3D Printing with Reusable Voxels: A Faster and Greener Future

Audrey Stipe* and HungDa Wan

Department of Mechanical Engineering and Center for Advanced Manufacturing and Lean Systems
University of Texas at San Antonio
San Antonio, TX 78249, U.S.A.

ABSTRACT

Many of the applications in the 3D printing market have been for manufacturing prototypes in an inexpensive and relatively fast manner. Today, 3D printers make this possible by no longer having to use third party manufacturers. For all of the purposes that 3D printing is used, many of them, such as 3D geographic maps, visual art, model support structures, dioramas, prototypes, do not require a high precession. Furthermore, for such applications, there is no need for permanent prints. Due to the advancements in technology, and its residual pollution from waste, there is a need for a 'greener' method to 3-D printing. To meet this demand, we propose MIRV (Mechanically Interchangeable and Reusable Voxels), for voxel-based printing, a new method for 3-D printing. MIRV uses pre-built volumetric elements to build 3-D objects, by employing specially designed reusable and interchangeable building elements in voxel-based printing. When there is no longer need for the printed object, the object can be disassembled and the parts reused. This eliminates any wasted material. Meanwhile, all building elements of each layer are displaced in one simultaneous motion. Thus, the overall time to build a print can be significantly reduced compared to other 3D printing technologies.

1. INTRODUCTION

Today, 3D printing is being used for a broad spectrum of applications. In the manufacturing world, 3D printers are being used to print parts 'in house' instead of outsourcing. A basic example would be the printing of an object incorporated into the assembly line, or production process as a whole, instead of waiting for the part to be made elsewhere by hand. At the same time, 3D printing is being incorporated into uses of the small businesses, entrepreneur, and other personal fields. Some of these users are making jewelry, prosthetic limbs, living organs and other objects that require a high resolution. There are also many novice users utilizing that capability of 3D printers too, in order to make cheaper prototypes, or even pieces of art, on the spot, instead of having to pay additional costs of third party manufacturers. Therefore, a demand has risen for fast 3D printing with acceptable quality. On the other hand, due to the advancements in technology, 3D printers are gaining popularity. With its residual pollution from waste (e.g., scrapped plastic, chemical for post-process, etc.), there is a need for a 'greener' method to 3-D printing.

To meet the demand of fast and green 3D printing, a new method named MIRV (Mechanically Interchangeable and Reusable Voxels) is proposed in this paper for voxel-based printing. MIRV uses pre-built volumetric elements to build 3-D objects, by employing specially designed reusable and interchangeable building elements in voxel-based printing. The MIRV method incorporates three building elements into each layer where the main element is a cylindrical 'bead' along with a horizontal and vertical 'clip'. For each layer, all building elements are displaced from an upper platform in one simultaneous motion. By doing so, the build time spent using a two-dimensional tool path working in cross sectional areas (e.g., laser scanning or fused deposition) is decreased. Thus, the overall time to build and process a print can be significantly reduced compared to other 3D printing technologies. Furthermore, when there is no longer need for the printed object, the object can be disassembled and the parts reused. This eliminates any and all wasted material. Therefore, the MIRV is expected to achieve a faster and greener future of 3D printing.

* Corresponding author: Tel.: (210) 458-6325; Fax: (210) 458-6504; E-mail: audrey.6gentx@gmail.com

2. CURRENT 3D PRINTING TECHNOLOGIES

3D Printing technology is generally referred to as a special layer forming and stacking process, also known as *Rapid Prototyping (RP), Additive Manufacturing (AM), Direct Digital manufacturing (DDM), Layered Manufacturing,* and *Freeform Fabrication*. The concept is similar to adding a third dimension to a regular printer. Therefore, 3D Printing became a popular term used among non-technical persons. The additive process of 3D printing "grows" a three-dimensional object from bottom up, instead of carving one out of a solid block of material, like tradition machining processes. Therefore, there is no complicated tool path planning or restrictions on tool approach angles and so on. As a result, the process can build 3D objects directly with little limitation to the geometric design.

The first commercially available Rapid Prototyping machine was the Stereolithography (SLA), which came to the market in the 1980's. The SLA machine uses photosensitive liquid polymer, which is cured by laser scanning [1]. The additive process of 3D printing can be achieved by various alternative ways, such as selective laser scanning, UV light masked projection, powder with binder injection, and fused deposition [2]. Table 1 summarizes some key characteristics of several popular commercial 3D printers.

Table 1. Comparison of popular 3D Printers [3].

3D Printing System	**Material**	**Layer Thickness**	**Surface Finish**	**Freeform Capability**	**Cost**	**Post-Process**	**Build Speed**
Stereolithography (SLA)	Liquid photopolymer	0.001"	Smooth	Excellent	High	Yes	Average
Fused Deposition Modeling (FDM)	Plastic Filament (ABS and limited options)	0.005"	Rough	Good	Mid	Yes	Slow
Selective Laser Sintering (SLS)	Powdered material with high diversity	0.004"	Average	Good	High	No	Fast
3D Printing (3DP)	Plastic powder (and limited options)	0.002"	Rough	Good	Low	Little	Very fast
Laminated Object Manufacturing (LOM)	Sheet paper (and limited options)	0.002"	Rough	Limited	Mid	Yes	Fast
CNC-based Prototyping	Diverse options	N/A	Smooth	Limited	High	No	May be slow

Recently, 3D printing has become a more accessible for everyone. However, the new technology also has quite some limitations. In the Roadmap for Additive Manufacturing report [4], various challenges and emerging research directions of this technology have been reviewed in detail in the 92-page report. Among the various issues, we found that the speed of printing is a common limiting factor for the use of this technology. For example, there are two-industry grade 3D Printers in our university, i.e., a FDM machine and a 3DP machine. To build a coffee mug in regular size (about 3.5" tall), it will take the FDM machine about 10 to 15 hours to print and 8 more hours for post processing. The 3DP machine is one of the faster printers on the market, but it will still take about 5 hours to print and 2 or more hours for cooling, drying, and manual sealing. One of the largest 3D printers on the market place is the VX 4000, which has a 4m x 2m x 1m build volume [5]. The printing speed is 75 seconds/layer, while the layer thickness is only 0.3 mm. Therefore, to build a large object, it will still take 2 to 3 days just to print it out.

Analyzing the speed of commercially available machines, we observed that the printing speed is limited by the printing mechanism, mainly in material replenishment and material binding. The results are summarized in Table 2.

Table 2. Comparison of printing mechanism and printing speed.

Printing Speed	**Printing Mechanism**
Slow	**1-D material deposition** Example: FDM scans and deposits material with 1 nozzle.
Medium	**2-D material replenishment** and **1-D scanning for material binding** Example: SLS and SLA scan powder or liquid with one laser beam
Fast	**2-D material replenishment** and **2-D scanning for material binding** Example: 3DP deposits binder via a matrix of jet nozzles

The comparison clearly shows that 2D material replenishment and 2D scanning delivers faster result. For example, the earlier mentioned large-format VX 4000 printer (which uses 3DP mechanism) employs 26,560 nozzles to form a 2 meter long binder jet array in order to sweep a whole layer of powder-based material with a single pass. A newly emerged named Mask Image Projection (MIP) is claimed to be several times faster than the regular 3DP technology. The MIP uses a rapid material replenishment process, and it cures a whole layer of photosensitive liquid polymer with a 2-D array of lighting [6]. As a result, the print speed is ultimately limited by the Z axis. Can there be opportunities to relax this ultimate constraint and further speed up the printing speed? A different concept of 3D printing, the Voxel method, has emerged as a potential solution to increase printing speed in the Z axis [7]. This method uses pre-built volumetric elements to form 3D objects with a compromised surface smoothness. The Voxel method matches the objective of this paper very well. However, most of the faster processes, including Voxel method, use plastic as the base material. Can it be more environment-friendly? These questions lead to our effort in developing the new MIRV method.

3. Design and Application of MIRV

MIRV uses pre-built volumetric elements to build 3-D objects, which makes thicker layers to reduce printing time in Z-axis. Three types of building elements are used, including a cylindrical ‘bead’ along with a horizontal and vertical ‘clip.’ The result is reusable and interchangeable building elements in voxel-based printing. The building components can be made from any material. In the case of this study, measurements are based on the use of Acrylonitrile Butadiene Styrene (ABS) plastic. ABS plastic was chosen because of its relatively low density, 0.037-lb/in^3, compared to other plastics and metals such as silicon, nylon and aluminum alloys. Table 3 compares the densities of these materials. Another reason for the use of ABS was the convenience. A Dimensions SST 3D Printer was used in the initial design and modeling process. Therefore, measurements obtained are based on components made of ABS plastic. Due to the design of the building elements, less material is used resulting in a lower weight. Table 4 shows some of the specifications of the building components.

Table 3. Comparison of densities of potential materials.

MATERIAL	DENSITY
ABS	*0.037-lb/in^3*
PPS	*0.056-lb/ in^3*
SILICON	*0.084-lb/ in^3*
NYLON	*0.042-lb/ in^3*
6061-T6	0.097-lb / *in^3*
2024-T3	0.100-lb/ *in^3*

Table 4. Weight and volume of building components.

	WEIGHT (lb.)	TOTAL VOLUME (in^3)	VOLUME OF MATERIAL (in^3)
BEAD	0.027	1.000	0.743
VERTICAL CLIP	0.005	0.157	0.128
HORIZONTAL CLIP	0.001	0.019	0.015

3.1. Mechanical Design

The pre-built volumetric elements consist of a rounded cube shaped object; the bead (Figure 1), a horizontal clip (Figure 2), and a vertical clip (Figure 3).

The top of the main building element, the bead, consists of extruded cuts for the horizontal clips to nest in, as seen in Figure 1. There is also a stopper on the inside of the bead to hold the vertical clip in the appropriate position and prevent the clip from being lodged too far into the bead during the loading process. The stopper also ensures that there is enough surface area to grip to the bead being placed atop in order to hold the 2 beads together. The ledge prevents the vertical clip from being pressed too far inside of the bead due to the corresponding bead being forced on top. The squared edges allow for the beads to sit beside each other with more surface contact than a truly cylindrical bead. The rounded corners were designed to save volume of the object, consequently reducing weight. The design of the bead allows for more structural integrity, no matter the orientation the object is being printed.

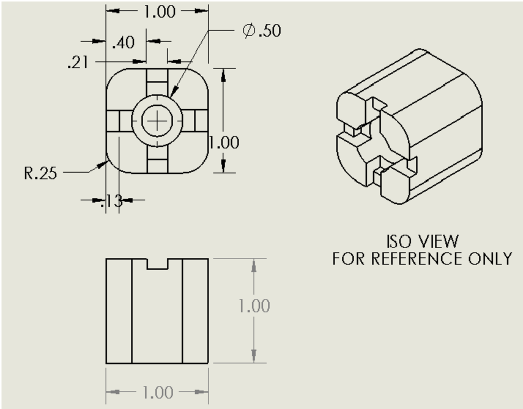


Figure 1. Specification for the bead.

The horizontal clip (Figure 2) resembles a squared 3-dimensional U. This serves to keep the layer of beads from moving in the lateral direction. The design for this component is relatively simple compared to the others. This is because the horizontal clip is held in place in the 'Y' direction by the bead placed on top. The only function of the horizontal clip is to keep the printed object from shift in the 'X' or 'Z' directions.

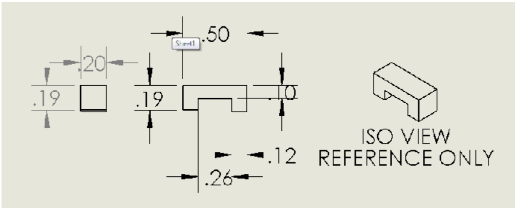


Figure 2. Specifcations of the horizontal clip.

The vertical clip (Figure 3) is an ovular cylinder with a maximum diameter of 0.5in, located at its center giving the ovular affect. Having the vertical clip widen at its center helps to keep the vertical clip locked into position. Take into consideration a Lego piece. The prongs of the Lego are rounded so that there is a more secure fit into the opening of the other Lego. The female pieces attach to the male pieces at the widest part of the prongs.

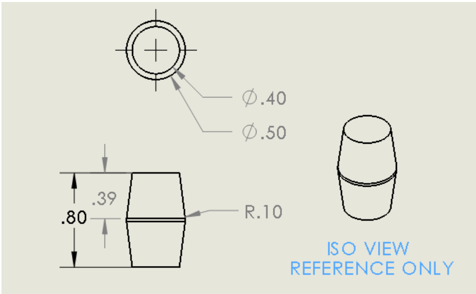


Figure 3. Specifications of the vertical clip.

3.2. Mechanical Application

The MIRV method can be implemented with a device that would include 3 upper platforms, a lower platform, and a feeding system that will dispense the building elements onto the lower platform. First, the beads would be fed to the top of their prospective upper platform and dispensed through a mesh to create a single layer of the 3D object. Then, the horizontal and vertical clips are also loaded to their prospective platforms, and too, are dispensed through the mesh, time selectively. The cycle would continue in this manner, layer by layer, until the object is complete. Figure 4 shows what a singular layer of beads would look like if a chair were to be printed. After the beads are laid, the vertical clips and then the horizontal clips would be laid. This cycle will continue until the chair starts to take form. This can later be seen in Figure 6, where the assembly of a chair is shown at 3 random points in production.

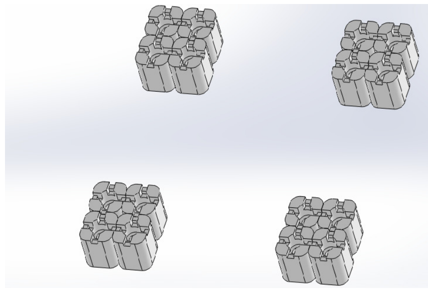


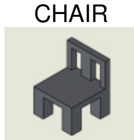
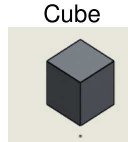
Figure 4. First layer of beads.

4. Preliminary Analysis

4.1. Analysis in Terms of Weight of Printed Objects

Table 5 compares the weights of objects between the MIRV method of printing and other methods that print a solid object. The table also compares the weights of objects varying in size and material. Within the table, the overall volume of the material is given to give perspective to the difference in weights of the varying objects. It is seen in the table that the weight of an object made by MIRV, versus other common methods, weighs significantly less.

Table 5. Comparisons of weight between objects and methods of printing.

	CHAIR 		Cube 		Sphere 	
PRINTER	**MIRV**	**OTHER**	**MIRV**	**OTHER**	**MIRV**	**OTHER**
VOLUME	122 in^3		1000000 in^3		523599 in^3	
ABS	3.81-lb	5.6-lb	32279-lb	36849-lb	18058-lb	19294-lb
PPS	5.76-lb	8.62-lb	42022-lb	56719-lb	27331-lb	29698-lb
SILICON	8.65-lb	12.79-lb	63033-lb	84176-lb	40996-lb	44075-lb
NYLON	4.32-lb	6.32-lb	31516-lb	41546-lb	20498-lb	21754-lb
6061-T6	9.979-lb	14.83-lb	72787.69-lb	97544-lb	47341-lb	51074-lb
2024-T3	10.288-lb	15.27-lb	75039-lb	100434-lb	48805-lb	523598-lb

The sturdiness of an object printed by the MIRV method is ideally considered reliable. The only limiting factors would be if a force were to be applied at an angle, pushing the component apart, or if the components are pulled apart. As with any object overused, wearing exists. It is not predicted for wearing of the components to prevalent, yet after prolonged use, wearing will inevitably occur.

4.2. Analysis in Terms of Printing Time

The MIRV method is expected to lay a singular layer of beads, 1 inch in height, in approximately 2 minutes and 30 seconds. This time is dependent on the elements needed per row. If the row does not require any vertical clips, then the time would be reduced 1 minute and 30 seconds. The time required to lay each element, as well as the time for the printer heads to interchange and reload between each phase, is depicted in Table 6 below.

Table 6. Estimated time for each phase of printing a single layer.

Phase	**Time (seconds)**
Bead	30
Vertical Clip	30
Horizontal Clip	30
Interchange	30
Reload	60

Each layer of the printed object follows the pattern as seen in Figure 5. Between each element, the time for the printer heads to interchange with one another, as well as the time for the printer heads to reload between each layer. Figure 5 also shows the process of printing a single layer as well as multiple layers.

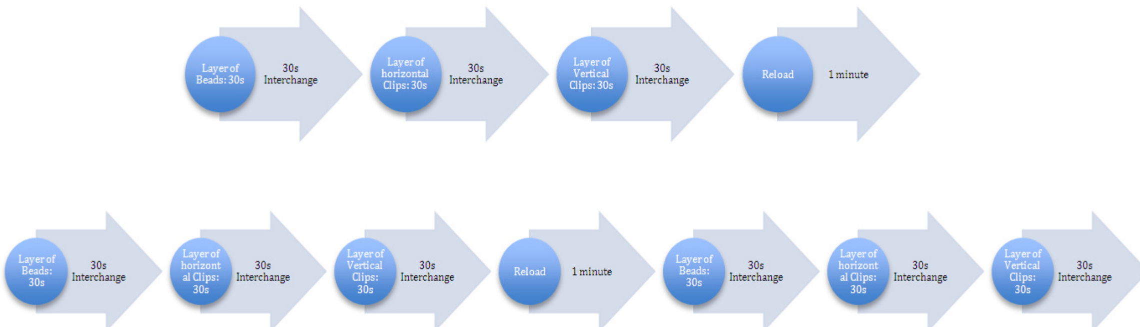


Figure 5. Process of printing multiple layers compared with time.

It is known that the top layer of an object would not contain any vertical clips. With this and the time information provided in Table 6, and the process from Figure 5, we are then able to calculate the time to build objects of various heights. Because the MIRV method of printing only has a time variable dependent of height, estimating the time to build an object is made simple. Table 7 shows the total time to print an object where each layer is one inch tall. Since whether or not the object is hollow, curves on the edges, or any other kind of intricacies, the time calculated is not based on overall volume as in Table 5, but overall height. It is also noticed in Table 7 that if the objects height is not a whole number, then MIRV will round up, or down, to the closest whole value. If the height of the object lies exactly between two whole numbers, i.e. 7.5, than the vertical clips will be printed on the top layer.

Because MIRV extrudes an entire layer of components simultaneously, the only time dependent factors are height and resolution, not the total volume or intricacies of the design. This concept can be visualized by considering a chair. For this scenario, reference Figures IV-VI. The chair is to be 6in wide and 10in tall; it is a 'doll' sized example. Because the chair does not have any contouring, smaller building components are not necessary. There for, concern of precise resolution is not an issue and a larger building component can be used for faster simulation. Thus, the chair can be printed with the main building component, the bead, consuming a volume of 1 cubic inch. If the design were to have curved, or angled surfaces, a smaller building component would be recommended. The production time would increase due to the additional layers needed; yet the resolution would comparatively better.

Table 7. Time to build objects of varying height.

Height of Object (Inches)	Number of Layers	Number of Reloads	Time to Print (Minutes)	Time to Print (Hours)
1	1	0	2	0.033
10	10	8	32	0.54
30	30	28	104.5	1.75
30.2	30	28	104.5	1.75
30.5	30.5	28	105.5	1.76
30.8	39	37	133.5	2.23
39	39	37	133.5	2.23
99.75	100	98	345.5	5.76
100	100	98	345.5	5.76
100.25	100	98	345.5	5.76
100.5	100.5	98	346.5	5.78

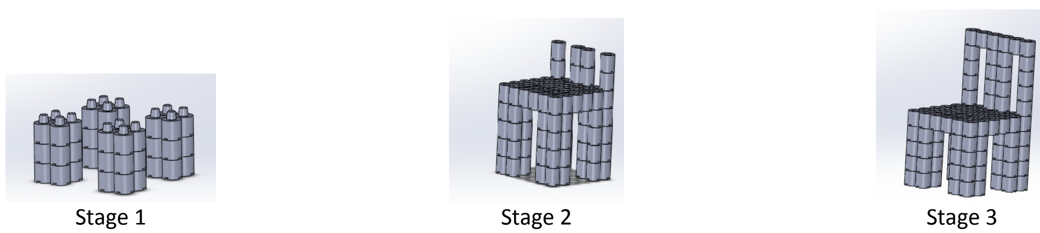


Figure 6. Three stages depicting the MIRV printing proccess.

Returning to the concept of height also being one of the time dependent factors, the speed of production is increased by the orientation of the chair. As seen in Figure 6, the chair is 10in tall; therefore MIRV would take approximately 32 minutes to build the chair. Though if the chair were to be oriented so that it is only 6in tall, then chair would take only 20.5 minutes to build. This would not change the structural integrity because of the squared edges. For example, if the object being printed is a rectangular prism that is 144 cubic inches, (12x3x4)in, and object were to be printed on the side of (3x4)in, the overall time to print the object would take longer than if it were printed it on the side that is 12x4. This means an abject can be rotated in order to print within a shorter period of time

If the object being printed is relatively small, the resolution would be noticed as low or poor. Though, if the object being printed is considerably large, than the resolution seen would not be a concern. This can be understood by considering how an Egyptian pyramid is built. From a distance, the edges of the pyramid look smooth because the overall size of the pyramid is large, but as approached, the steps of the bricks are increasingly more noticeable.

Since the Voxel Printer uses pre-built building element, the resolution is low. Therefore, the voxel printer is most ideal for large 3-dimensional geographic maps, prototypes, diorama, visual art, models, support structure, furniture, and more.

4.3. Analysis in Terms of Material Reusability and Limitations

Other comparable 3D printers on the market, using the additive processes, utilize either Fused Deposition Modeling (FDM) or Multi Jet Modeling (MJM). Though the Voxel Printer extrudes its building material from an upper platform, as in FDM, it is still most closely related to the field of multi jet modeling. A common manufacturer of this printer is Z Corp, which uses, "a feed piston and platform, which rises incrementally for each layer," and each layer consists of a powdery substance held together with a binder or glue [8]. Similarly, the MIRV method produces an entire layer of an object at once while the platform adjusts its height to the stages of production. Though, instead of using a binder to hold the layers together, the MIRV method uses volumetric components allowing the layers to stack on top of each other like Legos. By using this method, the printed object can be taken apart when finished, and all of the material reused without the aid of a dissolving agent.

The material used in multi jet modeling is a powder type substance in which the excess has to be removed after each binding stage for recycling purposes. The Voxel Printer utilizes the same methodology while printing with exception for a few differences. When a layer of beads have been placed on the lower platform, horizontal and vertical clips will be placed selectively to hold the beads in place while the next layer is being prepared. Once the print job is complete, all beads that have not been bounded to another bead will fall off.

MIRV is an additive process; therefore, there is not any wasted material. This helps reduce total manufacturing time by reducing the need of additional stages of production to remove excess material, thus saving and money. Because the support beads are not bound to the object as a whole, there is no need for post-processing.

In the case of MIRV, a whole layer is printed at once, instead of cross-sectional areas within sections of a layer; thus significantly increasing the speed of production. Therefor the length, width, or intricacies of the object are not factors in the total build time.

With all of the design variations attributed, the MIRV method is estimated to print a vertical height of 1” per minute - one layer, where as other printers range from 1” per 30 minutes to longer [9]. Multi jet modeling, or a Z Printer, has one of the highest resolutions currently on the market, ranging from 300–600 dpi [9]. With the focus of MIRV being low cost, reusability, speed and size, the resolution is comparatively low in comparison. Part of this is due to the size of the building components. If the components were to be smaller, the resolution would exponentially improve. Decreasing the size of the beads will add additional time to the total production, yet ultimately the Voxel printer would still be faster than most other printers on the market for printing large objects.

On a different perspective, adjusting the spacing between beads can further reduce resolution. However, if the beads are not placed exactly, the vertical clips will not align properly and not be able to hold beads together. Therefore, there are several tradeoffs when designing the MIRV system in terms of different aspects of its performance.

4.4. Potential Improvements

In the preliminary model, cylindrical beads of ABS plastic are used as the main building elements as used for Figure 6. Later on, another version of MIRV was developed based on cubed voxels instead of cylindrical as seen in Figures 1 thru 3. The assembly of the building components remains the same whether cylindrical beads are used or cubical beads. The only difference would be the sturdiness of the object.

The resolution is not ideal for smaller objects. In order to achieve speed, cost, and ‘green’ qualities of the printer, the resolution had to be compromised by using pre-built volumetric components. Because the main component is a type cylindrical bead, there is an offset space on objects with sharp angels or curves. When looking at a pyramid from afar, it looks as though it has straight edges, upon coming closer to the pyramid, a viewer will notice offset spaces from the large bricks. Similarly, with the Voxel Printer, when an object is quite large, these gaps will be miniscule in comparison to the object as a whole.

Even though the Voxel Printer is meant for temporary, non-precision applications, we have developed some ways to improve resolution and are working on higher quality resolution alternatives for the future. One alternative for a better resolution using the Voxel Printer is to use smaller beads. The resolution would still not be perfect, but it would be significantly better. Although, by using smaller beads, the build time of the object would increase because there would be more layers assembled in order to build the object to the same size. Yet, it is still believed that the Voxel Printer will still be a faster alternative even with the additional layers. Another alternative method to improve resolution is to lay a material over the object in order to smooth out the sharp edges and fill in the gaps. This process would be done just as one would with fondant on a cake.

5. Summary and Conclusion

3D printing is no longer just for manufacturers and people with extra money to spare. More and more people are becoming aware of 3D printing and are taking advantage of its capabilities. Though, what about the projects that have a limited time purpose, such as temporary models or prototypes? MIRV brings resolve to this issue. It gives more flexibility in its applications of 3D printing to both large companies and DIY’s by having the option to print temporary (or permanent) objects, where the material is completely reusable, space and money are ultimately saved.

In the case of the designer, novice, R&D team, or even manufacturer needing fast and inexpensive prototypes, there is often also the need to make changes to the existing prototype. Many manufacturers advertise the ease of being able to reprint an object, with the new changes, in hours instead of having to wait another extended period of time. With the proposed voxel printer methodology, MIRV, no ‘reprint’ is necessary. Instead of discarding and wasting the material from the original print, especially when due to minor changes, the user can make the changes themselves without any wait.

Due to the use of pre-built volumetric elements, the MIRV method does not require a complicated tool path programming. Moreover, forming a layer in one process (3 steps) results in shorter build time compared to one dimensional scanning methods used by the majority of existing 3D printers. The resolution of printed objects depends on the size of pre-built elements, thus it is more suitable for large, non-precision applications. The voxel printer incorporates many aspects of existing rapid prototyping methods, allowing one to print large, non-precision applications faster and cheaper, while also being completely reusable and having no excess waste.

While most common issues with 3D printing involves resolution, cost, and time, MIRV takes away these concerns by eliminating excessive variables. Most of the current methods of 3D printing, and their corresponding printers, have multiple time variable dependents. The intricacies of each printer's tool path, and how the printer works, makes it harder for consumers to decide which printer will produce the resolution needed in the desired time frame. By eliminating excessive time dependent variables, the result is a 3D printer with only two time dependent variables. By having the speed of the printer based solely on the height of the object as well as the size of the building components used, the build time is significantly reduced. This then allows the processes of choosing a 3D printer that fits the needs of the customer more effectively. In order to achieve the desired resolution, the only question for concern becomes the size of the material used. Since the MIRV method does not need additional support material, or a solution to remove support material, more time is saved. By removing extra processes, the overall cost is also reduced because of the fewer elements involved. In addition to saving cost by not having to use support material, MIRV significantly reduces the financial burdens of 3D printing by the use of pre-built voxel components. These components are completely reusable and interchangeable, which are then used as the building material in place of a melted or a bound material. With this approach, the concept of having to buy replacement material is obsolete.

In summary, the MIRV methodology allows for a cheaper, larger, faster, and more environmentally friendly form of 3-D printing.

ACKNOWLEDGEMENTS

The work presented in this paper has been supported, in part, by the UTSA Tenure-Track Research Award Competition (TRAC) FY 2012-2013. The authors would also like to acknowledge Francisco Balandrano, Vladimir Santalov, and Trumone Sims in Sustainable Manufacturing Systems Lab for their support during the project period.

REFERENCES

[1] T. Grimm, User's Guide to Rapid Prototyping, Society of Manufacturing Engineers, Dearborn, MI, 2004.

[2] C. K. Chua, K. F. Leong, and C. S. Lim, Rapid Prototyping: Principles and Applications, World Scientific Publishing, 2010.

[3] H. Wan, and F. A. Syed, "Preparing to Use Rapid Prototyping: Lessons Learned from Design and Manufacturing Projects," 2012 ASEE Annual Conference & Exposition, June 10-13, San Antonio, TX, 2012.

[4] D. L. Bourell, M. C. Leu, and D. W. Rosen, Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing, University of Texas, 2009.

[5] Voxeljet Systems, "VX 400 – The Large-format 3D Printing System," Voxeljet Technology GmbH, www.voxeljet.com, 2013.

[6] Y. Pan, C. Zhou, and Y. Chen, "A Fast Mask Projection Stereolithography Process for Fabricating Digital Models in Minutes," Journal of Manufacturing Science and Engineering, Vol.134, No.5, pp.051011-9, 2012.

[7] M. Somasekharappa, "Additive Manufacturing- The Voxel Method." 3D Printing Industry. 3D Printing Industry Insights. April 30, 2013. http:// 3dprintingindustry.com /2013/04/30/additive-manufacturing-the-voxel-meth/ (accessed August 26, 2013).

[8] "Concept Models." Z Corp. 2013. http://www.zcorp.com/en/Solutions/Rapid-Prototypes---CAD/Concept-Models/spage.aspx (accessed May 08, 2013).

[9] 3D Systems. "3D Printer." Z Corp. 3D Systems. 2013. http://www.zcorp.com/en/Products/3D-Printers/spage.aspx (accessed Januraury 08, 2013).