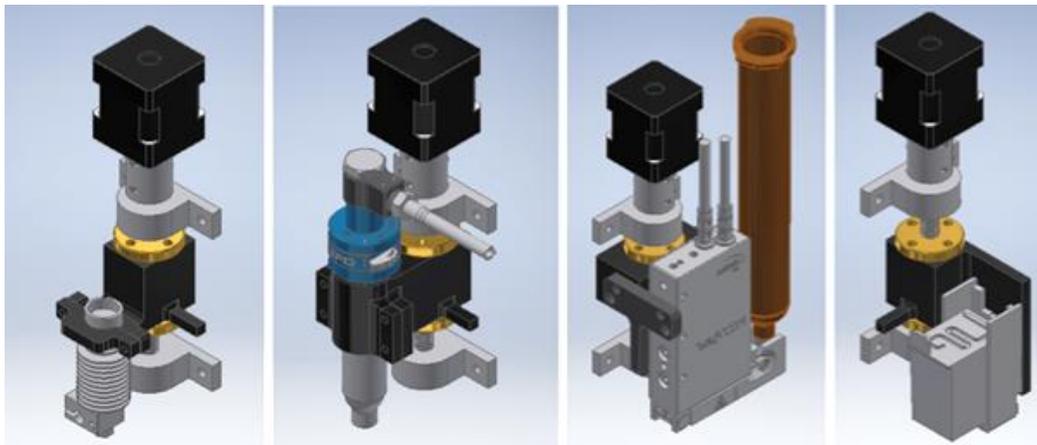


Figure 5. CAD models of (a) Filament Extrusion, (b) Paste Extrusion, (c) Material Jetting, and (d) Binder Jetting.

Figure 5 provides detailed schematic of each individual toolhead:

- Filament extrusion (Figure 5a): AV6 hot-end by E3D allows printing of thermoplastic filaments at extrusion temperatures up to 400°C. The robust and well-tested design includes a sharp thermal break to ensure filament will not be melted prior to entering the hot end.
- Paste extrusion (Figure 5b): A Nordson Ultimix V was selected because it offers precise starting, stopping, and control of applied and vacuum pressures.
- Material jetting (Figure 5c): A Nordson PicoPulse jetting valve for material jetting offers adjustable waveform and frequency, a jettable viscosity range of 1-

10,000 cP, and high accuracy and precision.

- Binder jetting (Figure 5d): An HP C6602A thermal inkjet printhead has the ability to send controlled electric pulses to each individual nozzle.
- Vat photopolymerization (not shown in the figure): An LC4500UV projector provides high resolution projections for UV curing, and it is mounted to the rear of the toolhead.

With all of the toolheads mounted to a single frame, the time to change between technologies is minimized.

3.3 Platform Design

The key build platform requirement was to be compatible with all intended materials, which includes, but is not limited to, powders for binder jetting and photopolymer resins for vat photopolymerization. To achieve this, a metal build volume was welded together with an actuator going through a seal in the bottom. Metal allows compatibility with corrosive resins and the ability to add heating pads to the walls. Heating pads are advantageous to remove humidity in powders, cure jetted binders, reduce thermoplastic part warpage, and reduce viscosity of highly viscous resins. A feed chamber, collection chamber, side overflow chambers, and a recoat system were included for the binder jetting modality. The recoater uses a rotating roller to increase powder flowability and compaction and an overhead heater to cure binders. The recoat frame is adjustable to ensure spread layers of powder are smooth and level. These components integrated into a single platform design is displayed in Figure 6.

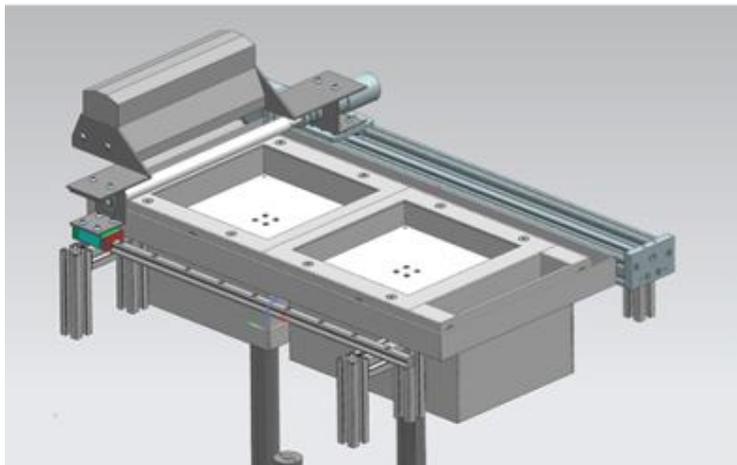


Figure 6. CAD model of the platform design.

A secondary requirement was to be reconfigurable for both research and production sized prints. The build volumes (8" x 8" x 5" in Figure 6) are removable allowing the user to insert any size build volume into the machine. The swappable strategy where the build volume inserts over the actuator followed by the build plate is shown in Figure 7.

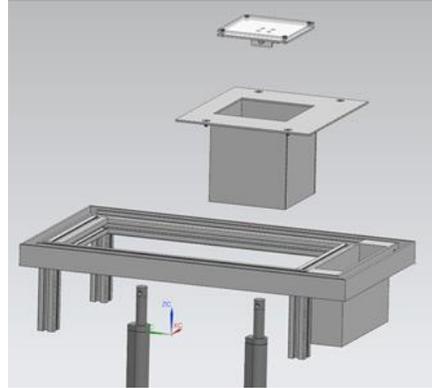


Figure 7. Swappable build volumes: 5" x 5" x 5" shown.

In addition to swappable build volumes, the build plates also had to be designed to account for different technologies. For example, extrusion requires a heated build plate for the best adhesion of filament to the surface, material jetting requires an anodized surface to avoid light reflection, and binder jetting requires a sealed build plate for the containment of powder. To account for this, multiple build plates were manufactured, and a tight-tolerance clevis bracket and pin connect an attachment plate to the linear actuator that controls Z axis movement. The actual build plates bolt to tapped holes in the attachment plate with spacers in between to provide room for the silicone heating pad needed for extrusion as seen in Figure 8. The bolts are countersunk to ensure there is no protrusion on the build plate that could cause a fatal crash of the toolhead.

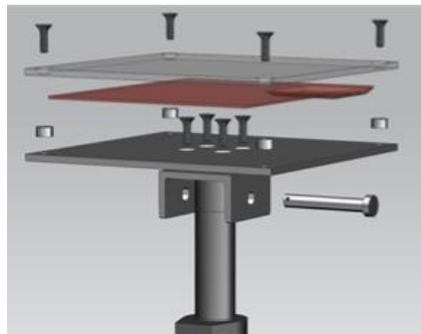


Figure 8. CAD model of the build plate attachment. Filament extrusion build plate is shown.

3.4 Control System

With such a complex system, there are many different aspects of the machine that need to be controlled such as toolhead actuation, nozzle firing, and temperature regulation. To accomplish this, the authors decided to use separate microcontrollers (Arduinos) synced to a central control system. Each microcontroller is designated to specific tasks as shown in Figure 9. Since temperature regulation and controlling Z position require constant monitoring, one microcontroller constantly accomplishes this without disrupting another system. The microcontrollers communicate with LabVIEW subVIs controlled by a master VI. Additionally, LabVIEW directly controls the stages and projector.

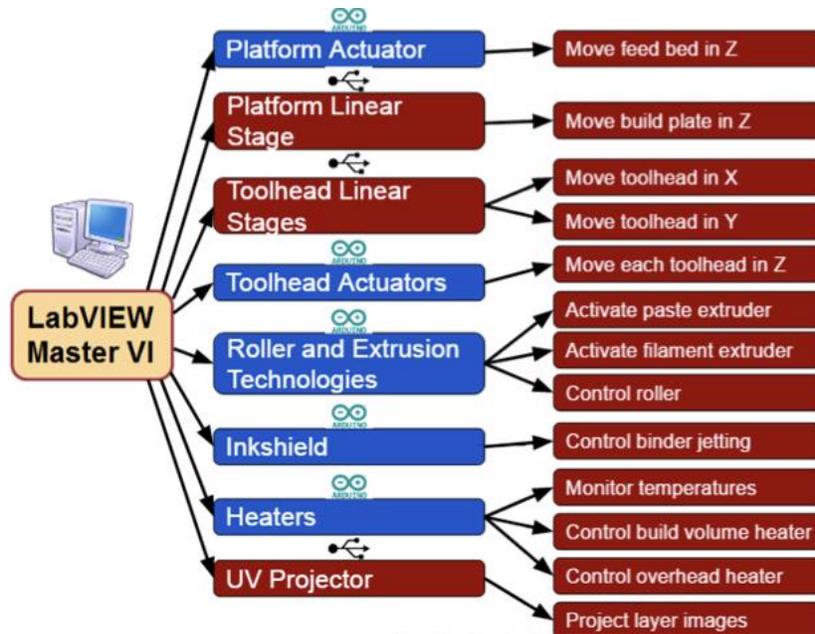


Figure 9. Control system hierarchy for all subsystem controllers and respective tasks.

The Master VI combines all of the subVIs for each system into a single interface for all processes as seen in Figure 10. All of the process-specific settings can be set, such as number of passes on a binder jetting head or delay between projected images. COM ports for all of the microcontrollers and stages, temperature settings, and motion can also be controlled from this screen. Within this system, the Master VI sends Serial Data to both of the linear stages for motion, as well as data, start, and stop commands to the Arduinos that control the subsystems.

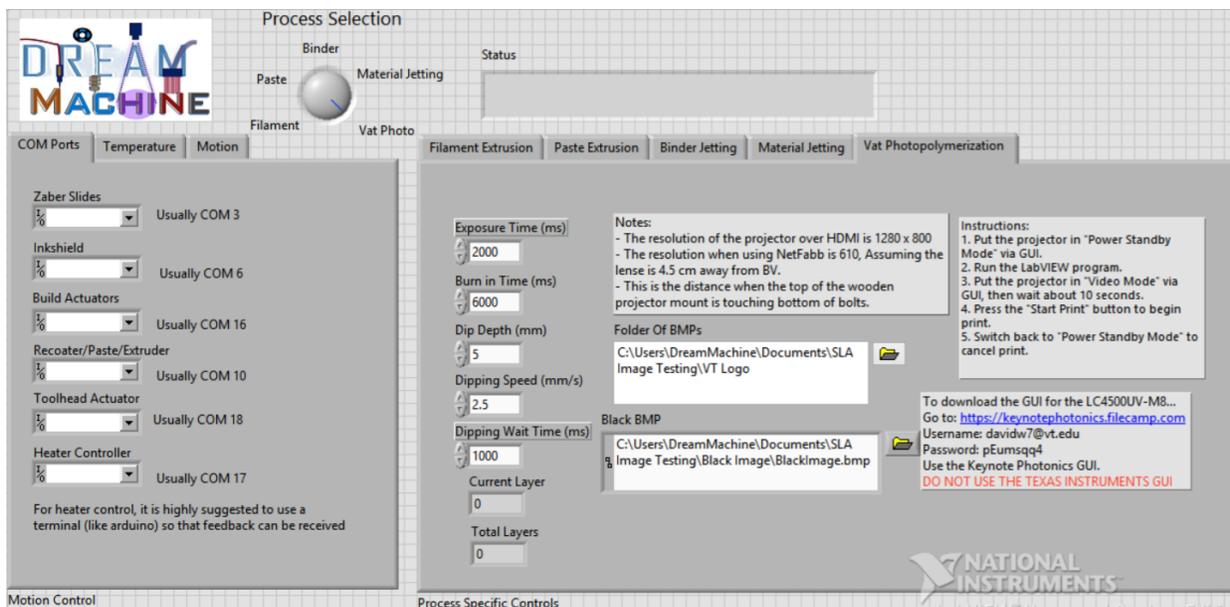


Figure 10. The LabVIEW front panel for the Master VI.

4. Results and Discussion

With the machine fully operational, general and technology-specific requirements and target specifications were tested to evaluate system performance.

4.1 System-level evaluation

The system level requirements were tested separately from the individual technology requirements. Binder jetting, vat photopolymerization, filament extrusion, and paste extrusion are all successfully designed for and included in the machine. Material jetting has been designed for, but has not yet been incorporated. The ability to print both low and high volume parts has also been successfully included with reconfigurable build volumes. In addition, reconfigurable build plates allow for all technologies to print in the same build volume, minimizing overall system size.

In order to test the fast reconfiguration among technologies requirement, a stopwatch was used to measure the time from when one toolhead finished depositing material until the next began laying material. The two toolheads used were filament and paste extrusion for maximum time since both toolheads need actuated, as opposed to other technology combinations such as paste extrusion and vat photopolymerization because the projector does not need actuated in the Z direction. Results showed the time to retract one toolhead and lower a separate toolhead into printing position was 18 s.

To ensure the machine was stable when printing the authors placed an accelerometer on the frame. To simulate worst case conditions, a minimum feature part was used with a 1D deposition technology, such as paste or filament extrusion. A small feature requires a toolpath that includes rapid back and forth motion of the toolhead causing oscillatory vibrations. Measuring acceleration with the fastest travel speeds and smallest predicted feature size showed only subtle vibrations with a maximum acceleration of 0.3 m/s^2 .

4.2 Technology-specific evaluation

The technology-specific customer needs were also evaluated. In order to achieve optimal process parameters, an iterative process was used in order to tune the parameters for each individual technology. First, the process parameters of a certain technology were selected based on similar parameters used in other additive machines. Next, a validation sample with varying features was printed using those settings. After printing a test artifact, the target specifications were reviewed to see if the part met the requirements. If not, the process parameters were adjusted and the process would repeat. Although performance of AM systems can be measured across various metrics, this paper discusses the minimum layer thickness and minimum feature

size for each technology implemented. Optical microscopy was used to analyze fine features on the test artifacts with high accuracy.

Binder Jetting

Binder jetting layer thickness and feature size are dependent on binder saturation of the powder. Enough binder must be jetted to ensure interlayer penetration and overlap between neighboring droplets. While the theoretical minimum feature size is the diameter of a single droplet, the actual minimum feature size is limited by post-processing. The feature must have enough green strength to survive depowdering. Binder jetting parts achieved layer thicknesses as small as 50 μm and features as small as 0.47 mm as seen in Table 3 and Figure 11.

Table 3. Target specifications and results of minimum layer thickness and minimum feature size for binder jetting.

Target Specification	Result
Min. Layer Thickness	50 μm
Min. Feature Size	0.47 mm

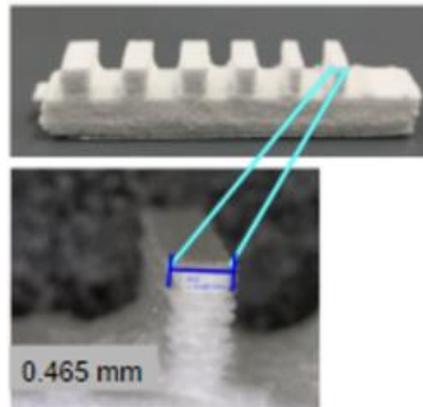


Figure 11. Binder jetting minimum feature size of 0.465 mm.

Vat Photopolymerization

Vat photopolymerization utilizing mask projection has the ability to fabricate fine features due to the precise control of digital micromirror devices. Layer thicknesses as small as 150 μm and features as small as 0.12 mm were achieved as shown in Table 4 and Figure 12. With a refined working curve, it will be possible to achieve even smaller layer thicknesses and features by avoiding overexposure.

Table 4. Target specifications and results of minimum layer thickness and minimum feature size for vat photopolymerization.

Target Specification	Result
Min. Layer Thickness	150 μm
Min. Feature Size	0.12 mm

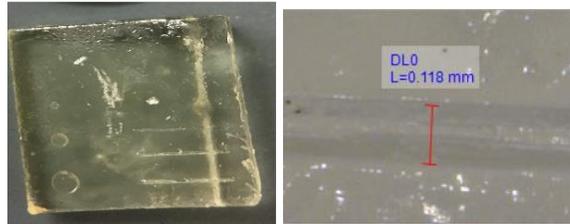


Figure 12. Vat photopolymerization test artifact with 0.12mm minimum feature.

Paste Extrusion

Paste extrusion performance depends on material, pressure, and nozzle size. The multi-tool AM system created a minimum layer thickness of 300 μm and minimum feature size of 3 mm, as seen in Table 5 and Figure 13. The figure shows the difference when printing with an applied pressure of 4 psi and 10 psi. Using a less viscous material and a smaller nozzle will allow us to achieve finer features in the future.

Table 5. Target specifications and results of minimum layer thickness and minimum feature size for paste extrusion.

Target Specification	Result
Min. Layer Thickness	400 μm
Min. Feature Size	3 mm



Figure 13. Paste extrusion minimum feature size test artifacts. The left shows paste extrusion with 4 psi and the right shows paste extrusion with 10 psi of applied pressure.

Filament Extrusion

Filament extrusion has several key parameters that influence the specifications of interest. Theoretically, the minimum feature should be the diameter of the extrusion nozzle. Although the hot end had a 0.6 mm nozzle on it, this system printed a minimum layer thickness of 500 μm and a minimum feature of 1.8 mm as seen in Table 6 and Figure 14. This is due to a limitation of the X and Y linear stages. The stages have individual motor controllers that require stopping after a given command. Filament extrusion typically relies on a continuous motion printing process so starting and stopping degrades the quality of the filament track laid. The authors have recognized this limitation and are considering other stages to enhance performance of the system.

Table 6. Target specifications and results of minimum layer thickness and minimum feature size for filament extrusion.

Target Specification	Result
Min. Layer Thickness	500 μm
Min. Feature Size	1.8 mm

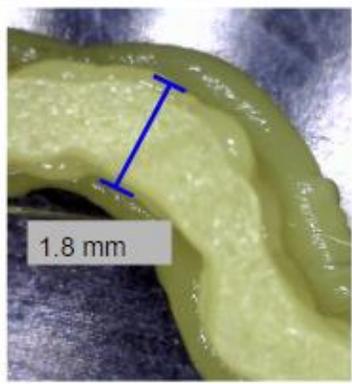


Figure 14. Filament extrusion minimum feature size of 1.8 mm. This feature size was limited due to XY stages stopping during arc movement.

With layer thicknesses and minimum feature sizes determined, the authors created a set of design guidelines to ensure successful manufacturing of parts. These design guidelines were used to manufacture complex parts with binder jetting and vat photopolymerization as seen in Figure 15.



Figure 15. Complex parts created via binder jetting and vat photopolymerization.

4.3 Multi-material evaluation.

Successful implementation of individual technologies lead to the opportunity to combine processes. To demonstrate this opportunity, vat photopolymerization was used with paste extrusion. In Figure 16(a) a soft silicone outer shell was extruded with paste followed by an interior rigid grid cured with UV light. In Figure 16(b) a conductive paste was extruded into the interior of a photopolymer cured part to work towards integrated circuits. These demonstrations display the designed functionality that allows the multi-tool AM system to expand AM applications.



Figure 16. Multi-material parts fabricated using both vat photopolymerization and paste extrusion. (a) A soft silicone shell was paste extruded with an interior rigid grid created with vat photopolymerization. (b) Conductive paste extruded inside vat photopolymerization parts.

The printer has been tested to print with various classes of materials including photopolymers, metals, thermoplastics, polymer powders, and viscous pastes. The individual processes have been tested in order to optimize parameters. More testing with different materials is required to further qualify the system. Additionally, the integration among technologies needs

to be improved, and the changes between technologies within a part needs to become fully automated. The multi-tool AM system is still being developed and improved, and the authors are confident that with continued advancements, it will soon give researchers the opportunity to revolutionize AM with multi-functional, multi-material parts.

5. Conclusion

All AM technologies share the layer-based approach to fabrication, which allows the possibility of combining them into one machine. A multi-tool AM system has been invented as the first system to combine five AM technologies in one system. The system has the following unique design features:

- Toolhead with all technologies in a single assembly
- XY movement of toolhead via linear stages
- Individual Z actuation for each tool
- Platform with a reconfigurable build volume
- Specific build plates for different technologies
- Z movement of build plate via linear actuator
- Powder feed chamber for binder jetting
- Recoater and overhead heater for binder jetting on linear rails
- Sealed build volume for vat photopolymerization

Vat photopolymerization, binder jetting, filament extrusion, and paste extrusion have all been successfully implemented and tested on the system. Material jetting has been designed for and will be implemented into the machine soon. Process parameters for each technology have been tuned in order to meet target specifications. Multi-material parts involving multiple technologies have also been fabricated to demonstrate the functionality of the system. Future work will include improving process parameters to achieve ideal minimum feature sizes, testing new materials, and exploring new multi-material combinations. The multi-tool AM system has successfully expanded the capabilities of AM technologies and has provided the opportunity to explore new AM applications that would not be achievable with single-technology AM systems.

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7. References

- [1] Williams, C, et al, 2011, “A Functional Classification Framework for the Conceptual Design of Additive Manufacturing Technologies,” *Journal of Mechanical Design*, **133**(12), pp 121-132.
- [2] Arnold, E, et al, 2015, “Designing a Hybrid Equipment for Additive Manufacturing,” *Advanced Mechanics and Materials*, **808**, pp 213- 218.
- [3] Keating, S and Oxman, N, 2013, “Compound Fabrication: a Multi- functional Robotic Platform for Digital Design and Fabrication,” *Robotics and Computer Integrated Manufacturing*, **29**(6).
- [4] Zmorph, 2015, <<http://www.zmorph3d.com/>>.
- [5] Hyrel 3D, 2017, <<http://www.hyrel3d.com/>>.
- [6] nScrypt, 2017, <<https://www.nscrypt.com/>>.
- [7] Stratsys Ltd, 2015, <<http://www.stratsys.com/3d-printers/technologies/polyjet-technology>>.
- [8] Sitthi-Amorn, P, et al, 2015, “MultiFab: A Machine Vision Assisted Platform for Multi-material 3D Printing,” *ACM Transactions on Graphics*, **34**(4), pp 129:1–129:11.
- [9] Inamdar, A, et al, 2006, “Development of an Automated Multiple Material Stereolithography Machine,” *Proceedings of 17th Annual Solid Freeform Fabrication Symposium*, Austin, TX, pp 624-635.
- [10] Malone, E, and Lipson, H, 2008, “Multi-material Freeform Fabrication of Active Systems,” *ASME 2008 9th Biennial Conference on Engineering Systems Design and Analysis*, American Society of Mechanical Engineers, pp 345-353.
- [11] Wang, L, and Liu, J, 2014, “Compatible Hybrid 3D Printing of Metal and Nonmetal Inks for Direct Manufacture of End Functional Devices,” *Science China Technological Sciences*, **57**(11), pp 2089- 2095.
- [12] Espalin, D, et al, 2014, “Multi-Material, Multi-Technology FDM: Exploring Build Process Variations,” *Rapid Prototyping Journal*, **20**(3), pp 236-244.
- [13] Lopes, J, et al, 2012, “Integrating Stereolithography and Direct Print Technologies for 3D Structural Electronics Fabrication,” *Rapid Prototyping Journal*, **18**(2), pp 129-143.
- [14] Clarke, C, 2017, “Brother-run Tech Initiative Merge FDM Process with SLA to Create

Alternative Method of 3D Printing.” 3D Printnig Industry, Web.

[15] Rize Inc, 2016, <<http://rize3d.com/printer>>.

[16] Raza, I, et al, 2017, “Introducing a Multimaterial Printer for the Deposition of Low Melting Point Alloys, Elastomer, and Ultraviolet Curable Resin,” 3D Printing and Additive Manufacturing, **4**(2), pp 83-89.