MultiFab

Fernando Pena

In this paper we will discuss MIT's new multi-material 3D printer, the MultiFab. In order to do so we must first explain what 3D printing is, how it works, compare it to MultiFab, and go into detail about the inner workings of MultiFab. MultiFab is the first of its kind in this new era of technology. “The MultiFab's enhanced multi-material capabilities, open platform, and order-of-magnitude cost reduction potential are high-value, high-impact challenges to the status quo among leading 3D printer companies and offer a clear path to affordable printing polymer parts with a much wider range and combination of properties” (Thryft 2015). The MultiFab markets itself with a number of features which include high-resolution, low-cost, multi-material, extensible with multi-material raster input and integration with auxiliary objects. These features make this printer unique to the others on the market and what make it so interesting and powerful. Each of the features will be described in more detail later in the paper.

Introduction

What is 3D printing? 3D printing is referred to as a style of manufacturing technique known as an additive, as opposed to subtractive, process. Additive manufacturing provides the ability to design and build structures that would be difficult to construct with other processes (Jacques 2012). An example of this would be a milling machine not able to reach the center of an object, additive manufacturing enables building from the bottom up, with plenty of access to all portions of the object. There are several additive fabrication techniques that 3D printers use today. The techniques are filament deposition modeling, fused filament fabrication, stereolithography, multi-jet modeling or material jetting, laminated object manufacturing, and z-printing. The MultiFab uses multi-jet modeling or material modeling, which is also known as polyjet. A polyjet printer is one that resembles that of an inkjet printer. The printing head moves above a platform while jetting micro droplets of a photo-polymer (Bernier 2014). A photo-polymer is a light-reactive resin. This means an ultraviolet (UV) light near the print head hardens, or cures the resin, this is achieved through radiation. Since this type of printer only prints one layer at a time. This gives the material time to harden before moving onto the next layer, it is a perfect candidate for multi-material printing. This ensures that all material is in its final state before the next layer is added. Multiple kinds of materials with different attributes can be layered upon each other with this printer. One of the advantages to the MultiFab, is the vast library of materials that can interweave with each other in order to produce intricate and complex products. This also means the MultiFab can achieve what most other printers cannot, a full spectrum of color.

MultiFab Stands Alone

The MultiFab system introduces itself as being the best in its class. The MultiFab is a high resolution system, it delivers at least forty micron resolution which it obtains by using a high-precision feedback loop. The MultiFab System is low cost in comparison to other products on the market today. It costs around seven thousand dollars to put together with off the shelf components. The per kilogram material cost is around twenty dollars. In comparison to other models that can achieve around the same results, it would cost five hundred dollars per kilogram for material and it would cost a quarter of a million dollars to purchase the system outright. Printed objects are built by stacking cross-section layers of materials through the use of polymer jetting. The production cost of the resulting model is directly related to the volume of material effectively employed in the printing process. This could be a costly operation for large and complex models(Lin Lu 2014). After the initial purchase, this system continues to maintain its low-cost value through production. The MultiFab system can also print ten different materials at the same time which means no replacing print heads or reservoirs of material during the production. The MultiFab has multiple pinheads, each with its own material reservoir. The MultiFab can use these materials interchangeably to create intricate products. The MultiFab system is extensive. In other words, at its bare minimum state users may add software, hardware, or reconfigure the existing entirely. New modules can easily be implemented with the software architecture being modular. The MultiFab system uses a raster file input file. A raster file is one that is made up of pixels, different from vector files which are composed of shapes. Lastly, the MultiFab can integrate with auxiliary objects. This means that the printer can print onto or in combination with physical objects placed on the printing plane (Pitchaya 2015).

Hardware

In order to control all of the components, the MultiFab system uses one main Central Processing Unit (CPU). The communication between the hardware is either using 100 Mb/s Ethernet or USB protocols (Thryft 2015). Each of the subsystems of the machine is controlled by a dedicated microcontroller (Pitchaya 2015). The subsystems are the positioning subsystem, print head modules, UV-curing module, the 3D scanning module, and the material feeding subsystem. Each of these components make up the MultiFab system. The positioning system is one of the more important hardware components, without this the printer heads would not get to their destination. An x and y axis is needed in order to have a two dimensional image, it take a z axis to make it three dimensional. The x-axis positioning system is carried by the y-axis using a timing belt to reposition itself. The x-axis and y-axis make a plane, while the z-axis only has to move up and down. The z-axis has three different lead screws that move the x-y-axis plane up and down. It can also angle the plane at different angles. This comes in handy later on when using machine vision in order to correct errors in printing.

In order to make the system affordable, it adapts consumer print heads from polymer 3D printers. It is a piezoelectric drop-on-demand print head used in 2D printers from the Epson workforce 30 printer. It has a 600 DPI resolution and nozzles that can eject droplets ranging from 6pL to 26pL in volume, with five independent ink channels. The piezoelectric pinheads operate by applying a voltage change to the piezoelectric material in each chamber (Pitchaya 2015). The voltage change deflects the piezoelectric material to change the pressure in the chamber and force ink to eject through the nozzle.

The MultiFab system can hold up to ten materials at once and print them simultaneously. All of these materials are UV-curable photo-polymers that have been previously tested with 2D and 3D patterns and structures. The materials are also tested for UV curing. A thin layer is manually applied to a glass slate and put under a UV light for a specific amount a time. If the material is not hardened in that time, the quantity of the photo initiator is modified. Additional materials such as solvent-based, hydrogels and co-polymers can be adapted to be used within this system. The library includes materials such as rigid material (RIG), elastic material (ELA), high refractive index material (HR), low reactive index material (LR), and support material (SPT). Some examples of the materials they use are as follows: D3210-R122 is a magenta pigment dispersion, a RIG and CN3105 is a low viscosity oligomer that it an ELA (Pitchaya 2015).

Software

The CPU runs a software program called the Fabricator which is the software used to run the MultiFab system. This software takes a 3D model in multi-material voxel format as an input. A voxel is a 3D pixel, or a volumetric pixel. This contains the information for attributes such as color within an image. It can also describe attributes about physical location within the 3D object such as the density, color, and opacity. In this scenario, the voxel also contains the material ID from the MultiFab material database (Kiril 2013). With this information, the Fabricator can calculate and send commands to the positioning system. This information consist of the model location on the build platform, the geometric location of the print heads and each nozzle, the droplet size, or resolution, and what material is currently loaded into each print head. With this information the system can determine the droplet firing sequences as well as the droplet size for the nozzles in each of the print heads. The system has complete control over the positioning system and where it needs to be positioned from to start and finish each layer of printing. In order to ensure that the print head can perform optimally the MultiFab system has a cleaning cycle that occurs as often as every ten minutes. In this process the positing system moves each print head to a cleaning position and begins a flushing sequence for each nozzle. This ensure that there is no residue build up between multiple layers.

Once the Fabricator has received the input, it interprets that information and positions the positioning system at the initial location on the build platform. Support material is then added to the model. The support material is needed for objects that overhang or parts of the product that cannot be support on their own. An example of this would be a bridge type structure. The image is then resampled to the appropriate printing resolution. Resampling an image changes the number of pixels in the model. After this process is complete the Fabricator processes each multi-material raster layer from bottom to top. Starting from z = 0, the Fabricator processes the x and y axis in a grid, the raster layer information dictates which coordinates, or in this case pixels, to illuminate in monochrome or color values. Prior to extruding materials, the best algorithm needs to be found for the best print speed. The Fabricator computes the number of movements along the x-axis needed to fill all non-empty voxels for each layer of the z-axis while keeping the y-axis at a fixed position . For every Y position on the carriage/print head, the Fabricator computes all non-empty voxels in the current layer that can be filled. That is if its material matches the material in the print head and if the discrete nozzle location falls within the voxel. The Fabricator picks the y position that fills the most voxels. This is subtracted from the set of voxels that need to be filled. Meanwhile, the Fabricator continues to compute the x-axis passes until all non-empty voxels are filled. This process happens for all materials that will be used in the production simultaneously. For each pass along the x-axis, commands are sent to the positioning subsystem. Firing patterns of the nozzles are dictated by which voxels need to be filled. These firing patterns are then sent to the specified print heads. This occurs for each and every layer of the printed finished product. This ensure speed and quality for the algorithm.

The Fabricator has three modules that communicate with it via Ethernet and one that communicates with it via USB for four total modules. Each of these modules use a dedicated microcontroller to handle low level operations. The UV-curing module is the only module to use the USB for communication with that Fabricator. This microcontroller decides the intensity of the LEDs and if they should be on or off. The next three modules communicate with the Fabricator via Ethernet. The positioning control module's microcontroller reads the current position, moves to the desired location, and will wait until the move is completed. In addition to these functions, the microcontroller is responsible for generating the sync signal for the print heads for each step in the x-axis direction (refer back to page 6). The print head module microcontroller is in charge of the print function, this function determines which nozzles to fire at each sync counter value. The print head module uses the sync signal of the positioning system to determine the current x position accurately. Finally, the feeding and temperature microcontroller implements the PID controller for both temperature and pressure.

One of the MultiFab system's key component is called the feedback loop. This component ensures that the finished product is of quality resolution by fixing any errors that occur in the printing process. The system will print one or more layers of the voxelized model. Then compute a binary mask according to where the material was placed on the current layer. A 3D scanning algorithm computes the depth within the mask. As more layers are printed this mask gets smaller and smaller. A correction layer can then be created with this information. For the points below a certain depth level, calculated by the 3D scanning algorithm, the pixels are marked in the correction layer raster. This algorithm will be further explained in the next paragraph. For each of the marked pixel locations, the material ID is taken from the layer below. The correction layer is sent to the printer with the material ID's needed. It would be ideal to do this process with every layer of the printing process but it would slow the printing process considerably. Instead, it is done every fifteen layers or so. This function has the ability to correct multiple layers at once. The process is the same for one layer except for filling in one layer on top, it may fill it up to fifteen layers of correction, or until the depth is even with the current binary mask.

The 3D scanner algorithm uses an optical coherence tomography (OCT) scanner(Pitchaya 2015). This scanner provides a very high resolution, as good as one micrometer. The build platform is moved along the z-axis to allow the scanner to scan each layer. The scanner takes a number of images at each position at the z-axis. After trial and error, the number that works best is 6 images per z-axis. These images have to be processed in to depth information, in order to do that, the following steps are taken: For each pixel at each depth value the standard deviation is computed within its 3 by 3 neighborhood. Then for each pixel the depth value with the maximum value of the standard deviation is found, this is used as the depth estimate. The depth confidence is calculated by using the maximum standard deviation. The scanning area for this system is about 7x7mm, which is not sufficient for most objects. In order to adjust for this, multiple scanning areas are stitched together to form one larger depth map (Pitchaya 2015). The Fabricator does this by overlapping each portion scanned by five to ten percent, and then overlaps the images to ensure that they form an accurate depth map

Another key component of the MultiFab system is machine vision. This is run as an interactive application on the CPU. This application is in command of the 3D scanner previously discussed, its associated camera and all other printer modules, such as the positioning control module and print head modules. The four main functions of this application are as follows: a geometric calibration of the print heads with respect to the build platform and positioning system, 3D scanning of printed objects, 3D scanning auxiliary objects and an alignment of auxiliary parts with a model to be printed(Pitchaya 2015). Machine vision makes it possible to 3D print multi-materials onto already existing components. There exist two modes for this action. The first is to scan the auxiliary component on the build platform then overlay a model to be printed on top of it. The second way to achieve this is to click on two or more corresponding points between the model and component then compute the best transformation matrix. The data may also be exported to use other tools to ensure both models are aligned properly.

Applications

The MultiFab has a number of promising uses for production. One example of a finished product is optical fiber bundles. These optical bundles can be used to create custom color display elements and used for cameras. The downside is that the quality is low due to the base materials. Another example of a finished product is a multi-material tire with a honeycomb structure that uses four different materials and empty space, including both RIG and ELA materials. These finished products can have different base pigments, different texture, and subsurface scattering such as that used in a microlense. In order to create a smooth texture, the UV-curing is delayed by a few seconds. These end products were all made from scratch, but the MultiFab can also print onto auxiliary components. The most fascinating example is that of an LED. The MultiFab has the capability to print a lens right on top of an existing LED. Another example, mentioned earlier is printing a privacy right on an existing cell phone, with the edges aligning perfectly with the edge of the screen, not the phone. Lastly this printer can create fabrics using RIG and ELA materials.

Final Specs

This printer was built with optimization and resolution in mind; speed was not an seriously important factor. Each of the printed layers are thirteen micrometers thick, seventy seven layers are needed for a one millimeter object, and printing each x pass takes more than four seconds. There are a number of things that could be done to improve the speed of the printing, such as, filling the same materials in each of the print head locations, but, that would take out the functionality of printing ten materials at once. Another way to speed up the process would be to increase the droplet size, at the price of resolution. The resolution exceeds that of high-end commercial 3D printers, it can be increased, but at the cost of printing time. The MultiFab has forty materials it can use. Some of those are pigments that overlap on different type of material such as RIG and ELA, but both have magenta and cyan pigments. The pricing and availability of parts for such a machine cannot be beat. Seven thousand dollars to make it with off the shelf parts and twenty dollars per kilogram of material. Finally the feedback loop and machine vision allow the MultiFab to locate errors in its print and correct them according to the voxelized multi material input file.

Conclusion

The MultiFab is an innovation for what is to come with 3D printers as well as 3D multi-material printers. It has been seen that this machine is high-resolution multi-material machine that is capable of integration with auxiliary objects and is very low-cost in comparison to its competitors. I have learned a lot about how 3D printers work and how many different ways of printing an object through an additive process exist. I think the MultiFab is a big step in the right direction for the development of 2D and 3D printing, as well as multi-material 2D and 3D printing. It was astonishing to see how a sophisticated high-end multi-material 3D printer operates under the hood, and what software it uses to run the machine. I had no knowledge of that prior to my research. MIT hasn't released any source code for this machine yet, it would have been interesting to get a look at how it specifically works, the source code and not just verbal algorithms. MIT has founded a great machine that no current model can rival and that can help the development of the computer graphics community.

Works Cited

Bernier, Samuel N. Reinhard, Tatiana. Luyt, Bertier. (2014). Design for 3D Printing. San Francisco: Maker Media.

Jacques Calì, Dan A. Calian, Cristina Amati, Rebecca Kleinberger, Anthony Steed, Jan Kautz, and Tim Weyrich. 2012. 3D-printing of non-assembly, articulated models. ACM Trans. Graph. 31, 6, Article 130 (November 2012), 8 pages. DOI=http://dx.doi.org/10.1145/2366145.2366149

Kiril Vidimče, Szu-Po Wang, Jonathan Ragan-Kelley, and Wojciech Matusik. 2013. OpenFab: a programmable pipeline for multi-material fabrication. ACM Trans. Graph. 32, 4, Article 136 (July 2013), 12 pages. DOI=http://dx.doi.org/10.1145/2461912.2461993

Lin Lu, Andrei Sharf, Haisen Zhao, Yuan Wei, Qingnan Fan, Xuelin Chen, Yann Savoye, Changhe Tu, Daniel Cohen-Or, and Baoquan Chen. 2014. Build-to-last: strength to weight 3D printed objects. ACM Trans. Graph. 33, 4, Article 97 (July 2014), 10 pages. DOI=http://dx.doi.org/10.1145/2601097.2601168

Pitchaya Sitthi-Amorn, Javier E. Ramos, Yuwang Wangy, Joyce Kwan, Justin Lan, Wenshou Wang, and Wojciech Matusik. 2015. MultiFab: a machine vision assisted platform for multi-material 3D printing. ACM Trans. Graph. 34, 4, Article 129 (July 2015), 11 pages. DOI=http://dx.doi.org/10.1145/2766962

Thryft, Ann R. "MIT's MultiFab Can 3D Print 10 Different Materials at Once." Design News Oct. 2015: 30. General Reference Center GOLD. Web. 5 Nov.201<http://go.galegroup.com/ps/i.do?id=GALEA433009755&v=2.1&u=csustan_main&it=r&p=GRGM&asid=e2dbbfe2529f3f 4589e461f15aa43a10>.