Automated Storage and Active Cleaning for Multi-Material Digital-Light-Processing Printer

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Purpose - *Digital light processing (DLP) printing uses a digital projector to selectively cure a full layer of resin using a mask image. One of the challenges with DLP printing is the difficulty of incorporating multiple materials within the same part. As the part is cured within a liquid basin, resin switching introduces issues of cross-contamination and significantly increased print time. In this paper, a novel technique for printing with multiple materials using the DLP method is introduced.*

Design/Methodology/Approach - *The material handling challenges are investigated and addressed by taking inspiration from automated storage and retrieval systems, and utilizing an active cleaning solution. The material tower is a compact design to facilitate the storage and retrieval of different materials during the printing process. A spray mechanism is used for actively cleaning excess resin from the part between material changes.*

Findings - *Challenges encountered within the multi-material DLP technology are addressed, and the experimental prototype validates the proposed solution. Our system has a cleaning effectiveness of over 90% in 15 seconds with the build area of 72 inches, in contrast to the previous work of 50% cleaning effectiveness in 2 minutes with only 6 inches build area. Our method can also hold more materials than the previous work.*

Originality/Value - *The techniques from automated storage and retrieval system (ASRS) is applied to develop a storage system, so that the time complexity of swapping is reduced from linear to constant. The whole system is sustainable and scalable by using a spraying mechanism. The design of the printer is modular and highly customizable, and the material waste for build materials and cleaning solution is minimized.*

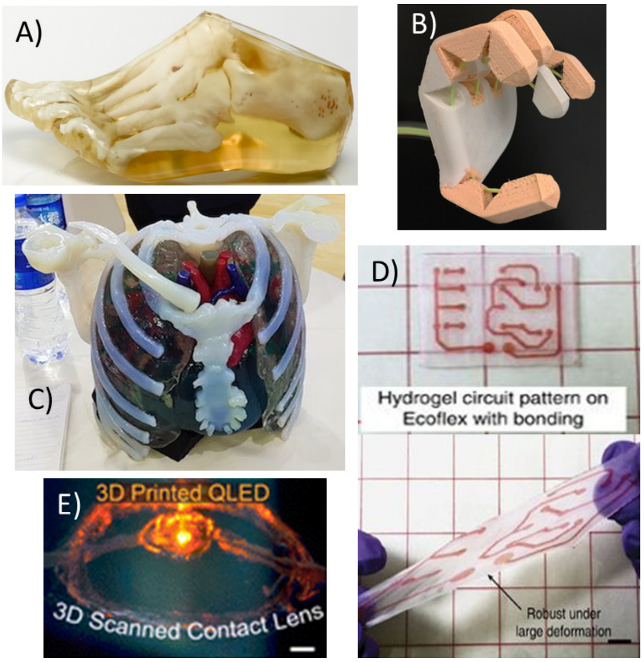

Fig. 1. Multi-material applications: A) 3D printed foot with simulated bone and skin [3]. B) A soft robotic hand [4]. C) Physiologically accurate rib cage [5]. D) A conductive Hydrogel and Ecoflex circuit [6]. E) 3D printed Quantum Dot - LED [7]

1 Introduction

Currently, the world of three-dimensional (3D) printing is advancing at great speeds. From increases in performance, accuracy and strength, all the way to the utilization of multiple materials for a single print [1]. This has great implications on the versatility of parts which can combine properties of different materials placed precisely where desired. The added design flexibility has a large impact for industry, home fabrication and the business models innovation [2]. Multi-material 3D printing offers designers more degree-of-freedom (DOF) in design with fewer limitations allowing them to put more focus on the intended functionality of a product. For example, functionality can refer to assigned mechanical deformation by printing materials with various properties. With more DOF, products can be smarter and can better complete highly dexterous tasks. Some examples of multi-material applications are demonstrated in Fig.1.

There are several existing 3D printing methodologies, each has its own advantages and challenges. Multi-material printing, as a more complex process, adds a unique set of problems to be solved for each of the different methods. Fused deposition modeling (FDM) uses thermoplastics just beyond their melting point and extrudes them, by means of a nozzle, to construct the layers [8]. Polyjet technique jets the material out of a nozzle similar to FDM, except the material is a photo-curable polymer and is cured using ultraviolet (UV) light as soon as it leaves the nozzle [9]. Due to their deposition mechanisms, both technologies have been able to utilize multiple materials for some time by using multiple nozzles or swapping the feed-stock material. Nevertheless, because of the deposition method, there are also some undesirable characteristics, such as poor coalescence, limited feature size, precision, and anisotropic material properties. In addition, both technologies are limited by the viscous dynamics of their materials through the delivery system of the nozzle.

On the other hand, the stereolithography (SLA) process is one of the most important 3D printing technologies, and also the first one to be commercialized in 1980s. The Digital Light Processing (DLP) process, a variant of SLA, shares the same principle to cure liquid resin to solid through a vat polymerization technique. The main difference is the curing method. While SLA uses a guided laser which cures by drawing out the image layer, DLP cures the entire layer using the projection of an image [10]. However, SLA/DLP printers are still very limited in multi-material printing with only a few researches exploring this technology [11–13]. This is because SLA/DLP printers need to swap entire vats to change materials, which takes far longer than the deposition approaches. Furthermore, whenever there is a swap of material, the part has to be cleaned due to it being submerged in different resins, contaminating both the current layer and previous layers. One way to address this issue is to soak the part in a cleaning solution [12], however it takes a long time to reduce the contamination. In spite of the difficulties, compared to other polymer 3D printing technologies, SLA/DLP produces parts with the highest accuracy and the best surface finish. As such SLA/DLP printing shows itself to be one of the most promising technologies for the future of additive manufacturing. Moreover, as DLP has the ability to print an entire layer at once, its fabrication speed is remarkable. Therefore, there is a huge interest in developing multi-material DLP printing. To realize a practical multi-material DLP printer, a solution must be provided to the following research question: how to speed up the material swapping process and minimize the cleaning time without an increase in contamination?

In our study, it is observed that the material swapping in DLP printer is similar to a storage and retrieval process; and currently most of the cleaning systems are relatively passive (such as soaking). Trying to answer the research question based on these observations, two hypotheses are made:

1. If the material swapping is formulated as a storage system, it will speed up multi-material DLP printing.
2. If an active cleaning system is employed, it will enhance the cleaning effectiveness and efficiency.

In this paper, development of a multi-material DLP printer is created to test these hypotheses. However, there are several challenges in implementing the systems. On one hand, to maintain the robustness and simplicity of the printer, the integration of a storage system should not increase the process complexity too much. On the other, taking into consideration the safety and sustainability of the printer, the cleaning system should minimize the exposure of cleaning solution to the environment and conserve the material usage.

By overcoming these challenges, the contributions of this paper are:

1. We apply the techniques from automated storage and retrieval system (ASRS) to develop a storage system for multi-material DLP printer. The whole system only has three axes of actuation and the time complexity of swapping is reduced from linear to constant.
2. We take the advantages of showering over bathing and apply “running water” to develop a spraying mechanism that can effectively clean parts with complex features. The cleaning solution is recycled and kept airtight.
3. The whole system is sustainable and scalable. The design of the printer is modular and highly customizable, and the material waste for build materials and cleaning solution is minimized.

The theoretical analyses and experimental studies are also done to verify the functionality of the systems and test the hypotheses.

The rest of the paper is organized as follows. In Section 2, a brief overview of the current multi-material 3D printing technologies are presented. Section 3 presents the material storage and retrieval system, and Section 4 outlines the cleaning system. Section 5 discusses the results acquired from the prototype. In the last section, the conclusion and the future work are presented. The hardware setup of the printer is given in the Appendix.

2 Literature Review

This paper is related to multi-material 3D printing, and particularly multi-material SLA/DLP printing. Before reviewing those works, the applications are briefed.

2.1 Applications of multi-material printing

Multi-material printing allows for the creation of functionally graded materials which have variations in the properties as the dimension varies [14–16]. Utilizing this principle, biopolymer structures and liver cells for free-form construction of 3D tissue scaffolds is possible [17]. In this context the use of multiple materials has allowed for advances in soft robotics by allowing the placement of soft materials with harder materials [18] and the ability to add specific properties such as conductivity to materials and parts [19]. In the field of robotics, more and more design for anthropomorphic hands are utilizing some form of 3D printing with multiple materials. This allows for unique compliance and performance of joints and actuators to better control and design such hands [20–22]. As suggested by Wang et al. [23], the possibilities do not simply extend to the engineering world, artists and fashion designers can also take advantage. From prototypes to end products, it can be seen that the technology is being applied to various fields, from organs to airplane parts [24].

2.2 Multi-material 3D printing

Development on multi-material printing is happening for almost all technologies. For FDM to change materials, it must have multiple nozzles or swap the filaments. This requires motors to pull out and insert the next filament which then must purge the old material left in the model. An example of this is the Prusa i3 multi-material printer [25] as a commercial solution, but the likes of Khalil et al [17] have developed triple extruder system for the printing of scaffolds. Similarly, Leu et al [26] also developed a triple extruder which can control paste extrusion. A multi-material Polyjet printer was created by MIT CSAIL [9] capable of handling up to 15 materials through ink-jetting technology. Selective laser sintering or melting (SLS/SLM) is also a technology that can fabricate multi-material parts by using different powders [27, 28].

2.3 Multi-material SLA/DLP printing

SLA/DLP technology requires more considerations, as FDM or Polyjet printers would use independent nozzles for various materials, entire resin vats must be used for SLA/DLP. There are only a few multi-material SLA/DLP printers presented in literature. Holtrup [29] recently constructed a multi-resin DLP printer that has a series of reservoirs arranged linearly between the printing stage. The materials are swapped by engaging a conveyor in order to change the current vat. However, this system has long wait time during cleaning of resin and material swapping. In contrast, a carousel design has been approached and improved upon several times over the last decade. Wicker et al. [30] modified an existing 3D Systems SLA 250/50 and added multi-material capabilities by appending a horizontal carousel to the side of the printer. Inamdar et al. [11] developed a similar system as a standalone solution to multi-material SLA. Like the previous two carousels, Zhou et al. [12] developed another rotary printer, which rotates two material vats along with their cleaning system comprised of brushes and an ultrasonic bath. Alongside these designs is again a rotary design [31] using UV and IR radiation. Though quicker than the linear setup, the rotational printer makes it difficult to increase the number of materials, or the build area as the size of the printer would grow exponentially. The previous works have proved that SLA/DLP technique can be extended to multi-material printing, although with certain challenges still needing to be solved. In this paper, the concept of a storage system is applied to facilitate the material swapping process, and it is presented in the next section.

3 Material Storage and Retrieval System

One of the primary concerns with multi-material 3D printing, especially with DLP printers, is the time and the mechanism for swapping materials. This mechanism differs from other 3D printing processes since an entire container must be removed from the build area and replaced with another. Additional considerations are the storage density of the system, the scalability in terms of build area and number of materials, as well as the complexity of the printer. Although swapping and storage mechanisms have been used in many industrial applications, they have particular requirements and use cases which do not easily translate over to the DLP process. While some existing methods [11, 12, 29] use linear or rotary stages to swap different materials, they have poor scalability and suffer from long material swapping time. To address this problem, the objective here is to apply the techniques from automated storage and retrieval system (ASRS) to establish a material storage and swapping system for multi-material DLP printing. The storage system is discussed first, and it is followed by the swapping mechanism.

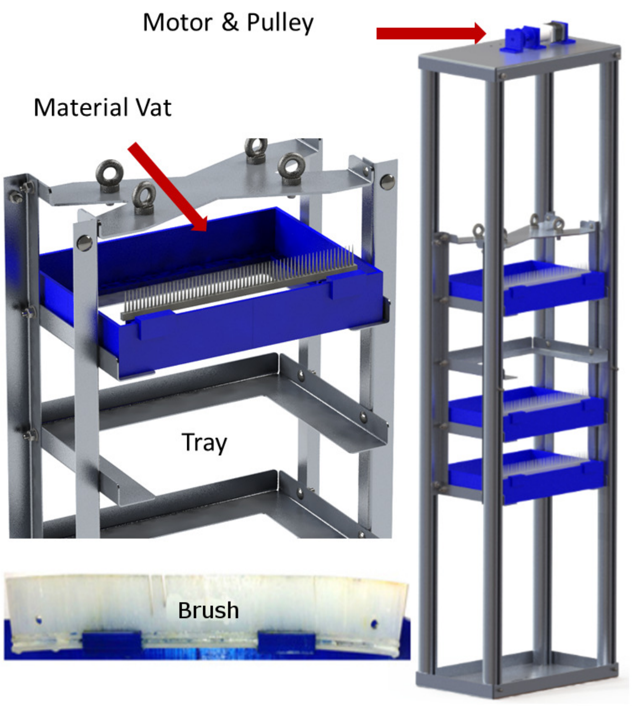

Fig. 2. Material tower with vats and silicone brush

3.1 Storage System

The common geometry for a material vat is having rectangular shape or is a circular disk for experimental setup. To maximize the print size, the rectangular vat is employed in this study as depicted in Fig. 2. Observing that the material vat is a boxlike storage compartment without a lid, a drawer design that is made to slide horizontally in and out is employed for the storing process, and a material tower as shown in Fig. 2 is developed to provide a high-density vertical storage solution. A vertical approach is desired because of the fact that material vats have much greater length or width than they do height, as such not only can storage be more dense and efficient, there is also less distance that needs to be traveled to access the next material. A stepper motor and pulley at the top of the tower is used to raise and lower the trays holding the material vats. The detailed hardware setup of vertical storage tower is described in Appendix A.3.

Although the design is simple, it is sufficient to test the first hypothesis of employing ASRS in multi-material DLP printer. Due to the vertical and independent nature of our current design, to be able to access the top most material, there needs to be enough room on the bottom of the tower to accommodate the other materials. In the current design, 4 inches of clearance was given between each material. Following these measurements, 8 additional inches would be required for one more material. The current height of the prototype tower is 60 inches and can accommodate 8 vats. Compared to the rotary design [12] which housed 2 materials, this design hosts more materials. More importantly, the rotary design needs to fit a number of material vats in the circular platform, the size of which varies greatly with the size of vats and the number of materials. This may limit proper industrial implementation. In contrast, our design has much better extensibility and has an effective use of floor space. In terms of packing density, which is calculated by dividing the volume of the vats by the volume of the storage solution, our design can achieve a factor of around 0.6 while the rotary design is only about 0.3, for the same number of materials with similar print size.

The packing density can be improved in the future by incorporating a vertical carousel storage system to rotate with multiple towers, so that no empty space is needed within the tower.

The tower design with adjustable partitions and dividers is modular and highly configurable. The number of trays, thus available materials, can be modified with minimal additional design work by simply changing the length of the corner extrusions. Moreover, increasing the build area of the printer changes the size of the vats. For the vertical tower design, only the top and bottom braces as well as trays need to be re-sized to accommodate such changes, see Fig.2. The use of common stock materials, a simplistic design, and designing for manufacturing makes the storage solution easily scaled to the required size, and for the desired number of materials.

3.2 Material Swapping

In a linear design, the complexity of material swapping is directly proportional to the number of materials, i.e., $O(n)$ where n is the number of stations on the conveyor. In other words, the worse case scenario is changing material from one end to the other. This requires it to pass through every station on the conveyor in order to get to the next material. A rotary design is better as it can turn the table in either clockwise or counter-clockwise direction, but the complexity is still linear. Due to the necessity of moving entire vats in and out of the print area, it is impossible to completely eliminate swapping time. However, because the swapping and cleaning do not need to be related to each other, they can be decoupled in the design of the storage solution, and it is possible to set the next material vat in the ready position while the cleaning process is underway.

As the material tower is a vertical lift system, we design a storage/retrieval (SR) machine that can push and pull the material vats from the tower. Actually, the SR machine is permanently attached to the cleaning vat (explained in Section 4), such that the positioning of the cleaning vat is combined with the material swapping. It is worth noting that it is a compact and efficient design which can accomplish material storage/retrieval and cleaning by one single degree of freedom (X-axis) without the need of complex controls. The procedure created to swap materials has several steps and is illustrated in Fig. 3. First, our storage solution, the vertical tower, should already be in the receiving position with an empty tray aligned to the printer platform. A rack-and-pinion mechanism then pushes the vat onto the tray and into the tower. Guide rails on either side ensure proper alignment. In this sense, as the material vat goes into the tower, the cleaning vat is also moving into its cleaning position. The cleaning vat is equipped with the red hooks which are used to latch onto the material vats. Once the material vat is properly inserted, the tower lowers to disengage the hooks and the cleaning vat is pulled away to prevent interference. With the material vat in the storage system, it is free to rearrange the materials, which allows the tower to position the next material while the part is being cleaned. After cleaning is complete, the cleaning vat moves forward to receive the next material vat. The tower then raises to engage the hooks and the new material is pulled into place. The following layer is now ready for printing. In this way, the complexity of the process is constant, i.e., $O(1)$. This supports the first hypothesis and the tower-based ASRS speeds up the material swapping process for multi-material DLP printing from linear complexity to constant.

4 Active Cleaning System

Another challenge in multi-material DLP printing is the cleaning of residual resin on the build part and bed. If the previous uncured material is not removed, contamination happens on both the part and the vats containing other materials. There are a number of considerations in the cleaning system: cleanliness, material usage and waste, speed, size and scalability of the cleaning system, as well as the evaporation of the cleaning solution. The proposed method must also be able to reach complex geometries.

The existing systems for cleaning are using a cloth to wipe the printed part [32] and soaking the part [12]. The cloth method is fast but it is unable to deal with intricate geometries. In addition, the process would have to be done manually which is undesirable and inconsistent. It is more promising to soak prints in isopropyl alcohol for several minutes, anywhere from 5 to 20 minutes depending on the resin used [33]. The purpose is to dilute and clean the excess resin from the print before further operation. In this sense, utilizing an ultrasound machine in conjunction with the cleaning agent would further increase the efficiency of the process. The ultrasound method adds vibrations to the cleaning solution which in turn leads to cavitation. This effect causes bubbles of air to implode on the surface of the part and dis-

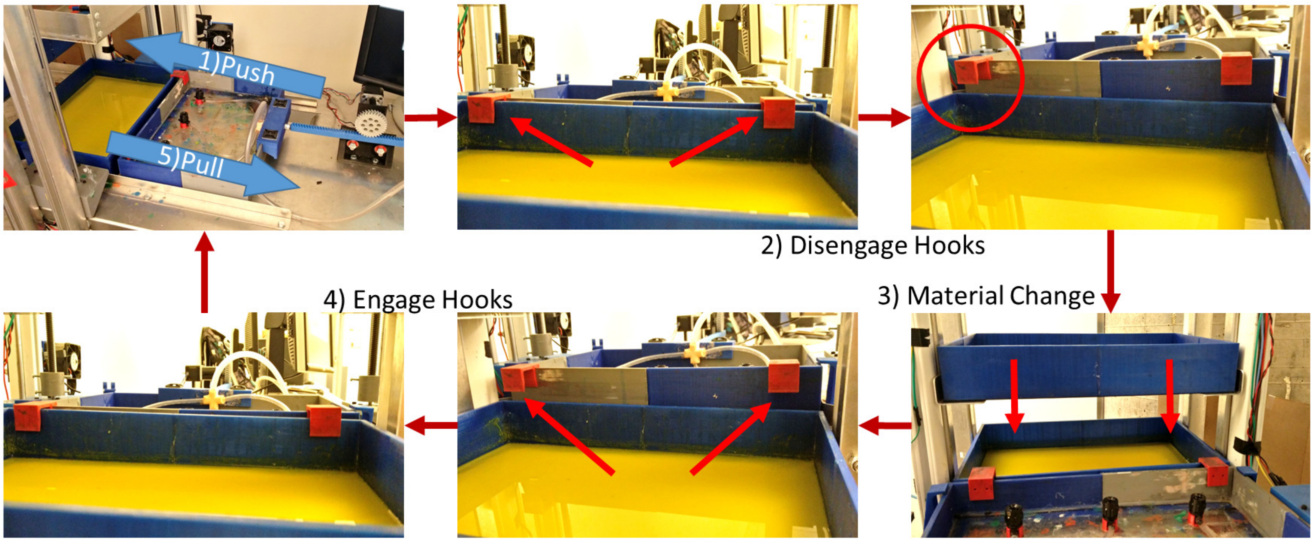

Fig. 3. Material swapping process: 1) The material swapping process starts with the cleaning vat pushing the material vat into the tower. 2) The tower lowers to disengage the hooks. 3) The cleaning vat moves back to allow clearance of the hooks, and the tower selects the next material. 4) The material vat advances and the tower rises to engage the hooks. 5) The cleaning vat pulls the material vat into place

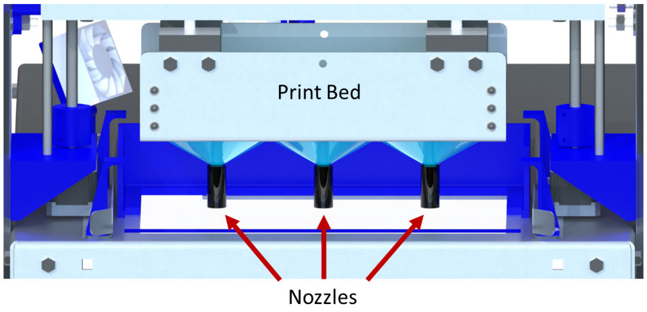

Fig. 4. Spray pattern of the 3 sprinkler heads

lodge the contaminant [34].

In terms of cleanliness, the soaking method would become less and less effective with every cleaning step, since the cleaning agent would become more contaminated. Furthermore, having a large bath constantly exposed in ambient air would lead to excess evaporation, bringing additional concerns to size and scalability of the approach. Therefore, our goal is to develop an active cleaning system to have the contaminants running off from the part and down into a filtered drain with the cleaning solution, such that the aforementioned considerations can be achieved.

4.1 Spraying Mechanism

Showering is known to have advantages over bathing such as being more environmental friendly, less cleaning time, and cleaner. Learning from showering, here we develop an active cleaning system that utilizes three sprinkler nozzles and a pump to spray the part. Once the material vat has been placed in the tower and the cleaning vat positions itself under the print bed. The pump then turns on and the cleaning solution is ejected from the sprinklers. This is a direct approach to deliver the cleaning solution onto the print bed and hit the part in places that are hard to reach.

The spray pattern is angled towards the part as can be seen in Fig. 4. To ensure proper coverage of the print bed and piece, the cleaning vat oscillates from side to side in the *X* direction while the print bed rises and lowers. The spray itself is similar to a heavy mist in a cone. Additionally, this system is easily scalable for larger build volumes by adding/removing sprinklers or simply adjusting the positions of the sprinklers. The spray method combines both the cleaning power of the cleaning solution with the impact force of the spray. Consequently, this also creates movement of the cleaning solution which means it is further able to penetrate complex geometries and cycle the solution so that resin can escape from crevices. This theoretically decreases the exposure time to the cleaning system, and increases the efficiency of the cleaning solution. This is important because prolonged exposure to the cleaning agent can cause swelling in the printed part and affect print quality and accuracy [35].

Proper tuning of the pump is done to ensure there is enough pressure to spray the parts but not too much such as to damage the part. After cleaning is complete, the cleaning vat then moves into position to pull the new material into place while fans angled towards the print bed help dry the print for the next layer.

4.2 Sustainability

Both the resin and the cleaning solution are consumables that the cleaning process uses up. Minimizing the waste of these materials is crucial to reduce the cost and improve the sustainability of the system. In addition to the spraying mechanism that reduces the amount of cleaning solution being used, two other components are also incorporated in the system: a silicone brush and an airtight reservoir. The silicone brush is integrated into the material vat, as seen in Fig. 2, and the reservoir houses the cleaning solution with a

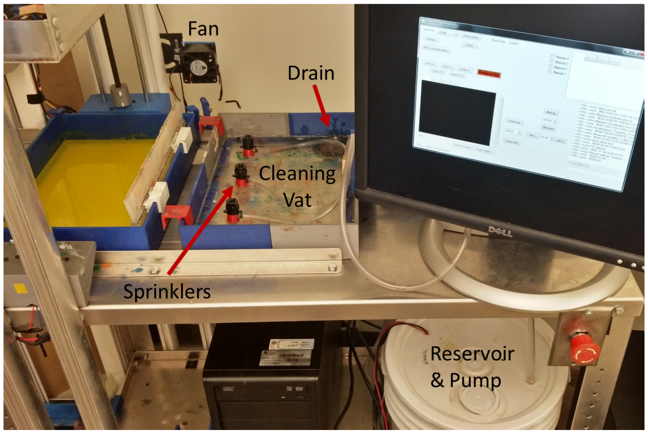

Fig. 5. Cleaning system: sprinklers, brush, drain and reservoir

diaphragm pump which supplies the sprinklers. The reservoir is also connected to the material vat where the resin and the excess cleaning solution can be drained after spraying. The general layout of the cleaning hardware and system can be seen in Fig. 5.

Because all the uncured resin dissolved in the cleaning solution will be material waste, a substantial cleaning is done by the silicone brush installed in the vat. Silicone was used so that none of the resin gets absorbed by the brush, and placed within our material vats so that all excess resin that is wiped off is directly returned to its vat, which further reduces waste and initial resin required at the start of the print. Additionally there is no risk of loosing bristles during the cleaning. Whenever material swapping is required, the print bed raises to a height such that the silicone brush can make contact with the contaminated area to remove and recuperate as much resin as possible back into the material vat. This cleaning is performed implicitly when the rack-and-pinion pushes the material vat back into the tower, and thus no additional time is required.

The cleaning solution used, and recommended for cleaning resin, is an isopropyl alcohol-water mixture of 90%-10% [11]. This means that leaving a large vat exposed would lead to quick evaporation of the solution, filling the environment with dangerous fumes. As such, the proposed system uses an airtight reservoir (Fig. 5) with a pump submerged to supply limited amounts of cleaning solution when needed. The excess resin and solution is recollected and recycled through a drain, made of a filter and funnel, placed in a corner of the cleaning vat which feeds back into the reservoir, so that the amount of alcohol evaporated can be minimized.

5 Results

This paper has two hypotheses regarding to the material swapping and active cleaning. To test the hypotheses, a prototype multi-material DLP printer was built as shown in Fig.6. The overall hardware and software architecture is available in the Appendix. The printer uses a bottom up approach to limit the contact of the printed part and the resin. The printer consists of three degrees of freedom: build platform (Z_b-axis), material tower (Z_m-axis), and rack-and-pinion (X-axis). A custom C# application was developed to handle the sorting algorithm and control the prototype based on the RepRap framework [36]. A piece is first designed as separate bodies and sliced individually to generate a set of black and white images for each material. Once a layer is printed for one material, it checks if there are images for the other materials. If there is, it initiates the swapping process, else it prints the next layer.

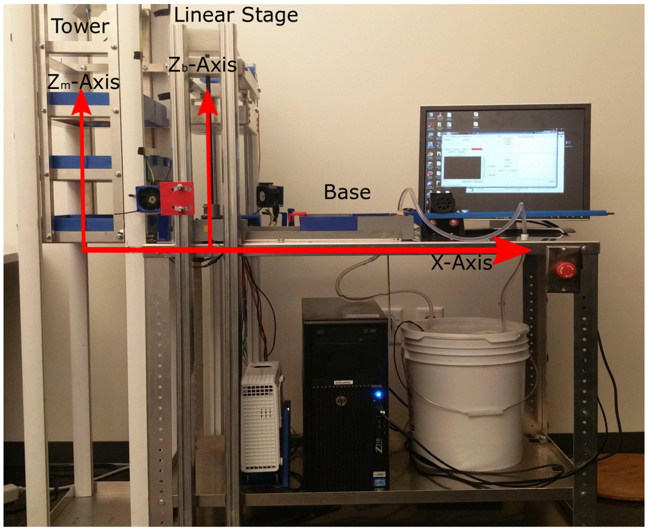

Fig. 6. Multi-Material DLP Printer Prototype

Table 1. Comparison of previous prototype and ours

Prototype	Zhou et al. [12]	Our
Build Area	6 in^2	72 in^2
# of Materials	2	8
Swapping Time	180s	62s
Cleaning Time	120s	15s

A series of different parts with varying features were printed to test this system, and duration of both the exposure time to the cleaning system as well as the drying times were determined experimentally, the results of which are presented in this section. All tests were preformed with the G+, and semi-flex resin from MakerJuice [37]. Some of the fabricated multi-material examples are shown in Fig. 7 to validate the correctness and functionality of the system. Furthermore, we compare our method with the previous work [12], and Table 1 summarizes the key differences including the number of materials for the two prototypes, the build area, the time it takes to swap from one material to the next, and the cleaning time. The cleaning percentage is the average of the testing presented in Section 5.2. In the following, the quantitative comparison will be presented in detail.

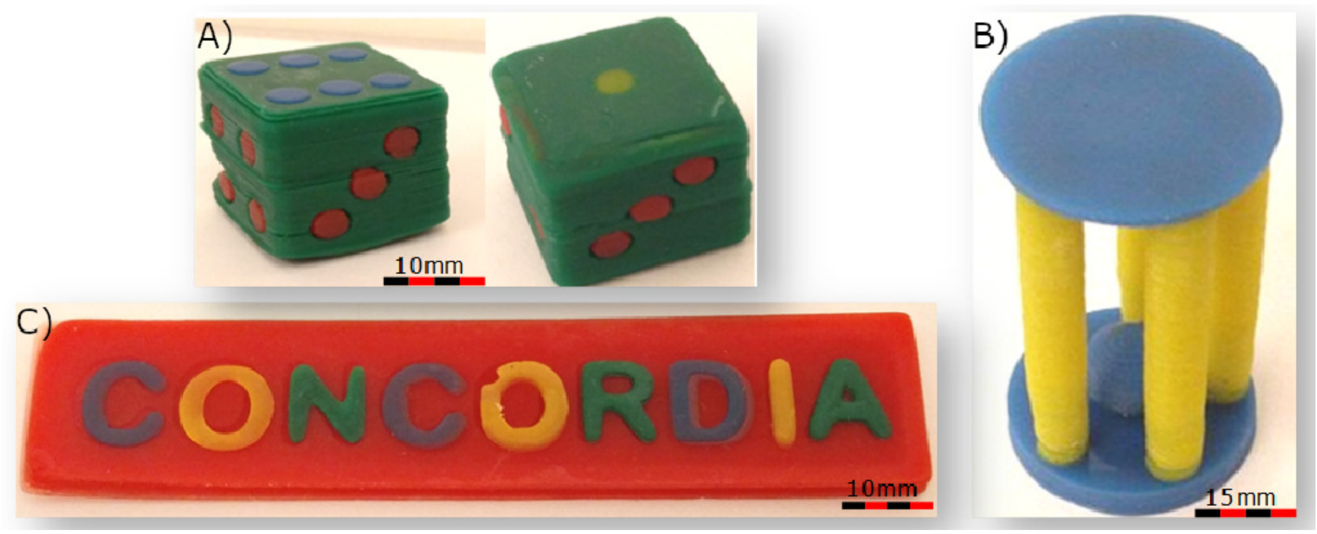

Fig. 7. Examples of multi-material prints: A) 4 colored die; B) Ball in a cage with two colors; C) Concordia printed in 3 colors on a semi-flexible backing.

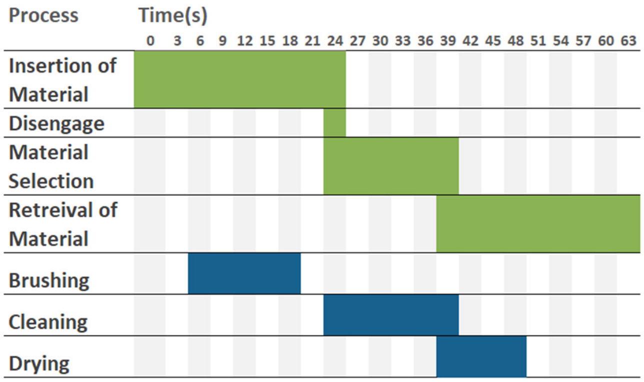

Fig. 8. Figure shows the breakdown of the varying steps within the material swapping process. In green are the tasks that involve moving and swapping the material vat. In blue are the steps involved in the cleaning process

5.1 Material Swapping

In Section 3, we have discussed the theoretical speedup that could be achieved with the tower-based design, and this section is going to present the experimental data. With the current configuration, the material swapping cycle includes part of the cleaning cycle. In this sense, both subsystems are paired together to save time overall and increase the efficiency of the material swap. Additionally, by allowing the storage system to select the material independently, the rest of the printer is free to perform any other task, in this case, spraying and cleaning the print bed. Finally, by making every operation linear, the scalability of the solution is ensured. As the print area increases or decrease, the travel distance follows in a one to one ratio, and as the number of materials increase, it does not affect the material swapping time. Fig. 8 illustrates each of these individual processes and when they occur relative to each other throughout a complete material swap and cleaning. The time for the brushing phase of the cleaning process is partially dependent on the speed of the material storing process, however it is sill displayed as its own process because it helps to demonstrate clearly the total time required to clean the part effectively. From the figure, the total material swap time takes 63 seconds. The insertion of the material as well as the retrieval process take up the majority of the time at 24 seconds each. Both processes are affected by motor speeds of the X-axis as well as the distance needed to travel due to the size of the print area. The material selection time of the prototype takes 15 seconds. The disengage time, 3 seconds, is illustrated as well since it is still possible to optimize the hook geometry or use a system, such as electromagnets, to reduce the time. The previous work [12] had an approximate swapping time of 180 seconds, and there is a 3× improvement in speed for our prototype. Although it may not sound significant, it should be noted that there is a huge difference in the build area, i.e., $6in^2$ [12] vs. $72in^2$ in our case. Therefore, the proposed solution is three times faster while having a build area that is twelve times larger. These results support our first hypothesis that applying ASRS can increase the material swapping speed for multi-material DLP printing.

5.2 Cleaning System

For a successful cleaning system, contamination must be as close to zero as possible. This condition takes priority over total print time as multiple material changes will continuously accumulate to the total amount of contamination during a print. To determine the effectiveness of the proposed active cleaning system, a residue test is conducted to compare the amount of residue left on the part by different methods.

The residue test involves printing pieces with varying geometries and features, and weighing them after the print. The geometries of the parts were designed to represent different features to clean and test the cleaning system capability to deal with overhangs, hard-to-reach surfaces, cavities and

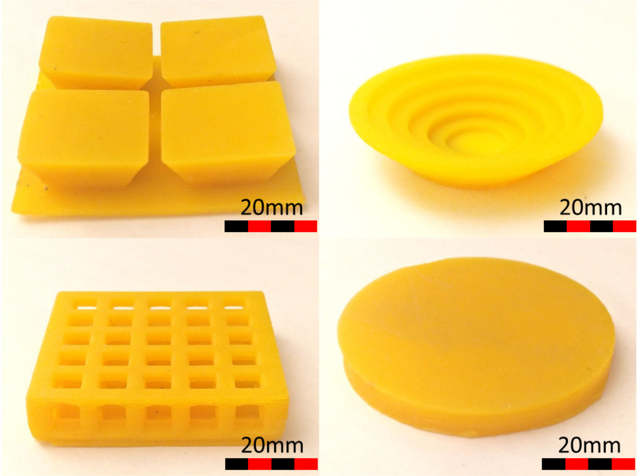

Fig. 9. Pieces used for contamination test. Top left: Four inverted Pyramids . Top Right: Staggered Cone. Bottom Left: Scaffold. Bottom Right: Cylinder

complex geometries. Pictures of the testing samples cleaned by the spray system are shown in Fig. 9. Increasing the vertical surfaces and overhangs ensures cleaning systems have to be able to reach the entirety of the piece. Smaller features and intricate cross sections, such as the scaffold, create large amounts of cavities, and surfaces that continually get contaminated and covered by subsequent layers and thus more difficult to clean.

These pieces were printed and weighed when exposed to 6 different scenarios. Firstly, it is weighed without any cleaning thus being the most contaminated piece. Secondly, it will then sit in a bath of alcohol for two hours to ensure that all resin has been diffused from the part and will act as the basis for a completely cleaned part. In the third scenario, the contaminated pieces are be wiped using a cloth [32] to see its effectiveness. The fourth and fifth cases expose the pieces to the ultrasound (U/S) bath for 15 seconds and 120 seconds [12], respectively. Sixth, the pieces are exposed to the proposed spray cleaning system for a single oscillation of the cleaning vat lasting 15 seconds, this ensures the cleaning solution covers the entirety of the print bed. The fourth scenario is designed to be compared with the sixth one to illustrate the effectiveness between passive and active cleaning for the same amount of time. The difference in weight between each trial and the fully cleaned part will be the excess resin, and thus the level of cleanliness. Results of the residue test can be seen in Table 2 where the percentage illustrates the cleanliness of the piece.

Table 2 shows that using cloth to wipe a printed piece will give varying results based on the geometry. Although the method is very fast, at 5 seconds to perform, its performance is inadequate. The ultrasound bath performed better than the cloth in every scenario except the cylinder which predominantly has a one flat face which favors wiping. It can also be observed that exposing the contaminated part for longer in the ultrasound bath, first 15 seconds and then 120 seconds, did reduce contamination but with varying results.

Table 2. Contamination test results, weight in g. U/S = ultrasound

Piece	No Clean	Full Clean	Cloth	U/S (15s)	U/S (120s)	**Spray (15s)**
Cone	8.10	7.21	7.99 (12%)	7.86 (27%)	7.74 (40%)	**7.22** **(99%)**
Scaffold	16.40	15.20	16.31 (7%)	16.30 (8%)	15.60 (67%)	**15.30** **(92%)**
Cylinder	15.60	14.90	15.12 (69%)	15.39 (30%)	15.32 (40%)	**14.92** **(97%)**
Pyramids	17.00	16.21	16.79 (37%)	16.55 (27%)	16.3 (57%)	**16.28** **(91%)**

By comparison the proposed active cleaning system utilizing the spray of a cleaning solution reduced contamination to as low as $0.1g$ from the full clean piece in 15 seconds, which results in parts that are over 90% clean. The proposed method outperforms the passive systems in cleanliness and time required.

The previous cleaning systems, using ultrasound [12] and cloth [32], reported that they took 3 minutes and 2 minutes for cleaning respectively. Comparatively, the prototype system takes only a total 25 seconds for the whole cleaning cycle to achieve a nearly full-clean result, which is an order of magnitude faster than both systems. This experiment supports the second hypothesis that an active approach to cleaning resin results in low levels of contamination and a significant reduction in cleaning time.

6 Conclusion & Future Work

In this paper, a new method for multi-material DLP printing has been presented. To increase the efficiency of material swapping, the technique from automated storage and retrieval system was used to design the material swapping mechanism which utilizes a tower as a storage system and the retrieval system is coupled with the cleaning system, so that the overall process complexity is just three degrees of freedom. An active cleaning approach was then devised using sprinklers to deliver the cleaning agent to clean the build part in-between the material swapping. The prototype was then tested to prove the merits of these solutions. By decoupling of the material swapping and cleaning systems, it allows for independent optimization as well as an increase in efficiency of the overall system. The prototype showed a swapping time of one minute between vats, and a cleaning time of 15 seconds. Due to the prototype being a proof of concept, several components, while functional, are not fully optimized. There are a number of things that could be improved.

The current speed of the material-swapping process is dependent on the size of the print area, as well as the speed of the stepper motors selected. Upgrading motors could drastically affect travel times as well. The latching mechanism could also be improved to eliminate any additional displacement by using electromagnets. The current spray pattern functions but is rather simple, optimizing the spray pattern could result in faster cleaning time and less solution being used. In addition, the effects of cleaning solution and swapping mechanism on different part geometries, accuracy and material properties are to be investigated. To start challenging the likes of FDM and Polyjet printers in terms of available maximum materials per print, an improved storage system would have to be developed to allow more towers to be interchanged during the course of the print or have a wall of vats with an independent system to retrieve the desired material. Additionally mutli-material DLP printing requires a more complete software solution. This would mean a new slicing program to efficiently generate the image files and generate the required g-code to control the printer.

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References

[1] Kruth, J.-P., Leu, M., and Nakagawa, T., 1998. “Progress in additive manufacturing and rapid prototyping”. *CIRP Annals,* **47**(2), pp. 525 – 540.

[2] Rayna, T., and Striukova, L., 2016. “From rapid prototyping to home fabrication: How 3d printing is changing business model innovation”. *Technological Forecasting and Social Change,* **102**, pp. 214 – 224.

[3] Excell, J., 2013. The rise of multi-material 3d printing. https://www.theengineer.co.uk/issues/may-2013-online/the-rise-of-multi-material-3d-printing/.

[4] Fang, G., Matte, C., Kwok, T., and Wang, C. C. L., 2018. “Geometry-based direct simulation for multi-material soft robots”. In IEEE International Conference on Robotics and Automation (ICRA), pp. 1–6.

[5] Davies, S., 2018. Sailner exhibits multi-colour and multi-material 3d printing capabilities at tct asia. https://www.tctmagazine.com/tct-events/tct-asia/sailner-mulit-colour-material-3d-printing-tct-asia.

[6] Yuk, H., Zhang, T., Parada, G. A., Liu, X., and Zhao, X., 2016. “Skin-inspired hydrogelelastomer hybrids with robust interfaces and functional microstructures”. *Nature Communications,* **7**, p. 12028.

[7] Kong, Y. L., Tamargo, I. A., Kim, H., Johnson, B. N., Gupta, M. K., Koh, T.-W., Chin, H.-A., Steingart, D. A., Rand, B. P., and McAlpine, M. C., 2014. “3d printed quantum dot light-emitting diodes”. *Nano Letters,* **14**(12), pp. 7017–7023.

[8] Pham, D., and Gault, R., 1998. “A comparison of rapid prototyping technologies”. *International Journal of Machine Tools and Manufacture,* **38**(10), pp. 1257 – 1287.

[9] Pitchaya, S.-A., Ramos, J. E., Wangy, Y., Kwan, J., Lan, J., Wang, W., and Matusik, W., 2015. “Multifab: A machine vision assisted platform for multi-material 3D printing”. *ACM Trans. Graph.,* **34**(4), pp. 129:1–129:11.

[10] Groth, C., Kravitz, N. D., Jones, P. E., Graham, J. W., and Redmond, W. R., 2014. “Three-dimensional printing technology”. *J Clin Orthod,* **48**(8), pp. 475–85.

[11] Inamdar, A., Magana, M., Medina, F., Grajeda, Y., and Wicker, R., 2006. “Development of an automated multiple material stereolithography machine”. In Annual Solid Freeform Fabrication Symposium, pp. 624–635.

[12] Zhou, C., Chen, Y., Yang, Z., and Khoshnevis, B., 2013. “Digital material fabrication using maskimage-projectionbased stereolithography”. *Rapid Prototyping Journal,* **19**(3), pp. 153–165.

[13] Choi, J.-W., Kim, H.-C., and Wicker, R., 2011. “Multi-material stereolithography”. *Journal of Materials Processing Technology,* **211**(3), pp. 318 – 328.

[14] Mahamood, R. M., Akinlabi, E. T., IAENG, Shukla, M., and Pityana, S., 2012. “Functionally graded material: An overview”. In Proceedings of the World Congress on Engineering, Vol. 3, WCE, pp. 2–6.

[15] Udupa, G., Rao, S. S., and Gangadharan, K., 2014. “Functionally graded composite materials: An overview”. Vol. 5, pp. 1291 – 1299. International Conference on Advances in Manufacturing and Materials Engineering, ICAMME 2014.

[16] Oxman, N., Tsai, E., and Firstenberg, M., 2012. “Digital anisotropy: A variable elasticity rapid prototyping platform”. *Virtual and Physical Prototyping,* **7**(4), pp. 261–274.

[17] Khalil, S., Nam, J., and Sun, W., 2005. “Multinozzle deposition for construction of 3d biopolymer tissue scaffolds”. *Rapid Prototyping Journal,* **11**(1), pp. 9–17.

[18] Raviv, D., Zhao, W., McKnelly, C., Papadopoulou, A., Kadambi, A., Shi, B., Hirsch, S., Dikovsky, D., Zyracki, M., Olguin, C., Raskar, R., and Tibbits, S., 2014. “Active printed materials for complex self-evolving deformations”. *Scientific Reports,* **4**, pp. 7422–7430.

[19] Macdonald, E., Salas, R., Espalin, D., Perez, M., Aguilera, E., Muse, D., and Wicker, R. B., 2014. “3d printing for the rapid prototyping of structural electronics”. *IEEE Access,* **2**, pp. 234–242.

[20] Odhner, L. U., Jentoft, L. P., Claffee, M. R., Corson, N., Tenzer, Y., Ma, R. R., Buehler, M., Kohout, R., Howe, R. D., and Dollar, A. M., 2014. “A compliant, underactuated hand for robust manipulation”. *The International Journal of Robotics Research,* **33**(5), pp. 736–752.

[21] Odhner, L. U., Ma, R. R., and Dollar, A. M., 2013. *Experiments in Underactuated In-Hand Manipulation*, Vol. 88. Springer International Publishing, Heidelberg, pp. 27–40.

[22] Tavakoli, M., and de Almeida, A. T., 2014. “Adaptive under-actuated anthropomorphic hand: Isr-softhand”. In IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1629–1634.

[23] Wang, G., Yao, L., Wang, W., Ou, J., Cheng, C.-Y., and Ishii, H., 2016. “xPrint: A modularized liquid printer for smart materials deposition”. In Proceedings of the

CHI Conference on Human Factors in Computing Systems, CHI '16, ACM, pp. 5743–5752.

[24] Murr, L. E., 2016. "Frontiers of 3d printing/additive manufacturing: from human organs to aircraft fabrication". *Journal of Materials Science & Technology,* **32**(10), pp. 987 – 995.

[25] Prusa, J., 2017. Multi-material Prusa i3 MK2. https://www.prusaprinters.org/original-prusa-i3-mk2-multi-material-upgrade-release/.

[26] Leu, M. C., Deuser, B. K., Tang, L., Landers, R. G., Hilmas, G. E., and Watts, J. L., 2012. "Freeze-form extrusion fabrication of functionally graded materials". *CIRP Annals,* **61**(1), pp. 223 – 226.

[27] Chivel, Y., 2016. "New approach to multi-material processing in selective laser melting". *Physics Procedia,* **83**, pp. 891 – 898.

[28] Demir, A. G., and Previtali, B., 2017. "Multi-material selective laser melting of fe/al-12si components". *Manufacturing Letters,* **11**, pp. 8 – 11.

[29] Holtrup, R., 2015. "XZEED DLP: a multi-material 3D printer using DLP technology". Bachelor thesis, University of Twente, Enschede, Netherlands.

[30] Wicker, R. B., Medina, F., and Elkins, C., 2004. "Multiple material micro-fabrication: extending stereolithography to tissue engineering and other novel applications". In Proceedings of 15th Annual Solid Freeform Fabrication Symposium, Austin, TX, pp. 754–64.

[31] Vaezi, M., Chianrabutra, S., Mellor, B., and Yang, S., 2013. "Multiple material additive manufacturing–part 1: a review". *Virtual and Physical Prototyping,* **8**(1), pp. 19–50.

[32] Huang, P., Deng, D., and Chen, Y., 2013. "Modeling and fabrication of heterogeneous three-dimensional objects based on additive manufacturing". In ASME 2013 International Mechanical Engineering Congress and Exposition, p. V02AT02A056.

[33] Formlabs, 2018. Form wash time settings. `https://support.formlabs.com/hc/en-us/articles/115001347744`.

[34] Fuchs, F., 2015. "19 - ultrasonic cleaning and washing of surfaces". In *Power Ultrasonics*, J. A. Gallego-Jurez and K. F. Graff, eds. Woodhead Publishing, Oxford, pp. 577 – 609.

[35] Formlabs, 2018. Solvent compatibility. `https://support.formlabs.com/hc/en-us/articles/115000018064`.

[36] Reprap project. `http://reprap.org/wiki/RepRap`.

[37] MakerJuice G+. `https://makerjuice.com/`.

Appendix

A Printer Architecture

The printer is broken down into five main components: printer base, build platform, material tower, cleaning hardware and the electronics/software.

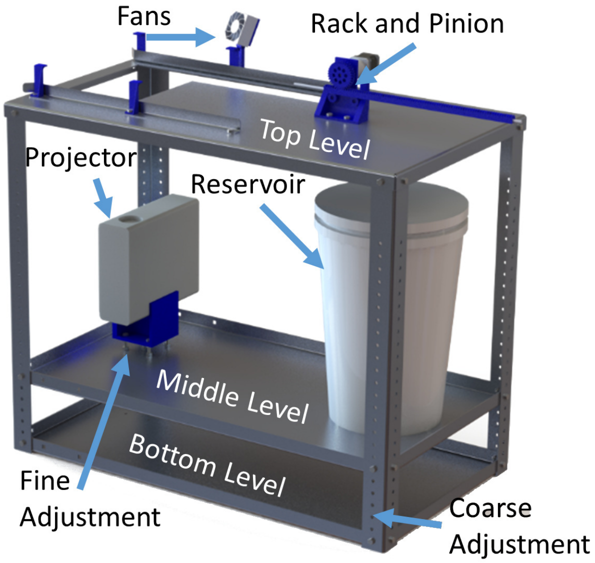


Fig. A.1. Printer base with detailed components and sectioning

A.1 Printer Base

The base of the printer, shown in Fig. A.1, is the main foundation to connect all the modules. The printing and cleaning process take place on the top level, while the second and third house the equipment. All other subsystems are attached directly to the base. The systems integrated into the base are as follows:

A.1.1 Top level

The top level accommodates the vat displacement and movement control. In order to move the vats on the top level (for shearing and material swap operations), the X-axis is driven by a geared stepper motor using a rack and pinion system. The rack-and-pinion uses a herringbone design to self-align and is attached to the cleaning vat using a printed hook. In addition, two rails are attached on the surface to help guide the vats. An opening is cut through the top level to allow the projected image to cure the resin through the material vats glass bottom. A second cut is performed to accommodate the cleaning vat drain, as well as a hole above the reservoir to pass the primary cleaning hose.

A.1.2 Middle level

The middle platform houses the projector, whose position and height is adjustable, and an airtight bucket which acts as a reservoir. The adjust-ability is threefold: The first adjustment is the vertical position of the middle tray using the hole pattern on the four base legs (Fig. A.1). This is a coarse adjustment wherein the projector can be moved closer or farther away by one-inch increments. The second adjustment is for higher precision and accomplished by a alignment stage setup on the projector support. The support has four mounting points so that the proper angles and focal distances can be attained. Finally, it is noted that as the projector is moved up or down, the projected image also shifts

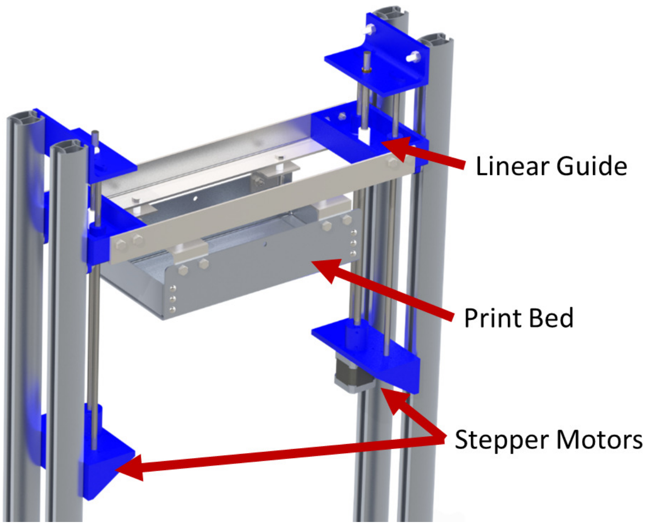


Fig. A.2. Parallel linear stage with build platform

location. As a counter measure, slots are provided in the tray to accommodate horizontal displacement of the projector to ensure a centered image on the print bed.

A.1.3 Bottom level

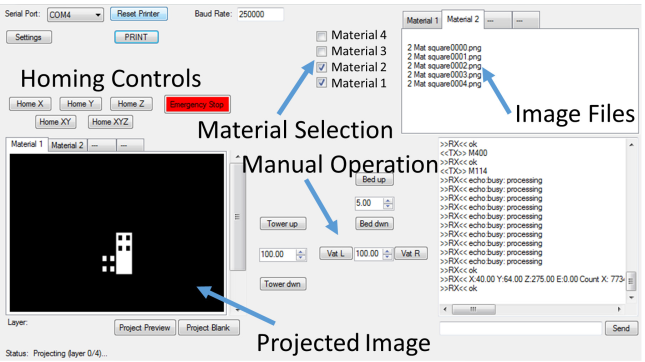
The bottom of the base is used to store and organize some of the electronics that will be outlined in section A.5. This includes the arduino, ramps board, as well as the power supply. Build materials can also be stored in this level.

A.2 Build Platform

The print bed shown in Fig. A.2 is a 12 by 6 in^2 surface made from aluminum sheet metal. The bed is attached to two L-stock extrusion cross beams. The bed level can be adjusted by varying the height of the four bolts fastened to the L-stock corners. The cross beams are anchored to two linear guides, each of which has a 10mm lead screw and two guide rods with linear bearings. The build platform displacement is controlled by two synchronized stepper motors, each turning a lead screw. The prototype print height is 12 inches.

A.3 Material Tower

The material tower system is designed to be a simple solution that allows the printer to easily store and retrieve the desired materials for any given print layer. The tower itself is built using four t-slot aluminum extrusions for the corners. The extrusions are held together with top and bottom flanged sheet metal plates with holes for fastening. Within the frame are trays that support the material vats. The sides of the trays are bent up to secure the vats in place. They have holes in each corner for attaching to a rail which is in turn guided by the t-slot extrusions during movement. To move the trays up and down, a geared stepper motor is mounted to the top bracket. The motor spins a small spool with a nylon strap attached to the trays.


Serial Port: COM4
Baud Rate: 250000

☐ Material 4
☐ Material 3
☑ Material 2
☑ Material 1

2 Mat square0000.png
2 Mat square0001.png
2 Mat square0002.png
2 Mat square0003.png
2 Mat square0004.png

```
>>RX<< ok
<<TX>> M400
>>RX<< ok
<<TX>> M114
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< echo:busy: processing
>>RX<< ok
>>RX<< X:40.00 Y:64.00 Z:275.00 E:0.00 Count X: 773
>>RX<< ok
```

Status: Projecting (layer 0/4)...

Fig. A.3. Custom software depicted during operation

A.4 Material Vats

The vats are rectangular with borosilicate glass laid down onto a plastic frame. A layer of polydimethylsiloxane (PDMS) is used as a non-stick coating to protect the glass and printed parts. The mask images will be projected through the glass to the print bed. The prototype tower supports four vats, each of which have an internal volume of 234 in^3. The overflow of the resin has to be considered once the bed is submerged, therefore the maximum resin will be the volume of the vat minus the bed volume which is calculated to be 44 in^3. Depending on the material quantity needed, the vats can have the same resin in two or 3 vats to increase print size. A silicone brush is attached to the inside of the material vat for cleaning purposes.

A.5 Electronics and Software

The electronics and control system design is based off of a DIY RepRap project, and it is an easy to replicate system that could be adapted for different printers [36]. The electronics system is composed of the following: A computer, an Arduino Mega 2560 R3 microcontroller, a RAMPS 1.4 board, a 12 V power supply, three limit switches, four stepper motors, two fans, a diaphragm pump and an emergency stop. Stepper motors equipped with a 99:1 planetary gear box are used to run the rack-and-pinion (X-axis) and the material tower (Z_m-axis), while two low-current stepper motors are used to control and run the vertical motion of the build platform (Z_b-axis).

The firmware that controls the printer operations on a system level is a fork of the popular open-sourced 3D printer firmware Marlin. This code base was selected primarily due to its compatibility with the RAMPS hardware interface. Adjustments to the firmware were made in order to accommodate the multi-material functionality of the printer. The peripheral devices of the printer, such as the pump and fans for the cleaning system, were wired to some auxiliary ports, so that no additional electronic or control component is needed. Marlin uses the popular CNC communication protocol known as G-code. A custom Windows Forms application was written in C# in order to control the movement of the printer and synchronize the projection of the layer images. The user interface is presented in Fig. A.3 with the key elements being denoted. G-code commands are sent via USB serial communication in real time while the Windows application processes the next move sequence. Models are first ported to a program called Creation Workshop which slices the models into png images. These images are then loaded into the software where the logic of controlling the printer happens. If a folder of images contains any blank or black images then the material is not present on the current layer, and the software skips it. If the last material printed on the current layer is also present on the next layer then it will be processed again before switching materials.