



Project Number: 11552

DEVELOPMENT AND FABRICATION OF A LIGHT CURING BASED RAPID PROTOTYPING SYSTEM

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ABSTRACT

In this paper, the process and results of the development and fabrication of a light curing based rapid prototyping system is explained. The goal of the work is to produce a complete system that autonomously produces a three dimensional prototype upon inputting a computer model. Therefore, numerous subsystems of the device will carry out specific tasks to complete the physical prototype. Currently, commercially available devices exist that perform this task of rapid prototyping. This discussed work will leverage techniques found in existing technology to aid in the development of the complete system. A key feature of this work is the intended expansion of the device. This work will provide the foundation for future iterations of a light curing rapid prototyping system. Therefore, it is essential that the design decisions made in this stage will be conducive to modularity and expansion. Key areas of expansion include: multiple build materials and various light sources/wavelengths. The critical design features that allow for this expansion will be explained in detail. Although the device was not completed in its entirety, significant progress was made and will be a solid foundation for future iterations to expand upon. The majority of the components for the resin-spreading sub-system were fabricated and the motor control software was developed and tested. Future work will focus on developing the model slicing software required for the displaying images from the projector as well as implementing multiple resin cartridges.

NOMENCLATURE

DLP-----Digital Light Projector
RP-----Rapid Prototyping
RIT-----Rochester Institute of Technology
MSD-----Multidisciplinary Senior Design
CN-----Customer Needs
ES-----Engineering Specifications
For the purpose of this paper, the x-direction will refer to movement in the horizontal direction, left to right in respect to the front of the DLP system. The z-direction will refer to movement in the vertical direction.

BACKGROUND

This work is the result of the Multidisciplinary Senior Design (MSD) capstone package as a prerequisite of an engineering major completion at the Rochester Institute of Technology (RIT). The capstone course is divided into MSD I and MSD II. During MSD I, the system concepts were selected and evaluated in a methodical manner. Documentation of the critical design decisions was generated and system component three dimensional models were created. Upon approval from the faculty guide at the end of MSD I, the project team was allowed to advance to MSD II where fabrication begins.

During the first phase of MSD, the goal was to design a modular, light curing, rapid prototyping device for

less \$2000. This work is being funded by Dr. Denis Cormier. Dr. Cormier is the primary customer of this work as well as the faculty guide.

During the concept generation phase, the customer worked closely alongside the team to create needs and specifications for the final product. Investigation of current technologies generated possible concepts for system requirements, but also exposed inadequacies in existing technologies. These gaps are areas where the team deemed that improvements were possible to implement. The team highlighted the lack of adaptability to multiple build materials as well as complex component control and operation. To alleviate these issues, the design was generated to allow for the expansion to multiple build materials as well as simplified subsystem operation and control. The gaps in current technologies were determined by an extensive literature search within presently known corporations that develop and produce light curing rapid prototyping devices. The V-Flash RP device was used as a starting point for the investigation to the operation of specific subsystems of the device. The V-Flash Modeler was chosen because of its unique resin application technique. The V-Flash device lays down a thin layer of curable resin, and then lowers a build platform into the resin layer. Figure 1 illustrates the basic concepts of the V-Flash Resin Application subsystem.

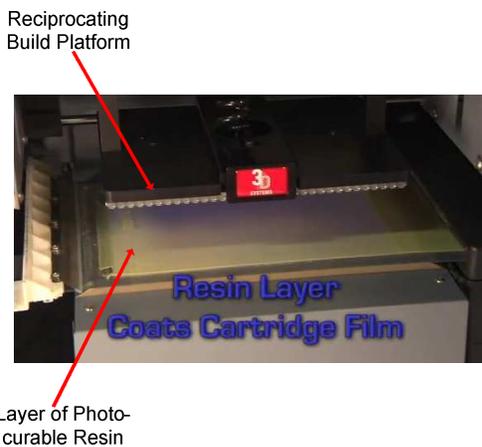


Figure 1: V-Flash Resin Application Technique [1]

The application method used by the V-Flash is conducive to multiple materials since different materials can be laid down onto the cartridge film like that shown in Figure 1. Other devices such as the Z-Corp ZBuilder® use a "bath" type method of resin dispensing. In this method, resin rests in a vat and a build platform is incrementally lowered to iterate each layer of the prototype.

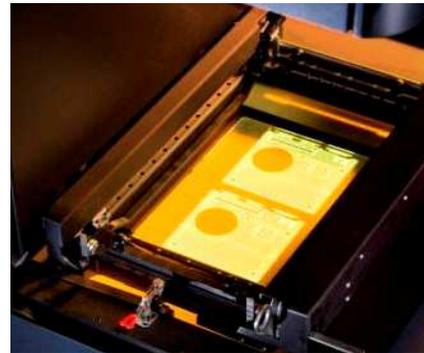


Figure 2: ZCorp ZBuilder Resin Bath Method [2]

Figure 2 illustrates the bath method in use in the ZBuilder device. The bath method would not allow for multiple material prototypes because the bath would mix the materials and invalidate the usage of a second material.

Further investigation into the operation of V-Flash led to the patent drawings and descriptions generated by its founders. The patent drawings for the V-Flash resin cartridge begin to demonstrate the complexity of the system. Figure 3 depicts the cross section view of the resin cartridge. Although the V-Flash is built for compactness, this level of complexity is still too difficult to achieve for the time and budgetary constrictions of this project. The image illustrates how the projector is located beneath the build platform and projects an image onto a mirror which then reflects the image in an upward direction onto the resin. The arrow indicates the projector location.

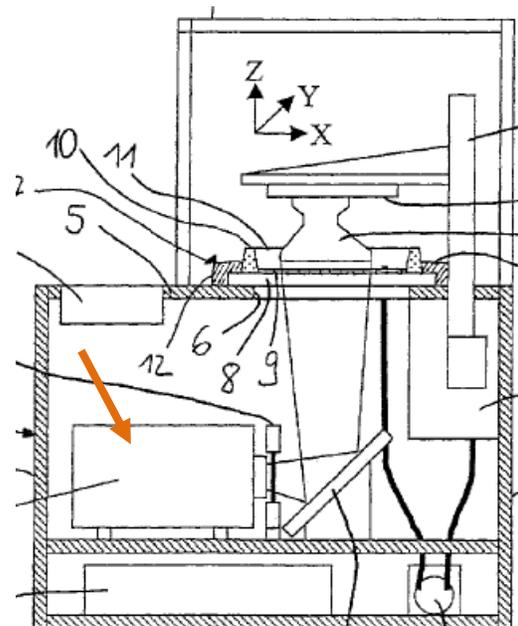


Figure 3: V-Flash Resin Cartridge Patent Drawing [3]

DESIGN PROCESS

Customer Needs/Engineering Specifications

In order to develop an acceptable product, a list of Customer Needs (CN) were generated through discussions with the customer. Engineering Specifications (ES) were then developed in order to create quantifiable, measurable goals that would ultimately satisfy all Customer Needs. Due to the 22 week deadline imposed on this project, a extensive examination of the CN's was conducted to determine which CN's would be fulfilled in during the duration of this project and what CN's would be addressed in future iterations of this project family. It was determined that the CN requesting the ability for the device to use multiple photopolymers would not be fulfilled. Rather, the device would be designed in a modular fashion that would allow future teams to develop this capability. The design would also allow for future groups to develop the ability for the use of both visual and UV light curing resins. All other CN's were initially scheduled to be accomplished within the 22 week project time span. The Customer Needs are depicted in Table 1.

| Customer Need # | Importance | Description |
|-----------------|------------|--|
| CN1 | 9 | Device utilizes a DLP Projector |
| CN2 | 9 | Utilize a 3D software model for replication by prototype |
| CN3 | 9 | Fully automated after the command to print is sent |
| CN4 | 9 | Use a photosensitive polymer resin as a medium |
| CN5 | 1 | Ability to use multiple types of curing resins |
| CN6 | 9 | Thorough documentation of design |
| CN7 | 9 | The system is safe to operate |
| CN8 | 3 | Device adheres to budgetary constraints |
| CN9 | 9 | Acceptable quality of final prototype part |
| CN10 | 3 | Device has simple user interface |
| CN11 | 3 | Reasonable fabrication time |
| CN12 | 9 | Reasonably sized finished prototype |
| CN13 | 1 | Reasonably sized DLP system |

Table 1: Preliminary List of Customer Needs

Benchmarking

In order to assist the team in the generation of concepts for the DLP prototyping system, various commercially available prototyping systems were investigated. Both the Z-Corp and V-Flash prototyping systems were used as models of functional RP systems.

Concept Generation

In order to develop various design concepts, a Functional Analysis was performed. A list of required system functions was generated and various concepts were then generated to fulfill these functions. The concepts from the Functional Analysis were then combined to create multiple possible systems. These systems were then rated in order to determine an optimal system design through the use of a Pugh Chart.

System Level Design

Through the use of the concept development tools introduced in MSD I, a high-level concept design was developed. The proposed design resembled the concept implemented by the V-Flash system. This is due to the fact that this concept will allow for future teams to expand upon. A key design requirement was to allow for the use of multiple photopolymers. A design concept that implemented a resin bath (similar to the ZBuilder system) was explored but ultimately rejected due to the fact that it was not conducive to a high caliber of resin control. The selected design implements a resin cartridge that controls the release of resin, making sure that all resin is either used to fabricate the prototyped part or removed to a catch basin. Although the fine control of the resin is not essential for the operation of machine when one type of resin is used, this will be important for future project iterations that implement multiple resin types.

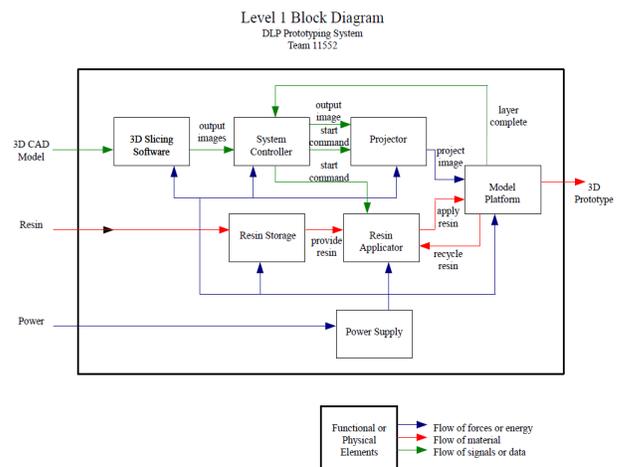


Figure 4: Level 1 Block Diagram

The system process is displayed in Figure 4. The concept requires a resin cartridge to dispense a small amount of resin onto a transparent platform that will then travel over the projector. Once the resin platform is positioned above the projector, a build platform will lower into the resin. The projector will then display an image onto the underside of the liquid resin, curing the

resin to the build platform or previous layer of cured resin. Once the resin is fully cured, the build platform will be elevated and the resin platform will return to the cartridge area. As the resin platform returns, the uncured resin will be removed to a catch basin. This uncured resin must be removed because it contains partially cured resin that may compromise the accuracy of the finished prototype. Once the uncured resin is removed, the process repeats until the prototype is completed.

Detailed Design

Due to the group’s experience in fabricating parts from sheet metal, a majority of parts were designed from sheet metal. Also, in order to reduce the total required budget for the project, parts from a spare Fab-At-Home rapid prototyping system were used whenever possible. All stepper motors used in the DLP system were taken from the Fab-At-Home system.

The detailed design of the DLP system was developed using Solidworks© software. The resin cartridge was designed to be fabricated from sheet metal. A stepper motor is used to open the cartridge in order to dispense resin onto the resin platform. The resin cartridge is then brought to the curing area in the x-direction by the use of a stepper motor and guide rails. In order to ensure the resin height is at an appropriate height (approximately .010 inches) a doctor blade made of stainless steel is stationed between the resin cartridge and the curing area. The design of the resin cartridge is shown in Figure 5.

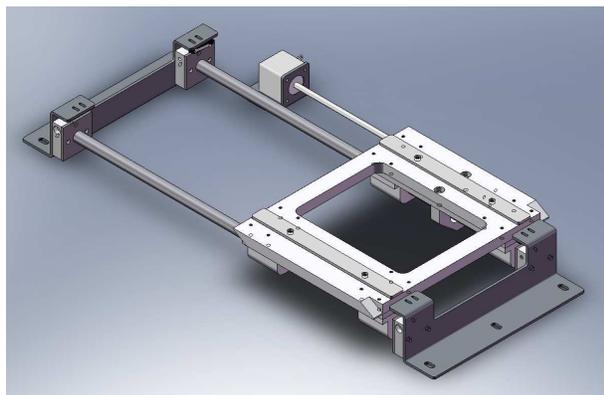


Figure 5: Resin Spreader Sub-System

Figure 5 displays the opening in the resin platform where a transparent Teflon film is used, which will be conducive to allowing the resin to cure without adhering to the film. The projector will display its image through the opening in the platform in order to cure the resin. Once the resin is cured, it will be removed from the resin platform by a neoprene blade. The blade is not controlled by the computer system, but rather is controlled by the path of the resin platform. The blade is attached to springs that

essentially follow a reciprocating motion, rising when the platform travels to the curing area and lowering when the platform returns to the resin cartridge. The resin is then removed into a catch bin located below the resin cartridge. Although the V-Flash system is capable of filtering and recycling removed resin, it was determined that this capability would not be included in the scope of this project due to time constraints.

The build platform sub-system moves in the z-direction and is controlled by a stepper motor. The build platform has a removable base that is also used in another rapid prototyping system located in the Brinkman Lab. The base is designed to allow the resin to adhere to it. The build platform was designed to be fabricated from sheet metal. The build platform component is displayed in Figure 6.

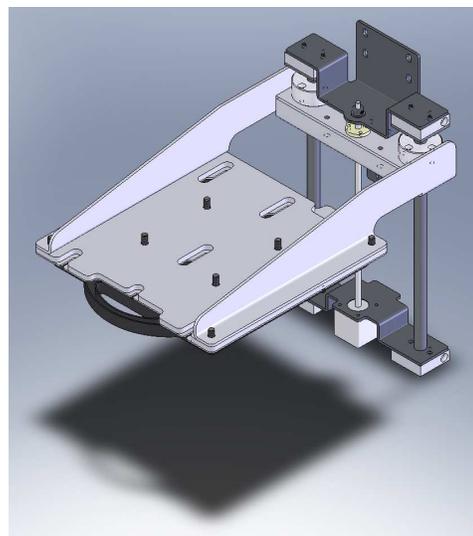


Figure 6: Build Platform Sub-System

The DLP determined to be used in this project is the Texas Instruments DLP LightCommander. It was determined that this projector would be used prior to the start of the project. In order to protect the projector from the potential of dripping resin, the opening in the baseplate could not be simply left open. Rather, a transparent material would be required. Because the DLP system has been designed to allow for both visible and UV light curing resin, simple glass could not be used. Rather, a quartz plate was used. This will allow for both types of light to be used. In order to ensure safety of operators, safety switches were installed, as well as an emergency stop. The total envelope of the DLP system was determined to be 24x24x58”. The maximum build envelope of the system was designed to be 4x4.5x5.33” .

Control System

The motor control system was developed using the open source development environment by Arduino. In order to control the stepper motors, the stepper motor library, also developed by Arduino, was imported. Each motor requires a direction command and a step command. The direction indicates the direction the motor will move and the step command indicates the number of steps to take in the specified direction. The total number of steps per revolution must be indicated to initialize each motor. In this case, all three stepper motors were set at 6400 steps per revolution. Although it would be possible to set the minimum step to one 6400th of a revolution, the smallest step was set to one eighth of a revolution. This theoretically allowed for a precision within 0.000625 inches of the desired position for any one of the motors. Once these commands were hard-coded onto the Arduino micro-controller, the user indicates the step and direction by sending a command through the serial port cable to the Arduino. The Arduino interprets the command and sends the correct signals to the motors to complete the desired action. Each command and corresponding action was programmed into the micro-controller. For example, sending a command of '1' would turn the x-axis motor in the positive direction by one eighth of a step. This serial port acts as a two way communication between the user and the motors.

Although the serial monitor is an effective way to communicate across the serial port, it is not very efficient in the face that each step requires a command. Moving a great deal of steps would occupy time or additional and unnecessary commands. Instead, a graphical user interface was written using Visual Studio 2010 to give the user a simple and understandable method of controlling the motors without a command line. Graphical components, such as buttons and text boxes, were strategically put in places to ensure the user is able to understand without prior instructions. By pushing certain buttons or entering values, the corresponding commands were sent to the micro-controller through the serial port. For example, by entering a new position in the text box for the x-axis, the total number of steps required for the motor to reach the desired position from the current position and the direction of movement was calculated internally. Then the software would automatically send the correct commands to the micro-controller through the serial port communication. This reduces the amount of effort required by the user and the complexity of the software from the user's point of view. The graphical user interface is displayed below in Figure 7.

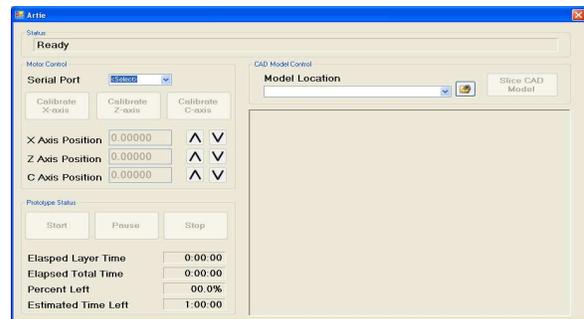


Figure 7: Graphical User Interface

In addition to motion control, limit switches were also attached to the micro-controller for an added layer of safety and security. These limit switches were strategically placed throughout the system. Each motor required limit switches at each end of the tracks to ensure the motor did not surpass these positions. Limit switches were also placed at the doors, build platform, and resin cartridge to ensure the system did not perform any curing without these essential items. The micro-controller was programmed not to execute any command given the state of the limit switches. If for any reason, a command was not executed due to the state of a limit switch, a message is sent from the micro-controller to the user interface. The user interface interpreted the command in a way the operator would understand and displayed the error or warning.

Feasibility/Risk Mitigation

In order to ensure that the motors would be acceptable for use in the DLP system, the potential maximum required force was determined. This would occur when the motor that controls the build platform must lift the largest possible prototyped part. This was calculated to be less than 10 pounds, which was determined to be within the motor's capabilities.

The feasibility of accurately leveling the resin to .010 inches on the resin platform was investigated by contacting Scott Williams of the Print Science Lab. It was determined that a process called "gap coating" would be used, which is very similar to the initial design concept.

The possibility of damaging the DLP projector was a major risk that needed to be addressed. Due to the design of the device, the potential for uncured resin to drip onto the projector is created, as well as the potential for a partially finished prototype to fall from the build platform onto the projector. In order to eliminate these risks, a protective barrier was required. After diligent research, it was determined that a quartz plate would be sufficient to protect the projector while allowing the transmission of UV and visible light.

MANUFACTURING/FABRICATION

Manual Machining

Fabrication of the 80/20 aluminum frame was performed using the drop saw and mill located in the RIT Machine Shop. The drop saw was used to make rough cuts that were then later made more precise through the use of a mill.

Peko Precision

The majority of the DLP system components were fabricated using various machines located at Peko Precision, including a water jet and laser cutter. This was possible due to the fact that one team member is currently employed at Peko Precision in the sheet metal manufacturing department. Scrap aluminum was also made available to the group through this connection, greatly decreasing the project’s total budget used.

TESTING PROCEDURES

Motion Control Testing

Preliminary testing was performed on the motor controller circuit in order to determine whether the control system would operate properly. The motor drive voltage was examined, as well as the accuracy of the motor movement. The voltages for the motors were determined to be acceptable, with each motor measuring approximately half of the maximum allowable voltage. The accuracy of the motor movement was determined to be acceptable, measuring within the .001 inch tolerance determined by the team. The accuracy of the x-axis motor (resin platform) was measured to be .000625 inches and the accuracy of the z-axis motor (build platform) was measured to be .00015625 inches. The motor accuracy was measured by moving the motor a number of steps, measuring the traveled distance, and then dividing that measurement by the number of steps traveled. This provided the team with the minimum distance the motor is able to travel. The motor test results are displayed below in Table 2.

| Motion Control Testing | | |
|-------------------------|---------------------|-------------------|
| Stepper Motor | Acceptable Accuracy | Measured Accuracy |
| Resin Platform (x-axis) | .0010 in | .000625 in |
| Build Platform (z-axis) | .0010 in | .00015625 in |

Table 2: Motor Test Results

Cartridge Design Testing

Preliminary testing was performed on the original cartridge design. The cartridge would dispense resin at the base of the cartridge when a small tab at the base

was moved horizontally by a motor. This would open a small gap that the resin would exit through. Testing indicated that there were sealing issues that would allow the resin to leak from the cartridge. The cartridge design was then modified to allow for a spring-loaded lever to be pressed that would allow for a small gap to open. Preliminary tests of this design indicated that the sealing issue was resolved. The accuracy of the resin flow was not determined due to time constraints.

Resin Curing Testing

Testing was done with the resin that was selected for use with the DLP system. The resin used was 98 ml of 1,6 Hexanediol diacrylate with 2 grams of a photo initiator, phenylbis phosphine oxide. Initially testing was done using a 60 watt light bulb. The results from testing showed that the resin would only gel under the light source. Testing was then done to attempt to duplicate the apparatus of a study done at the University of Illinois using a data projector and a magnifying glass[4]. After spreading resin on a transparency, it was found to cure acceptably in a minute and a half. The projector was then setup in the bottom of the frame with a magnifying glass over it and resin was cured on the Teflon. The projector was about 30 inches from the Teflon surface with the magnifying glass 5 inches above the projector. The light projected a 4 inch diameter on the Teflon. The test proved that the resin would cure on the Teflon and that the resulting cured part could easily be removed from the Teflon surface, confirming the design concept.

Scraper Testing

To test the scraper blade, water was placed on the Teflon surface when under the z-axis build platform. The scraper successfully removed the water from the resin platform as the resin platform returned to its original position. Further testing is needed to determine how the system will perform with the resin.

RESULTS

Although the project was not completed, major accomplishments were made. The majority of the resin-spreader sub-system components were fabricated. All of these parts were also tested with the exception of the resin cartridge (due to time constraints). The resin platform motion and build platform motion were tested and determined to be satisfactory. The limit switches for these components were also installed and tested, ensuring that the two platforms will not run at inappropriate time. Figure 8 displays the resin-spreading sub-system without the resin cartridge in place.

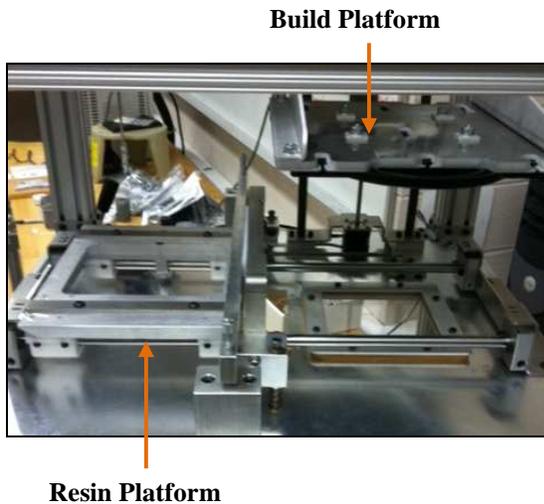


Figure 8: Resin-Spreading Sub-System

The graphical user interface was also developed for interaction between the DLP system and the operator. The GUI currently allows for manual manipulation of the motors. It also allows for the automated prototype fabricating process, which will need to be developed during the next project iteration. The frame for the DLP system was also fabricated, which will house the entire system. The frame is displayed in Figure 9.



Figure 9: DLP Prototyping System Frame

Three major complications delayed completion of the DLP prototyping system. The supplied resin would not cure when exposed to light, removing the possibility of testing the build accuracy. The projector also malfunctioned during the third week of the project

and would no longer generate a light image. The circuit board used for the motor controls also malfunctioned, although motor testing was performed before this complication.

CONCLUSIONS

While the intent was to finish the project in its entirety, the goal of the team was to leave future project iterations with a solid foundation to build from, rather than a “fully functional” system that lacked in quality and required excessive redesign. Due to the magnitude of the project, as well as the finite 22-week timeline, it became clear that the main focus of the group was to develop a fully functional resin spreading sub-system, as well as the system frame fully intact. This would allow for future teams to move forward with progress on the DLP system, rather than devoting a majority of their time to redesign of the system. It was imperative to allow the opportunity for future teams to satisfy all customer needs. This focus was consistent throughout the project, ensuring that the design did not compromise any system requirements. The total budget used during the project was approximately \$1800, about \$200 less than the total project budget of \$2000.

RECOMMENDATIONS/FUTURE WORK

Hardware

Future iterations will need to develop the capability to use multiple resins when building a single prototype. This will most likely be possible through the use of a resin pump sub-system in which the resin containers will be located in the body of the DLP system (adjacent to the projector). The resin can then be pumped from the containers to the resin platform that has already been fabricated. Future teams may also want to develop the capability to recycle uncured resin in order to reduce waste material, decreasing the cost of each prototype fabrication.

Software

Although a foundation for the control system has been developed, the code to allow the system to be fully automated must still be written. The key variable in this will be release of resin from the resin cartridge. As the resin is consumed, the velocity of the resin leaving the cartridge will decrease, which must be accounted for in the system control. If too much resin is released, the system should still operate correctly, but will produce excess resin waste. If too little resin is released, the build platform may not enter the new resin layer and the system will not operate correctly.

Because the dispensing of excess resin will theoretically allow the system to operate correctly, preliminary controls should err on the side of allowing excess resin until the control system is finalized.

ACKNOWLEDGMENTS

We would like to sincerely thank Dr. Denis Cormier for all of his guidance along the way. We would also like to thank Scott Williams of the Printing Science Lab, who assisted us in determining our resin spreading technique. We would also like to thank Peko Precision for the usage of their fabricating equipment and scrap materials

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