MASTER OF SCIENCE BY RESEARCH

Feasibility study of key components & algorithm design for multi-material RP&M machine

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Award date:
2011

Awarding institution:
Coventry University

Feasibility Study of Key Components & Algorithm Design for Multi-Material RP&M Machine

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September 2011

Coventry University

The work contained within this document has been submitted
by the student in partial fulfilment of the requirement of their course and award

ABSTRACT

Sophisticated Rapid Prototyping & Manufacturing (RP&M) systems have been developed to produce products up to conventional production standards. However, there are a number of limitations in the current RP&M systems, such as material choice, component size, software technique, and product quality. Most of the developed RP&M systems can fabricate objects with one build material and one support material. There is an increase in demand for an RP&M system which can fabricate objects with the help of multi-materials (Anderson, 2009). So far there have been some initial progresses. However, the industry still needs to go a long way until a complex multi-material RP&M system is developed.

In this dissertation, RP&M technology, its Industrial growth and current development is reviewed and then critically analysed to develop an understanding of its progress and issues related to it. Based on the analysis of current research gaps, "Feasibility Study of Key Components & Algorithm Design for Multi-Material Rapid prototyping (RP) Machine" is chosen as a proposed research topic. A complete design methodology is produced to develop a detailed feasibility design for a multi-material M^2-3D Printer nozzle deposition apparatus.

In this dissertation, a multi-material nozzle deposition RP&M system and key slicing/control algorithms have been designed to handle up to seven materials in a bid to achieve the flexibility and accuracy during deposition control. Photopolymer is the material choice which can be deposited in a continuous or drop format. Deposited material can be fabricated by two UV curing options. The right choice of UV curing source and its set parameters affect directly the quality of fabrication.

Developed NURBS-based slicing algorithm can maintain the geometrical accuracy of original CAD model and to support multi-material RP&M technology. In addition, a nozzle change algorithm is also developed to reduce the build time of fabrication and to support the design of M^2-3D Printer.

Developed multi-material slicing and its nozzle control algorithm will reduce the processing time, data storage space and overall improve the quality of fabricated objects in the proposed M^2-3D Printer system. Based on that, the design of nozzle deposition system, its slicing and control algorithms can be further developed to be used in a future M^2-3D Printer system.

ACKNOWLEDGEMENTS

Firstly, I would like to thank God for granting me His strength throughout this project. I would like to take this opportunity to thank everyone who has helped me with my chosen project. I would in particularly like to thank Dr Weidong Li my project supervisor at Coventry University for his direction, help and patience with this project. I am very appreciative to Dr. Colin Page (late) my second supervisor for his advice and guidance through out the project. In addition, a special thanks to the research student Guo-qing Jin and the Jaguar research support centre at the Coventry University for providing resources to help me at many stages during the project. A special thanks to Miss Sehar Chaudary for proof reading.

I would also like to thank my beloved mother and my wife Faezah who have always believed in me, supported me and kept me motivated throughout my studies. I am also in dept for the prayers and support I have received from my beloved family and friends.

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GLOSSARY

2D	=	Two-Dimensional
3D	=	Three-Dimensional
3DP	=	Three-Dimensional Printing
ABS	=	Acrylonitrile Butadiene Styrene
AF	=	Additive Fabrication
BASS	=	Break Away Support System
BPM	=	Ballistic Particle Manufacturing
CAD	=	Computer Aided Design
CAE	=	Computer Aided Engineering
CAM	=	Computer Aided Manufacturing
CNC	=	Computer Numerical Control
CMB	=	Controlled Metal Build-Up
DFE	=	Data Front End
DFMA	=	Design for Manufacture and Assembly
DLP	=	Digital light processing
DMD	=	Direct Metal Deposition
DOE	=	Design of Experiments
DP	=	Degree of Polymerisation
DSPC	=	Direct Shell Production Casting
EBM	=	Electron Beam Melting
EOS	=	Electro Optical Systems
FDM	=	Fused Deposition Modelling
FDMC	=	Fused Deposition of Multiple Ceramic
FFF	=	Free-Form Fabrication
IGES	=	Initial Graphics Exchange Specification
IJD	=	Ink-Jet Deposition
FGM	=	Functionally Graded Material
LAM	=	Laser Additive Manufacturing
LEM	=	Laminated Engineering Materials
LENS	=	Laser Engineered Net Shaping
LOM	=	Laminated Object Manufacturing
M^2-3DP	=	Multi-Material 3D Printer
MEM	=	Melted Extrusion Modelling
MJM	=	Multi Jet Modelling system

MJS	=	Multiphase Jet Solidification
M-RPM	=	Multi Functional Rapid Prototyping and Manufacturing
NURBS	=	Non-Uniform Rational B-Spline
PLT	=	Paper Lamination Technology
POM	=	Precision Optical Manufacturing
RFP	=	Rapid Freeze Prototyping
RM	=	Rapid Manufacturing
RP	=	Rapid Prototyping
RP&M	=	Rapid Prototyping and Manufacturing
RTM	=	Rapid ToolMaker
SAHP	=	Selective Adhesive and Hot Press
SCS	=	Solid Creation System
SGC	=	Solid Ground Curing
SLA	=	Stereo Lithography Apparatus
SLM	=	Selective Laser Melting
SLS	=	Selective Laser Sintering
SOUP	=	Solid Object Ultraviolet laser plotter
SSM	=	Slicing Solid Manufacturing
STL	=	StereoLithography File
UC	=	ultrasonic consolidation
UV	=	Ultraviolet

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Chapter 1 – Introduction

Rapid Prototyping & Manufacturing (RP&M), which is also called Free-Form Fabrication (FFF) or Additive Fabrication (AF), has evolved as a new-generation manufacturing process and been increasingly used in design and manufacturing industries, such as automotive, jewellery making and consumer products (Wendel et al, 2008). The technique eliminates most of the constraints presented in the conventional manufacturing techniques and enables the component prototyping and production in a more flexible means (Kruth et al, 2005). The introduction of RP&M has opened a new horizon for small and medium design and manufacturing companies. It allows companies to develop new products with reduced design and production cost especially for low volume customised products (Wohlers Associates, 2008).

On the other hand, RP&M is relatively new and still in the process of development with respect to manufacturing process, software controlling, material choices & test data, and most importantly quality benchmarks for material, processes and software techniques. It is therefore essential to carry out further research and development on the technology in terms of cost reduction and efficiency improvement. It is also important to understand the potential of RP&M to be used in wider applications.

1.1 Background

A brief background overview of RP&M, its development and application in the design and manufacturing industry are explained.

Rapid Prototyping & Manufacturing (RP&M) techniques:

RP&M can be defined as a layer-based fabrication process. This new type of producing prototypes or components have completely altered the time scales involved from original conceptual design to actual marketing products. RP&M is also known as a suitable means for free-form fabrication. Usually, RP&M uses Computer Aided Design (CAD) data sources to fabricate physical objects. RP&M is unique in that they add and bond materials in layers to form objects without the need for machining or tooling (W Sidney, 2008; Ryall & Wimpenny, 2010).

RP&M wheel in Figure 1.1 shows an overview of the RP&M processes, features and applications attached to it. Where input sits on the top of hierarchy, where physical models are translated into a 3D CAD environment which are later transferred into a file format which can later pre processed in RP&M environment to translate the model into slices/layers. The translated model is then fabricated layer by layer by using an appropriate RP&M method and suitable material which can satisfy the mechanical physical properties of the desired object. Different RP&M techniques have different applications with respect to the industry. For example, in automotive industry, it can be used to produce functional or presentation models, whereas, in biomedical it can be used as a visual aid or for surgical planning.

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Figure 1.1 Rapid Prototyping Wheel (Chua , Leong& Lim , 2010)

RP&M has two primary applications, that is, prototyping and low volume manufacturing.

Rapid Prototype (RP):

A text book definition of prototype is "a *first or preliminary version of a device or vehicle from which other forms is developed*" (oxforddictionaries.com, 2011). In product development process a prototype can be the concept which can lead to a final design or product (Chua, Leong& Lim, 2003). Rapid Prototyping provides a mean of making physical object from CAD data to enable designers to evaluate their initial design in a quick and cost-effective way.

Note: Please see Appendix A for more details of "Types and Roles of prototypes"

Rapid Manufacturing (RM):

Direct part production is an emerging application which has led into the evolution of RM industry. Conventional manufacturing is an economical choice for large scale production. However, for low volume and/or small batch customised product production, conventional manufacturing will be time consuming and very expensive. RM is an excellent alternative to conventional manufacturing when low volume production is concerned. Recent research in materials and RP&M systems has increased the confidence of the manufacturing industry in RM. Applications of RP&M are presented in figure 1.2.

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Figure 1.2 RP&M Applications (Wohlers Report, 2011)

Development of RP&M:

In 1987 3D Systems unveiled world's first RP&M device Stereo Lithography Apparatus (SLA) and since then many commercial RP&M systems are introduced in the industry such as:

- Selective Laser Sintering (SLS)
- Solid Ground Curing (SGC)
- Laminated Object Manufacturing (LOM)
- 3 Dimensional Printing (3DP)
- Fused Deposition Modelling (FDM)
- Solid Creation System (SCS)
- Solid Object Ultraviolet laser Plotter (SOUP)
- Selective Adhesive and Hot Press (SAHP)
- Multi Jet Modelling System (MJM)
- Direct Shell Production Casting (DSPC)
- Multiphase Jet Solidification (MJS)
- Ballistic Particle Manufacturing (BPM)

Applications:

Most manufacturing industries have embraced RP&M at some level (Wohlers Report, 2004). RP&M has mainly been used for research and development, but the improved quality of fabrication process, better material properties and reduced system costs have led to an increased demand in various industries. So far consumer products have been main beneficiaries of developments in RP&M industry. However, improved processes and material properties have increased the confidence of other industries like automotive and aerospace engineering (see figure 1.3). Cost of design and development of low volume and/or customised products has led to the introduction of RP&M, which is now emerging as an industry.

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Figure 1.3 RP&M applications with respect to the industry (Wohlers Report, 2004)

1.2 Problem Definition

There are many features of RP&M but mainly it is being used commercially for product prototyping and small volume production purposes. Sophisticated RP&M systems have been developed to produce products up to conventional production standards. However, there are a number of limitations in the current RP&M systems, such as material choice, component size, software technique, and product quality.

Most of the developed RP&M systems can fabricate objects with one build material and one support material. Where build material is the main material choice from which an object is fabricated, where as support material is used to support the main structure of the fabricated object during fabrication process. Once the object is fabricated and cured, support material is removed. With the introduction of RP&M technology, the product prototyping and small batch production cost can be reduced dramatically. However, this has led to an increase in demand for an RP&M system which can fabricate objects with the help of multi-materials (Anderson, 2009). So far there have been some initial progresses. For instance, in 2007, the first multi-material RP&M system called “CONNEX 500” was introduced by Object Geometries Ltd, which can fabricate objects by using two simple build materials (object.com, 2011). However, the industry still needs to go a long way until a complex multi-material RP&M system is developed.

CAD and RP&M have made it possible to design and manufacture complex shapes, however, it still needs further development in the field of multi-material RP&M (Sun et al, 2005). This dissertation will act as an initial feasibility report, which presents a design of a multi-material Three-Dimensional (3D) RP&M deposition system, which can be used to prototype and fabricate objects from more than two materials.

1.3 Working Scope

The scope of the project is to investigate the design and engineering prospect of multi-material 3D PR&M system, which can be developed into a commercial Multi-Material 3D Printer (“M^2-3D Printer”) based on the initial findings of the project.

Based on a review on current single material commercial RP&M systems and research work done in the field of multi-material RP&M, the key research areas in this dissertation are to design a multi-material nozzle deposition apparatus, to investigate the suitability of the deposition system to handle more than two materials, to devise slicing and controlling algorithms of the multi-material nozzle system, and to explore the application aspects related to the designed system.

1.4 Rationale

The increase in use of commercial RP&M systems has led into the cost reduction of RP&M materials and systems. Current commercial RP&M systems used for direct part production are based on one build material and mostly used for low volume or customised part production. However, the sophistication of RP&M systems has increased the confidence of manufactures by improving production quality, and reducing system and manufacturing cost, which increased the use of RP&M systems to fabricate objects for direct part production. This is resulting into a growing demand of multi-material 3D RP&M system day by day, as its introduction will revolutionise the manufacturing process. This dissertation will produce initial grounds for the further research into the multi-material 3D printer development which can fabricate 3D objects for commercial use by reducing the manufacturing cost and product development time significantly.

1.5 Aim and Objectives

The aim of the dissertation is to design a multi-material nozzle deposition apparatus, to investigate the suitability of the deposition system to handle more than two materials, to devise slicing and controlling algorithms of the multi-material nozzle system, and to explore the application aspects related to the designed system. The major focus of the dissertation is on the feasibility study of developing a unique multi-material nozzle deposition system which is flexible, accurate and can handle up to seven materials with controllable deposition. The research can be improved in future research and development to support a fully functional multi-material 3D printer ("M^2-3D Printer").

In order to achieve the aims the following objectives have been set:

- To analyse and evaluate existing commercially available RP&M systems.
- To analyse and evaluate existing research on multi-material RP&M systems.
- To analyse and evaluate the need of multi-material RP&M system with respect to related industries.
- To review and analyse existing deposition apparatus design.
- To produce a research gap analysis.
- To produce design specifications for the key components of the proposed multi-material RP&M machine.
- To design a nozzle of "M^2-3D Printer" for a controlled and accurate deposition.
- To develop detailed design of deposition apparatus for the proposed *M^2-3D Printer.*
- To conduct detailed design of feeding apparatus for the proposed *M^2-3D Printer.*
- To design and develop algorithms for better controlling of the Nozzle system.

1.6 Chapter Organisation

The framework of this thesis is shown in figure 1.4. In Chapter 1, the introduction of the project is presented. In Chapter 2, the technologies, industrial trends, and research and development of RP&M are reviewed. In Chapter 3, the literature review is critically analysed and concluded by clearly establishing the proposed research. The research methodology is developed in Chapter 4. In the following Chapter 5, a detailed research of multi-material nozzle deposition apparatus is presented. In Chapter 6, software research of the algorithm design for slicing and Nozzle control is presented. Finally in Chapter 7, a conclusion was made about the research work and suggestions are given for the future work. In the last, appendixes are presented which support some technical details of work done in Chapters 1, 2, 3 and 5.

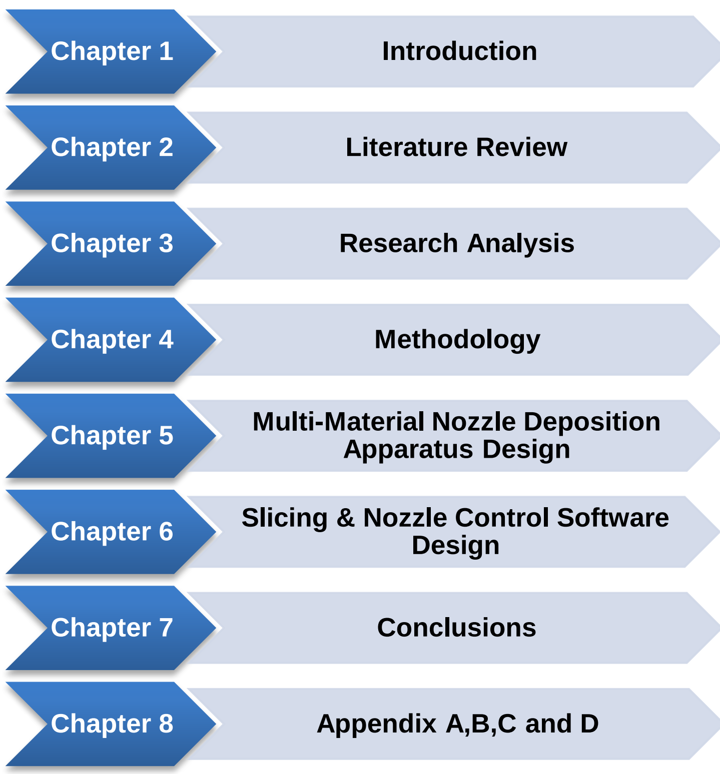

Figure 1.4 Framework of thesis organisation.

Chapter 2 - Literature Review

In this chapter, the technologies, industrial trends, and research and development of RP&M will be reviewed in three phases. In the first phase, the background of RP&M technology, RP&M industry and its growth over the years is reviewed. In the second phase, RP&M technology development and its commercially available systems are discussed. In the last phase, current research and development of multi-material RP&M systems is reviewed. The literature reviewed in this chapter develops an understanding of RP&M technology, its Industrial growth and current development in progress.

2.1 Historical Development and Industrial Growth of RP&M Technology

Historical development:

The declining cost and increase in the use of computers has spurred the advancement in many computer related areas such as CAD, Computer Aided Manufacturing (CAM) and Computer Numerical Control (CNC) machine tools. The advancements in CAD/CAM/CNC technologies and fields such as manufacturing systems and materials have been crucial in the development of RP&M systems (Chua, Leong & Lim, 2003). Back in 1987, 3D Systems unveiled the world's first RP&M device Stereo Lithography Apparatus (SLA) (Grimm, 2004). Since the commercialisation of the first RP&M machine by 3D systems in 1988, the RP&M industry has evolved and matured throughout the years. Table b2.1 (See appendix B page 88) presents the major commercial competitors in the development of RP&M systems and the level of maturity that this industry has achieved from the time of inception. These achievements have opened many doors for the RP&M industry which is introducing more serious and competitive ways of product prototyping and manufacturing to suit the demands of different manufacturers based on their size of production.

Market analysis:

The average annual growth in the RP&M industry in 2008 was estimated to 17.4%, which was mainly based on the RP&M systems with respect to unit sale (Wohlers Report, 2008). The RP&M market grew from $983.7 million (generated in 2006) to 16% worth $1.141 billion in 2007. It is reported that sales of RP&M products and services will increase to an estimate of $2.3 billion by 2012 worldwide. Table 2.1 shows the product and services directly associated with the RP&M market across the world.

Table 2.1 RP&M Market (Wohlers Report, 2009)

Products	Services		
Additive Systems	Parts Production	Training	Publications
System Upgrades	Seminars	Conferences	Contract Research
Materials	Exhibitions	Advertising	Consulting
After Market Products (Third party Software & Lasers etc)	Publications	System Maintenance Contracts	

In figure 2.1 estimated revenues for RP&M products and services worldwide are presented. It is clear that steady increase in the size of RP&M industry is due to its overall economic impact on countless design and manufacturing organisations across the world.

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Figure 2.1 Estimated revenues for RP&M Industry (Source: Wohlers Associates, 2008)

RP&M material sales:

Average annual estimated $220.9 million was spent on materials for the RP&M systems in 2007. This is estimated to be 16.6% up from material sales in 2006. The estimated amount consists of all the material types used for RP&M fabrication i.e. resins, powders, filaments, sheet materials etc. The rapid increase in the quantity of RP&M systems using photopolymers (see figure 2.2), increased the photopolymer material sales up to 14.4% in 2007 as compared to 2006, which also represents 46.4% of the total material sales in 2007 (Wohlers Reports, 2006, 2007, 2008). Following graph shows the photopolymer material estimated sales in millions from 2002 to 2007 across the world.

RP&M system sales:

Development in the field of RP&M has led to revolutionise the manufacturing industry. In 2007, estimated 3651 RP&M systems were sold, up 21.7% from 2006 (see figure 2.3). The following graph shows the growth of RP&M system unit sales from 1996 thought 2007.

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Figure 2.3 RP&M system unit sales (Source: Wohlers Associates, 2008)

In Figure 2.4 a chart shows the cumulative total of RP&M systems sold by the system manufactured through the end of 2007.

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Figure 2.4 RP&M system market share (Source: Wohlers Associates, 2008)

New generation Rapid Manufacturing (RM):

RM is referred to the manufacturing of end user parts made possible by the advances made in the field of RP&M technologies and materials for variety of production applications.

Table 2.2 Significance of Rapid Manufacturing (Wohlers Associates, 2008)

<table>
<tr><td rowspan="4">Significance of Rapid Manufacturing</td><td rowspan="2">Manufacturing Benefits</td><td>Possible to Manufacture Parts:
➢ With undercuts
➢ Highly complex internal and re-entrant features</td></tr>
<tr><td>Allows significant part consolidation and reduces cost of:
➢ Tooling
➢ Manufacturing
➢ Inventory
➢ Assembly
➢ Maintenance
➢ Inspection</td></tr>
<tr><td rowspan="2">Business Benefits</td><td>Reduction or elimination of fixed assets:
➢ Tooling
➢ Jigs
➢ Fixtures
➢ Cutting Tools</td></tr>
<tr><td>Reduction or elimination of stages in traditional supply chain:
➢ Lead times
➢ Inventory
➢ Supply chain transactions and logistics</td></tr>
</table>

	Environmental Benefits	➢ RP manufacturing produces little manufacturing waste which reduces carbon footprint of the component and/or manufacturing organisation. ➢ Majority of the waste material can be recycled and reused for manufacturing.

The elimination of need for tooling has made it possible to manufacture products of small batch sizes economically. Whereas, RM technology has moved product development away from conventional design for manufacture and assembly (DFMA) concept to a new concept of manufacture for design. This new concept backed by the RM technology has made it possible to manufacture the most complex and complicated part shapes and sizes. However, this new technology has a limit to the maximum part size and can be inferior in dimensional accuracy, material properties and surface finish when compared with the conventional manufacturing processes. To overcome these issues more work needs to be done in the field of materials and manufacturing processes.

Application of RP&M:

RP&M, according to the "Wohlers Report" published in 2002, is nearly a billion-dollar-a-year industry with more than 30 system vendors. Wohlers Associates, Inc. also reports that in 2008,

- 19.1% of rapid prototype models were used for functional models,
- 15.3% for visual aids for engineering,
- 14.9% used for rapid manufacturing,
- 13.7% for presentation models,
- 12.5% as patterns for prototype tooling, and
- 10% for fit/assembly.
- Another 14.5% of rapid prototype models were utilized for patterns for casting metal, tooling components and other industrial needs.

RP&M has already been used:

- To generate time and cost savings in fighter aircraft and the Space Shuttle.
- For the reproduction of ancient statues,

- For creation of art,
- And the modeling of anatomical structures is a few of the innovative applications.

Example 1: Rapid prototyping was used in 2001 to help surgeons separate two Egyptian twins who were born conjoined at the head (see figure 2.5). Through rapid prototyping, models were created to help surgeons visualize the Ibrahim twins' shared anatomy, and plan for their separation surgery in 2003. Happily, the twins were successfully separated late last year after more than a year of planning and a 34-hour-long operation (Grimm, 2004).

Figure 2.5 Ibrahim twins' (materialise.com, 2011)

Example 2: On the racing scene, rapid prototyping develops metal and plastic components for NASCAR and Formula 1 cars. In an environment where weight reduction is critical, race teams have found that rapid prototyping allows them to produce parts that improve performance (Grimm, 2004). Some of the other applications of RP&M can be seen in figure 2.6.

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Figure 2.6 Applications of RP&M technology

2.2 Existing RP&M Technology

RP&M technology developed over the years has resulted into numerous RP systems, which are categorised by Kochan and Chua (1995). They presented a simple way of categorising RP&M systems is with respect to the initial material used in each system (see table 2.3). With this technique RP&M systems can be categorised into three groups (Chua, Leong& Lim, 2003):

1. Liquid Based Systems
2. Solid Based Systems
3. Powder Based Systems

Note: Please see appendix B for details on "classification of RP process".

Table 2.3 Categorisation of RP&M System

Liquid Based Systems	Solid Based Systems	Powder Based Systems
Stereo lithography Apparatus (SLA)	Laminated Object Manufacturing (LOM)	Selective Laser Sintering (SLS)
Solid Ground Curing (SGC)	Fused Deposition Modelling (FDM)	EOSINT Systems
Solid Creation System (SCS)	Paper Lamination Technology (PLT)	Three Dimensional Printing (3DP)
Solid Object Ultraviolet-Laser Printer (SOUP)	Multi Jet Modelling Systems (MJM)	Laser Engineered Net Shaping (LENS)
E-Darts	ModelMaker and PatternMaster	Direct Shell Production Casting (DSPC)
Soliform System	Slicing Solid Manufacturing (SSM)	Multiphase Jet Solidification (MJS)
Meiko's RP system	Melted Extrusion Modeling (MEM)	Electron Beam Melting
Rapid Freeze Prototyping (RFP)	Multi Functional RPM Systems (M-RPM)	Lasform Technology
Two Laser Beams	Laminated Engineering Materials (LEM) Technology	Direct Metal Deposition (DMD)
Microfabrication	Offset Fabbing Technology	Prometal 3D Printing Process

2.2.1 Liquid Based RP&M Systems

The initial form of the materials used in the Liquid based RP&M systems is liquid which through a process commonly known as curing is converted into solid state. The RP systems which fall into this category are listed in table 2.3, whereas, SLA technology is explained later in detail.

Note: Please see appendix B for an overview of "SGC and SCS systems".

3D Systems' Stereo lithography Apparatus (SLA):

Patented in 1986, stereo lithography started the rapid prototyping revolution. This process is probably best known. There has been remarkable improvement made to the durability and choice of resin materials and the thinness such as rigidity, flexibility, high temperature resistance, and optical clarity (Chua, Leong& Lim, 2010).

Process: The technique builds 3D models from liquid photosensitive polymers that solidify when exposed to ultraviolet light (Jafari et al, 2000). Models require a degree of hand finishing in order to remove residual surface steps, which can be difficult within small cavities. The SLA process is based fundamentally on the following principles (McDonald, Ryall, & Wimpenny, 2001):

- Parts are built from a photo curable liquid resin that solidifies when sufficiently exposed to a laser beam which scans across the surface of the resin (see figure 2.7).
- The building is done layer by layer, each layer being scanned by the optical scanning system and controlled by an elevation mechanism, which lowers at the completion of each layer.

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Figure 2.7 Schematic of SLA Process (within4walls.co.uk, 2011)

Material: SLA systems available commercially use photopolymer resins to build 3D models. The vast majority of available SLA systems use Ultraviolet (UV) curable photopolymers. There is a large variety of photopolymer resins available for SLA systems, which may contain fillers and other chemical modifiers to meet the desired physical and mechanical properties required for the 3D model.

Software Model: A 3D model is designed in CAD package, later CAD data is converted into STL file which is supported by the SLA workstation software. The control unit slices the model and supports into a series of cross section from 0.025 to 0.5mm thick. The software used by the 3D Systems' SLA machines is known as 3D Lightyear, some of its main features include (3Dsystems.com, 2011):

- Windows user interface – Easy to learn and use
- Z-smoothing option – Slicing routines which can improve slice contours on certain part geometries.
- Parts verify – It confirm the integrity of StereoLithography (STL) files, identifies and corrects the flaws like gaps between triangles, overlapping triangles etc. It improves the part quality by eliminating anomalies in STL files.
- Fine Point supports – This feature reduces support contact with the part thus generating better down facing surfaces and increases part yield.
- Automatic support generation – This feature includes routines which can generate support structures that improve support region identification and support generation of point, line and curved surfaces to the platform when the part is free floating or its overhanging.
- Enclosed Regions – Identifies enclosed regions and avoids creating supports in those regions.
- Support Braces – Algorithm detects when a support brace intersects the part and eliminates that brace.
- Support Projections – Algorithm detects when a support projection intersects the part and regenerates the projection outside the part.

Liquid Bases RP&M System Comparison:

Table 2.4 Liquid Bases RP&M System Comparison (Chua, Leong& Lim, 2010)

Liquid Based RP&M Systems Comparison	SLA	SCS	SOUP	E-Darts	Soliform	Meiko's RP	RFP
Running Cost	3			3		3	3
Building Speed			3				3
Process Repeatability	3						
Build Volumes	3	3					

Surface Finishes	3						
Type of Material Deposition	S-M	S-M	S-M	S-M	S-M	S-M	S-M
Range of available materials	5						
Accuracy	3	5		4	4	4	4
Real time processing			4			4	
Scanning speed			4	5	4		
Compact size				5			
Portable				5			
Requires support structures	Y	Y	Y	Y	Y	Y	N
Requires post processing	Y	Y	Y	Y	Y	Y	N
Requires post curing	Y	Y	Y	Y	Y	Y	N
Requires a cold environment							Y
Range (1Low – 5 High) Range increases from 1 low to 5 High							
S-M = Single-Material	Y = Yes, N = No						

Note: Columns are left empty where no information is available from literature sources.

2.2.2 Solid Based RP&M Systems

Solid based RP&M systems are meant to encompass all forms of materials in the solid state. The solid form can include the shape in the form of wire, a roll, laminates and pallets. The RP&M systems which fall into this category are shown in table 2.3, whereas, FDM technology is explained below in detail.

Note: Please see appendix B for an overview of “LOM systems”.

Stratasys’ Fused Deposition Modelling (FDM):

FDM technology was introduced in 1992 by Stratasys, which uses an extrusion process to build 3D models. This process builds using wax, rigid plastic polymer, and elastomeric materials. The models can be used for quick visualisation of parts, as replication masters. Hand finishing is required to remove surface steps. The FDM process consists of three phases:

- 3D CAD Model is designed and transferred into a FDM workstation, where FDM software is used to for process planning and support structure generation.
- 3D model is produced using FDM build process.
- Support structures are removed and FDM models are hand finished.

Software Model: In the pre-process stage a 3D model is designed in a CAD environment and imported in STL or initial graphics exchange specification (IGES) format into FDM workstation which uses Insight of Catalyst XP software to generate supports automatically. Some of the features of Catalyst software (see figure 2.8) include:

- It generates a precise deposition path that guides the extrusion head to print model layer by layer.
- It automatically slices, orients and creates any necessary support structures.

Figure 2.8 Catalyst XP (virtualmdlab.eng.usf.edu, 2011)

Process: In FDM process, two types of material are used in filament form, support material and build material. Both materials are fed into a FDM liquefier head where heating elements melt the material, which is then extruded deposited through the nozzle in ultra thin layers, one layer at a time in a predetermined tool path generated by the FDM Insight or Catalyst XP software. Material solidifies on cooling and the process continues by moving the FDM head to create next layer (shown in figure 2.9).

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Figure 2.9 FDM Process (xpress3d.com, 2011)

The parameters which affect the performance and functions of the FDM system are (Chua, Leong& Lim, 2010):

- Material column strength
- Material viscosity
- Road widths
- Volumetric flow rate
- Envelop temperature
- Material flexural modulus
- Positioning accuracy
- Deposition speed
- Tip diameter
- Part geometry

Material: This process builds using wax, rigid plastic polymer, and elastomeric materials. Some of the materials available from fortus are shown in figure 2.10, 2.11 and 2.12.

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Figure 2.10 ABSplus material (fortus.com, 2011)

Figure 2.11 ABSi material (fortus.com, 2011)

Figure 2.12 PPSF/PPSU (polyphenylsufone) material (fortus.com, 2011)

Note: Please see appendix B for "Advantages, disadvantages and applications of FDM".

Solid Bases RP&M System Comparison:

Table 2.5 Liquid Bases RP&M System Comparison (Source: Chua, Leong& Lim, 2010)

Solid Based RP&M Systems Comparison	LOM	FDM	PLT	MJM	Solidscape	SSM	MEM	M-RPM	LEM	Offset Fabbers
Low running cost				5						
Building Time	5	2		5	2	5	2	3		
Precision	5			5	5				2	2
Build volumes		5		2	2					
Surface finishes			3							
Type of Material Deposition	S-M	S-M	S-M	S-M	S-M	S-M	S-M	S-M	S-M	S-M
Range of available materials	5			2	2					5
Accuracy		1		2			2	2		
Office friendly process			3	3	5					5
Minimal wastage		3					3	3		2
Adjustable Build layer	1				5				5	
Requires support structures	N		N			N		N	Y	
Requires post processing					Y					
Requires post curing	N					N		N		
Requires Precise Power Adjustment	Y					Y		Y	Y	
Fabrication of thin walls	1		2							
Integrity of prototypes	1		2			1		1	5	
Requires Removal of supports	Y		Y	Y		Y		Y		
Unpredictable shrinkage		1					1	1	1	

Range (1Low – 5 High)
Range increases from 1 low to 5 High

S-M = Single-Material
Y = Yes, N = No

Note: Columns are left empty where no information is available from literature sources.

2.2.3 Powder Based RP&M Systems

Powder is by and large in the solid state but it is intentionally created as a category outside the solid based RP&M systems to mean powder in grain like form. The RP&M systems which fall into this category are shown in table 2.3, whereas, SLS technology is explained below in detail.

Note: Please see appendix 2 for an overview of "3DP, DSPC and MJS systems".

3D Systems's Selective Laser Sintering (SLS):

SLS is a process that was patented in 1989. Its advantages over SLA revolve around material properties. Many varying materials are possible and these materials can approximate the properties of thermoplastics such as polycarbonate, nylon, or glass filled nylon.

Software Model: A CAD data file is transferred into sinterstation systems in STL format, where model is sliced and prepared for the SLS process to begin.

Process: Selective Laser Sintering (SLS) is a free-form fabrication technology developed by the 3D Systems. It is a layered manufacturing method that creates solid, 3D objects by fusing powdered materials with a CO_2 laser. A thin layer of powder material is laid down and the laser "draws" on the layer, sintering together the particles hit by the laser (Cindy Hartley, 2011). The layer is then lowered and a new layer of powder is placed on top. This process is repeated one layer at a time until the part is complete. Figure 2.13 below shows the system process chamber. The major distinction between this and other rapid prototyping technologies is the wide variety of materials that can be utilised. The functionality of materials allows SLS to cross over into the direct digital manufacturing class (Todd Grimm, 2004).

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Figure 2.13 SLS Process diagram (Milwaukee School of Engineering, 2010)

Material: The main types of materials used in SLS System are safe and non toxic, easy to use, and can be easily stored, recycled and disposed off. These are as follows (Chua, Leong& Lim, 2010):

- Polyamide
- Nylon
- Metal
- Ceramics
- Polycarbonate
- Thermoplastic elastomer

Note: Please see appendix B for details on "SLS materials".

Powder Bases RP&M System Comparison:

Table 2.6 Powder Bases RP&M System Comparison (Source: Chua, Leong& Lim, 2010)

Powder Based RP&M Systems Comparison	SLS	EOSINT	3DP	LENS	DSPC	Lasform	MJS
Running cost	5	3	2	3		2	
Building speed	3		5				3
Process repeatability	5	3	3	3	3	5	
Build volumes	3	5	1	1	1	5	3
Surface finishes	1		1	2	2		
Type of Material Deposition	S-M	S-M	S-M	S-M	S-M	S-M	S-M
Range of available materials	5	5	2	2	1	2	2
Accuracy	x	xxx	x	xx	Xx		
Compact size	N	N	Y	N	N	N	
Portable	N	N	Y	N	N		
Requires support structures	N	N	Yes	N	N		N
Requires post processing	Min	Min	Yes	Min	Yes	Yes	
Requires post curing	N	N	N		Yes		N
Range (1Low – 5 High) Range increases from 1 low to 5 High							
S-M = Single-Material Y = Yes, N = No							

Note: Columns are left empty where no information is available from literature sources.

2.3 Multi Material Fabrication in RP&M

RP&M systems reviewed so far are available commercially and most of them are based on the principle of fabricating a 3D object with a single build material. However, the sophistication of RP&M systems has increased the demand of new materials and RP&M systems which can fabricate parts using multi materials. Currently, most of the major RP&M system manufactures are developing new range of materials with full range of colours and Multi material RP&M systems, with an aim to meet the demand of industry to produce more functional parts (Anderson, 2009).

Research of Multi Material Fabrication Process:

Jafari and Han et al (2000) developed a fused deposition of multiple ceramic (FDMC) system for solid free form fabrication (SFF) of multiple for advanced ceramic objects.

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Figure 2.14 FDMC System over view (Jafari & Han et al, 2000)

The system is composed of a multi material deposition sub system and a positioning sub system, as shown in figure 2.14. The positioning system controls the X, Y and Z axis position, and it keeps the repeatability and the positioning accuracy within 2µm. In deposition sub system, deposition assembly is assembled for each type of material which mainly includes a motor, a temperature controller, a slide, a geared roller, a liquefier and a micro solenoid. In the proposed system, there is only one control unit controlling both sub systems (see figure 2.15).

Figure 2.15 Schematic of FDMC System (Jafari & Han et al, 2000)

Tool path generated for the CAD model is loaded onto the control unit, which translates the geometry to a machine specific structure. This structure is then used for online tool path simulation and later used for the motion control of both subsystems. The system is also equipped with a vision unit for online process monitoring, which captures the image of each built layer to analyse and identify defects in order to remove them online.

CAD is known best for traditional design and analysis applications but due to the advancements in software and hardware technologies, it is now being extensively used in the biomedical engineering (Sun & Lal, 2004). There is an increasing need in tissue engineering to adopt multi material objects and need RP&M technique to process the multi material and the relevant products. Khalil and Sun (2005) proposed a novel multi-nozzle FDM system which can be used for fabrication of heterogeneous tissue scaffolds, schematic diagram shown in figure 2.16. The system includes four types of nozzles which are used for biopolymer and living cell deposition for the construction of tissue scaffolds. Each nozzle can deposit a different material to fabricate object layer by layer.

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Figure 2.16 Schematic of multi-nozzle FDM system (Khalil & Sun et al, 2005)

Above deposition system includes:

- Data processing system – Processes the design model to produce a layered process toolpath.
- Motion control System – Controls the motion in x, y and z direction. The system uses a precise spatial position to fabricate complex tissue constructs which can be used to control the bioactive, growth factors and the number of cells.

- Material deposition system – Deposits the material in extrusion and droplet mode.
- Material Delivery system – Controls the flow rate of material extraction by adjusting the air pressure.

Weiss and Amon (2005) developed a RP system to fabricate fibrin based scaffolds. It has four ink jet heads, in which two heads deposit fibrinogen (Fg) and thrombin (Tr), another two heads deposit growth factors, as shown in figure 2.17. Bayesian surrogate modelling methodology allows obtaining more accurate models with fewer samples than required using factorial analysis. The Bayesian method compared to traditional methods for designing heterogeneous fibrin scaffolds reduced the true surface with in a mean relative predication error of minimum 6.73% and maximum24.61% compared to 8.00% and 40.61% for traditional approach.

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Figure 2.17 Multi-nozzle print head RP system for Multi-material scaffold fabrication (Weiss & Amon et al, 2005)

Liew et al (2001 & 2002) proposed a method for fabrication of dual material polymeric drug delivery devices. Delivery method is composed of two process models of SLS which can be integrated to form multi material fabrication technique. In the first process the developed ‘space creation’ technique is used by controlling the density of primary material, whereas, in the secondary process is designed and developed to deposit the powder based representative material into the space created during the first process. Figure 2.18 shows the layer produced by using space creation process (a), then a secondary process is used to deposit powder based representative material into the space created (b). After first layer is completed, the subsequent layers can be build using the two processes (c).

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Figure 2.18 Multi-material fabrication process (Liew et al, 2001 & 2002)

Ram et al (2007) examined the capability of ultrasonic consolidation (UC), which is a novel additive manufacturing process which can be used to fabricate multi material parts. It was found that a lot of engineering materials can be bonded to alloy Al 3003 matrix with UC processing. The results suggested SiC fibres and stainless steel wire mash can be successfully embedded in Al 3003 alloy, whereas, AISI 347 stainless steel and brass did not weld well.

Yan et al (2009) proposed a multi nozzle deposition manufacturing (MDM) system, which fabricate porous tissue engineering scaffolds by single nozzle deposition process, bi nozzle deposition process and tri nozzle deposition process. Arcaute et al (2009) reported a method for fabricated multi material bioactive poly scaffolds with a modified SL machine.

Wicker et al (2004) modified a 3D Systems SL 250/50 RP machine, which can be used to fabricate multi functional, multi material and multi coloured prototypes and models with some novel apparatus. The implemented design is shown in figure 2.19 which includes, rotating vat carousel, rotating platform which makes the part and platform accessible to the vats and the washing, curing and drying unit.

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Figure 2.19 Modified a 3D Systems SL 250/50 RP machine (Wicker et al, 2004).

Langrana et al (2001) developed a virtual simulation system to fabricate high quality multi material objects. It can be used for testing, evaluation and checking process parameters which enables the best selection of toolpath. The developed simulation system can be applicable to all fused deposition and many layer manufacturing techniques, which can provide accurate and detailed information for the selection of built parameters and appropriate toolpath. This approach can help achieve high quality multi material parts. Cheung (2007) developed a versatile multi material virtual prototyping system for modelling, process planning, evaluation and digital fabrication of multi material and FGM objects. It uses a virtual environment for analysis and optimisation of multi material fabrication process. Some algorithms are developed for generation of slice contours, sequential and toolpath planning. A fabrication time algorithm was also developed in this system to estimate the time of fabrication.

2.4 Functionally Graded Material Fabrication

The possibility to produce highly optimised parts for high performance applications led to the research development of functionally graded material techniques and material combinations. Most of the manufacturing processes and graded materials are geometry depended. However, the advances in the field of Layered Manufacturing (LM) opened more possibilities for research and development of techniques which provide possibilities of fabricating FGM parts successfully without any geometry limitations (Beal et al, 2004).

Research of Multi Material Fabrication Process for FGM objects:

Yang and Evans (2004) developed a unique powder deposition apparatus for fabrication FGM objects by selective laser sintering. A schematic diagram of powder delivery apparatus is shown in figure 2.20. The dry powder of CU and H13 are stored in two hoppers, in which the flow of dry powder is controlled by acoustic flexural vibration. The flow rate of powder can be controlled by:

- On/off vibration
- Amplitude
- Frequency
- Waveform
- Capillary diameter
- Capillary length

Whereas, different acoustic vibration will cause different flow rates of Cu and H13 powders in glass capillary.

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Figure 2.20 Schematic of a powder delivery apparatus for FGM fabrication (Yang & Evans, 2004)

Jackson (2000) described a 3D printing processing to fabricate a FGM object by selecting depositing different materials in powder planes (see figure 2.21). It proposed an information pathway for processing FGM parts. The design, processing and fabrication of FGM objects are clearly separated by the information pathway. Several data structures for representing FGM model are described and analysed, the cost of each data structure is calculated.

Figure 2.21 Schematic of a 3D printing process for FGM fabrication (Jackson, 2000)

Beal et al (2004) developed an X graded powder deposition system to fabricate some specimens with graded Cu within the H13 matrix. The system uses a multi container feed hopper which consists of eight compartments for the mixture of powders, shown in figure 2.22. The FGM powder is spread in layers which are fused by a high power Nd: YAG pulsed laser by following a specific scanning path.

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Figure 2.22 Schematic diagram of X graded powder deposition system (Beal et al, 2004).

Dwivedi et al. (2004 & 2006) developed a method to fabricate FGM objects with machine called MultiFAB^{TM} which integrates various deposition and machining techniques. MultiFAB^{TM} is designed for laser based deposition for fabrication of FGM parts. Figure 2.23 shows an overall picture of a complete FGM fabrication deposition system.

Figure 2.23 System for FGM fabrication using laser based direct metal deposition (Dwivedi et al., 2006).

The MultiFAB^{TM} machine in figure 2.24 is composed of several parts, where powder is stored in the powder feeder which is mounted by a computer based control which controls the delivery rate. The powder composition is deposited with the help of a metal deposition head mounted on a 6-axis robot, whereas, the substrate is mounted on the platform which can be manipulated in the space. Powder composition control, motion communication of the deposition head and substrate platform, and Laser control are all comprehensively controlled by one system.

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Figure 2.24 Schematic diagram of X graded powder deposition system (Dwivedi et al., 2004).

Mazumder et al. (2003) proposed a new method for design and fabricate FGM objects with Direct Meta Deposition (DMD). In this method powder material from different hopper is fed to powder mix which is then fed to the Nozzle assembly. Powder material is then melted on the substrate by laser beam which is then deposited to fabricate FGM objects. DMD set up is shown in figure 2.25, however, the deposition process quality and precision mainly depends on the powder mixer accuracy, feeding rate, laser and other process parameters.

Figure 2.25 Set up of DMD Machine (Mazumder et al, 2003)

Fessler developed a Shape Deposition Manufacturing laser deposition system to fabricate FGM object with mixture of Ni and Cr powders. The proposed process uses materials which can traditionally alloy to form homogeneous materials, which is used for single phase deposition. Chiu and Yu (2008) described a direct digital manufacturing methodology, which make it possible for fabrication of FGM prototype in 3D printing process. In the proposed method, an FGM object's mechanical information is established with the help of Computer Aided Engineering (CAE) analysis, this information is then converted into colour information which can be used directly in 3D printing process to fabricate an FGM object (see figure 2.26). In this approach, there is no need to design a new data format to represent FGM object.

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Figure 2.26 Mapping of CAE result to binder distribution of an FGM part (Chiu and Yu, 2008).

Chartoff et al (2003) reported a method to produce functional graded composites by combining fiber reinforcements or nanosized particulate with a photocurable thermoset matrix resin which can be incorporated in ink-jet deposition process (IJD) to produce functionally graded polymeric parts.

Zhang et al (2001) produced TiC-Ni FGM objects with LOM processing. The analysis of the microstructure and phases of TiC–Ni FGM part showed that there were continuous component distribution and overall presented anisotropic mechanical properties. However, test data analysis show that the TiC–Ni FGM part is stronger in the direction parallel to the thickness than in the direction perpendicular to the thickness.

Chapter 3 – Research Gap Analysis

In this chapter, literature review will be critically analysed to develop an understanding of issues related to the current RP&M technology, its industry trend and current research and development. The analysis are made and concluded to establish the current research gaps and topic of proposed research.

3.1 Brief Summary of RP&M Technology and its Industry Growth

In the literature review of Chapter 2, the development of commercially available RP&M systems, their limitations and advantages are analysed and compared. The RP&M systems are compared in three categories based on the initial type of material used (i.e. liquid, solid and powder based). Analysis of the comparisons shows that majority of the RP&M systems can only fabricate using a single build material, whereas the issues of accuracy, repeatability and reliability are also identified. Meanwhile, the analysis shows that the rapid increase in demand of the RP&M systems has reduced its unit price, which was a major barrier in RP&M industry's growth. The increased use of RP&M system has also reduced the running cost and increased the material choice. Therefore there has been significant development in RP&M industry but it still faces many challenges.

Challenges Related to RP&M:

There are still issues which need further development before the RP&M systems can be used as an alternative new generation manufacturing technique. Some of the challenges which need to be addressed are shown below (Wohlers Report, 2008), which are explained in detail in appendix C.

- Quality Standards
- Fabrication Process
- Build Area/ Volume
- Process time
- Quality control
- AF Materials

For instance, the challenges faced by the RP&M industrial growth are still the material and equipment cost, whereas the build volume is also a big concern as it limits the applications of RP&M systems. A collaboration of the conventional manufacturing and the RP&M techniques can help design and manufacture parts of different sizes, materials and shapes. However, this collaboration of two manufacturing techniques will affect the speed of production and there are improvement spaces in terms of fabrication cost.

Table 3.1 Obstacles Faced by RP&M

Obstacles Faced by RP&M	
➢ Physical factors of accuracy	➢ Surface finish
➢ Repeatability	➢ Choice of materials

Currently academic institutions train future engineers to follow the conventional design and manufacturing tools like design for manufacture, design for assembly and design for reliability. The introduction of RP&M technologies can enable product developers to apply the above principles effectively such as evaluating their design in an efficient way or making low volume components without constraints like tooling. On the other hand, a product with several components usually consists of two or more materials. The current RP&M systems are limited in such applications since majority of them can only support single material build processes. It is imperative to design a multi-material RP&M system so that more complex products can be supported by the systems.

3.2 Major Research Gap

The literature review of commercial RP&M industry and recent research developments have indentified its current needs and the challenges faced which need to be addressed (See Appendix C for Challenges Related to RP&M Industry). The gap analysis of the industry, available commercial RP&M systems and the current research done has identified that there is a need of an RP&M system which can fabricate multi-material components. Currently there is only one commercial RP&M system ("CONNEX 500" by Object Geometries Ltd) which has the capability to fabricate an object made from two simple materials. Whereas, the current research widely being done is focused on fabrication of objects from two materials, although there has been some development of RP&M manufacturing technology for heterogeneous objects, some of the heterogeneous RP&M systems only can fabricate two material objects with simple structure, and the product quality can hardly meet the design and functionality requirements. The research analyses of multi-material RP systems are compared in table 3.2.

Table 3.2 Multi Material RP&M Technology Comparison

Multi Material RP&M Technology Comparison	**More than Two Material Deposition**	**Two Material Deposition**	**FGM Deposition**	**Under- fill Problem**	**Over-fill Problem**	**Print Quality**	**Number of Nozzles**	**Material Choice**
Jafari and Han et al (2000) FDMC system	N	Y	N	3	3		Four	2
Yang and Evans (2004) FGM powder deposition apparatus	N	N	Y		3	2	One	
Khalil and Sun's (2005) Multi-material FDM system	N	Y	N	3	3		Four	2
Weiss and Amon (2005) fibrin based scaffolds RP system	N	Y	N				Four	2
Liew et al (2001 & 2002) dual material fabrication method	N	Y	N			2		
Ram et al (2007) UC processing method	N	Y	N			2		
Beal et al (2004) X graded powder deposition system	N	N	Y			1		
Mazumder et al. (2003) FGM fabrication method	N	N	Y			1		
Chiu and Yu (2008) direct digital manufacturing methodology	N	N	Y			1		2
Morvan et al (2001) heterogeneous flywheel fabrication by LENS	N	N	Y			1		
Kieback et al (2003) FGM fabrication on powder based 3DP system	N	N	Y			1		
Kieback et al (2003) FGM fabrication on SLS system	N	N	Y			1		
Kieback et al (2003) FGM fabrication on FDM system	N	N	Y			1		
Kieback et al (2003) FGM fabrication on SLA system	N	N	Y			1		
Range (1Low – 5 High) Range increases from 1 low to 5 High S-M = Single-Material Y = Yes, N = No								

Note: Columns are left empty where no information is available from literature sources.

So the research gap is identified in the following areas:

- Design of a novel multi material nozzle deposition system which can fabricate objects with more than two materials.
- Design an algorithm for the better control of the Nozzle system which can help improve the fabrication quality and process time.

- Design of Multi material RP&M system with a large build volume so it can accommodate large batch volume fabrication.
- A better statistical quality and control data needs to be developed with respect to the current RP&M systems which can be used as a benchmark for the manufacturing industry.
- A wide range of materials need to be developed which can be used as an alternative to the materials used in conventional manufacturing.
- A better statistical data with respect to testing and quality needs to be developed for the available variety of RP&M materials which can be used as a benchmark for the manufacturing industry.

The mentioned research gaps need further development and research, as all the topics need in-depth research hence it is not feasible in the current scenario to choose all as a research topic. The following two research gaps are chosen as a proposed research topic for the project.

- ***Multi material nozzle deposition apparatus design:*** Research gap analysis of the commercial market and the current research being done has clearly suggested that there is a need of Multi material RP&M system. Although commercial market of RP&M has no feasible solution available for multi material fabrication, whereas, current research done in this field has been focused on developing a multi material deposition apparatus which can be used to deposit up to two materials or to deposit FGM materials. There has been some progress in the field of multi material fabrication of an object from two build materials, however, there is no deposition apparatus designed to deposit more than two build materials.

  Hence, the chosen topic of research is to design a deposition apparatus which can deposit more than two build materials. To achieve this goal some specifications need to be established, mainly the choice of material and the process of fabrication for the chosen materials. The choice of material plays a critical role in the design of fabrication apparatus and process of fabrication itself. So before the apparatus design can begin fabrication material type needs to be identified.

Photopolymers: RP&M material sale analysis presented in chapter 2 clearly identified photopolymers to be the most popular material used for additive fabrication in the RP&M industry. According to the Wohlers report published in 2008, photopolymer sale in 2007 represented 46.4% of the total RP&M material sale recorded. Increase in demand of photopolymer materials makes it more economically feasible as compared to the cost of other RP&M materials. This also predicts the trend of the industry and its growing confidence, as more photopolymer materials are introduced by the material providers which can exhibit material properties of conventional material choices. For this reason photopolymer materials will be the choice of material for the proposed deposition system in this project.

- ***Algorithm design for better slicing and control of the Nozzle system:*** A detailed literature review of the available RP&M system, its processes and software has identified many problems such as accuracy, quality and process repeatability. The review has identified STL to be a de facto standard of many RP&M systems. However, STL format comes with many issues but in the current scenario of multi material object representation, STL file format is designed to represent one material type CAD models, comes with inherent issues of inaccuracy with respect to dimensional representation and requires large storage space for complex CAD model representation. Therefore a NURBS (Non-Uniform Rational B-Spline) based slicing algorithm will be developed for multi material representation of CAD model to improve the quality of the RP&M components in terms of better geometrical representation of multi material objects. The proposed NURBS slicing algorithm will be able to represent a multi material CAD model, provide accurate geometrical representation and low storage space requirement for the complex CAD model representation. To improve the quality and control of better multi material fabrication a nozzle change algorithm will be developed to help reduce the process time.

Chapter 4 – Methodology

In this chapter, the process to develop a detailed concept design for a multi-material M^2-3D Printer nozzle deposition apparatus will be presented. To achieve the objectives, a detailed secondary research is done to gather information and to identify the research gap. A detailed product planning is done to further sub divide the objectives and to clarify the task. After the task clarification, product design process is established to develop a detailed design of multi-material M^2-3D Printer nozzle deposition apparatus for proposed M^2-3D Printer machine.

4.1 Information Gathering

The first stage of the project is to analyse different RP&M systems, evaluate the deposition system, fabrication process and the growing needs of RP&M industry. As the project is of prime importance so it is vital to carry out an in-depth Primary and Secondary research. The information is gathered using qualitative and quantitative research methods.

The project has used the secondary data collection technique to provide the basic for the primary research. For this reason the information will be gathered from relevant journal, research articles, technical magazines and website. Relevant articles, research papers and company websites will be used for more authentic and accurate data. To gain up-to-date knowledge and professional view, informal meetings will be carried out with relevant people and companies at the exhibitions. The primary and secondary research methods will help to gather information on the following:

- Background of RP&M.
- Commercially available RP&M systems, fabrication process and applications.
- Current research on multi material RP&M deposition systems.
- Current RP&M market trend and growing needs.
- Analysis of the literature review and current research to identify the research gap.
- Design and develop a Multi material RP&M deposition system and algorithms for accurate deposition.

Secondary research will be a major source to develop an understanding and to build a firm base for the proposed research topic of multi material deposition apparatus and algorithm design. However, a systematic approach is taken for the design project which is based on engineering design methodology introduced by Pahl and Beitz (1996). The approach consists of four phases as shown in figure 4.1:

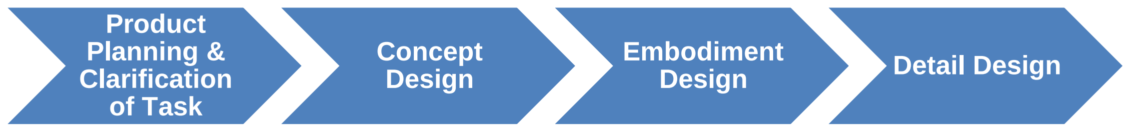


Figure 4.1 Phases of planning and design process (Pahl & Beitz, 1996)

These four phases are expanded into a complete design process which is derived from the design activity concept proposed by Stuart Pugh (1990) which is shown in figure 4.2.

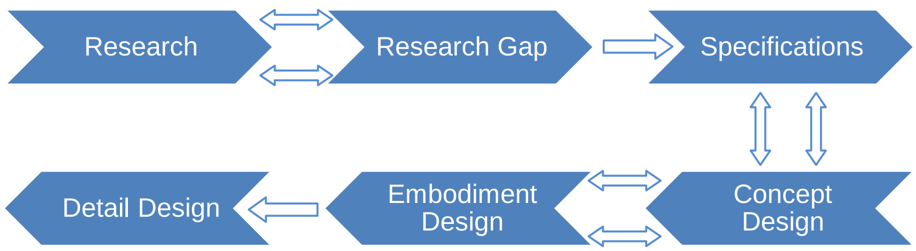


Figure 4.2 Design process activity chart

4.2 Project Management

Project Management will be used as a tool to manage and complete the project within defined scope, quality and time constraints. The key stages of the project which will require a systematic management will be:

- Back ground research
- Literature review
- Research analysis
- Research Gap Selection
- Product design and development planning
- Detailed product design
- Research conclusion and Future research

Gantt chart will be used for dividing the project into small achievable objectives to ensure the timely completion of the project.

4.3 Product Design Process

Product planning and clarifying the task:

This is the first phase of product design and development process. The established procedure of product planning and task clarification consists of three phases of design activity which are shown in figure 4.3.

Figure 4.3 Design process activities - Product Planning & Clarification of Task

A quantitative research is done in the first phase of design process activity to develop a situation analysis, where a detailed literature review is produced on the background of RP, its development and research, commercially available RP systems, fabrication processes, limitations, market trends and challenges.

In this phase the research is evaluated and transition is made from quantitative research to qualitative research. Based on the findings of literature review, a detailed research analysis is done where RP&M industry, its needs, challenges and future trends are established. Whereas, current research and development in the field of multi material deposition is critically analysed.

Based on the research analysis, a research conclusion is produced where all the research gaps are identified. From the identified research gaps following two research gaps are chosen as a research topic for the current research.

- Multi material nozzle deposition apparatus design
- Multi material fabrication quality and control design

These topics are selected for the current research on the bases of produced literature review and research analysis where the market trend, challenges and developed research help identify the problem definition and its scope.

Key Goals are set in the form of research objectives, which will help produce list of specifications need to be addressed to achieve the desired objectives. These specifications will help evaluate and improve the concept design for the multi material disposition apparatus design.

Concept design:

The conceptual phase of design activity begins as the task is now clearly identified and a requirement list of the proposed design is established. The conceptual design process goes through the following steps:

- Clarification of task and elaboration of requirement list: In this step key requirements of the multi material nozzle deposition system are established.
- Identification of essential problems: Based on these requirements tasks are elaborated which help identify the essential problems which need to be address. Such as, the nozzle deposition system needs to deposit photopolymer materials, so the nozzle should be designed for chosen material deposition.
- Establishing function and sub-function structures: Based on the requirements and specifications, product functions and sub functions are established.
- Working principles and Solutions: Working principles are established after identifying functions and sub functions of the proposed multi material 3D printer (M^2-3D Printer). With the identification of working principles, the concept design process beings to identify different concepts and ideas for preliminary layouts and principle workings of functions and sub-functions.
- Evaluation criteria: Proposed solutions are constantly analysed with the demands of the requirement list which results into an improved design.

Embodiment design:

Embodiment design phase begins after the completion of concept design. In this phase the over all layout design, preliminary form design and the production processes, and all auxiliary functions are determined. This phase progresses from the qualitative to the quantitative detailed design, which is analysed and improved by the emplaced set guidelines and checks during the embodiment design process.

Detail design:

Detail design phases compromises list of steps which can be further divided into three phases. In the first phase, the definitive layout is finalised, detail drawings of components are produced, and a detail optimisation of shapes, materials, surfaces, tolerances and fits are done. In the second phase, the integration of individual components into assemblies, sub assemblies and a through these a complete product is produced. In the last phase, documents with parts lists, assemblies, procedures and operational instructions crucial to the product design are produced which can be critical for product manufacturing and understanding for the further development in future.

Chapter 5 – Research & Design Justifications

In this chapter, selected RP&M material, its curing process and the design of a multi-material 3D deposition system for the proposed M^2-3D Printer system will be presented in three phases. In the first phase, the selected RP&M material and its curing techniques are discussed. In the second phase, the design and fabrication process of multi-material 3D nozzle deposition system for the proposed M^2-3D Printer system is presented. In the last phase, the concept design of a multi-material 3D nozzle deposition system and its fabrication technique is supported with the case studies. The feasibility design of multi-material nozzle deposition system presented in this research work develops feasibility study for the proposed M^2-3D Printer.

5.1 Overview of M^2-3D Printer

Proposed M^2-3D Printer is a multi-material RP&M system which can fabricate a 3D model by using more than two build materials. M^2-3D Printer shown in figure 5.1 comes with an innovative multiple nozzle deposition apparatus which can fabricate a 3D model by using multiple build materials. Initially a 3D model is designed in a CAD environment which is transferred into M^2-3D Printer workstation in an IGS format.

M^2-3D Printer workstation comes with a unique direct slicing algorithm technique, where a model is sliced into layers to get a closed two-dimensional (2D) cross-section of the model layer. Direct slicing algorithm then generates a closed NURBS curve to represent the contour of the cut layer based on Open CASCADE foundation. It represents the model layer more accurately and requires less storage space as compare to standard STL model. After Toolpath is generated, a multi-material 3D model is fabricated layer by layer in the proposed M^2-3D Printer.

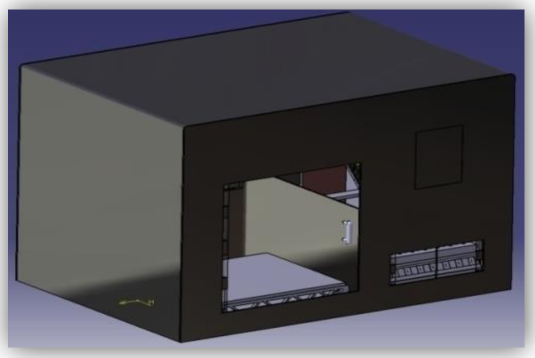


Figure: 5.1 M^2-3D Printer design

5.2 M^2-3D Printer Materials

Polymers:

Polymers are large molecules made up of many small, simple chemical joints, joined together by chemical reactions. The size of polymers is indicated by its molecular weight, where as another parameter which is used to distinguish the size of a molecule is called the degree of polymerisation (DP). The term DP refers to the number of repeat units in the chain. The range of DP in commercial plastics normally falls in the range of 75 to 750 mers per molecule (Doi, 1996).

Properties of polymers:

Polymers even with high molecular weight are below the resolving power of an optical microscope therefore the molecular weight determination is usually made indirectly by calculating physical properties like viscosity, osmotic pressure, or light scattering as all these properties are affected by the number, size or shape of a molecule (Lindberg, 1990).

Factor affecting polymer properties:

Material properties can be tuned with regards to processability, mechanical and physical properties by considering components such as basic cross linking, reactive diluents, fillers and initiators (Liska et al, 2007). However, factors which play a major role in determining the properties of polymers are shown in table 5.1

Table 5.1 Factor affecting polymer properties (Lindberg, 1990)

<table>
<tr><th colspan="2">Factor effecting polymer properties</th></tr>
<tr><td>Molecular weight</td><td>Heavier molecules are created by adding more carbon atoms and hydrogen atoms to each new carbon atom in a chain.</td></tr>
<tr><td>Branching</td><td>The density of a polymer is directly related to the number and length of the side branches. The greater the branching is, the less the density.</td></tr>
<tr><td>Copolymerisation</td><td>A polymer made from two different monomers is called copolymer, where as their properties main depend on the percentage of monomer A to monomer B and how they are arranged along the chain</td></tr>
<tr><td>Compounding polymers</td><td>Compounders can modify thermoplastics by adding:
<table>
<tr><td>Fibers</td><td>Increased strength and stiffness</td></tr>
<tr><td>Plasticisers</td><td>Flexibility</td></tr>
<tr><td>Lubricants</td><td>Easier moulding</td></tr>
<tr><td>Antioxidants</td><td>Higher temperature stability</td></tr>
<tr><td>Metals</td><td>Conductivity</td></tr>
<tr><td>UV stabilisers</td><td>Resistance to sunlight</td></tr>
<tr><td>Dyes</td><td>Colour</td></tr>
</table></td></tr>
<tr><td>Blending of plastics</td><td>Different polymers are blended together to create plastic blends with desired properties with respect to its application.
<table>
<tr><td rowspan="5">Factor affecting polymer blends</td><td>Choice of polymers</td></tr>
<tr><td>Composition</td></tr>
<tr><td>Compatibility of the polymers</td></tr>
<tr><td>Phase morphology</td></tr>
<tr><td>Method of blend preparation</td></tr>
<tr><td colspan="2">Source: (Dyson, 1990)</td></tr>
</table></td></tr>
</table>

5.3 Polymers to be used in proposed M^2-3D Printer machine

Polymers as explained earlier are large molecules with high molecular weight. The polymers required for the proposed machine are called “photopolymers”, which cure or become solid when they are exposed to light.

Photopolymer:

Photopolymer resins used will be of low molecular weight materials which will undergo cross linking to form a 3D network. These materials are in liquid form and during a high degree of cross linking brought by ultra violet light, causes the liquid system to harden to a rigid infusible solid (Dyson, 1990).

Photo polymerisation:

"Photo polymerisation" is a process of curing or controlled solidification of photopolymer resins from liquid to solid state. Liquid resin is deposited and cured layer by layer to form a 3D object. However, there are a lot of different factors which can affect or improve the result of photo polymerised layer. Generally, factors include the properties of resins used, especially the curing properties of material, selected process for curing etc. But the major factor which needs to be controlled is the light source (UV light). The curing penetration depth (D_P) plays a vital role in the quality of the cured layer. However, this topic will be discussed in detail later in "curing process selection".

UV Curing process and its effects on photopolymers:

Quality of cured layer depends on many features but with respect to the UV light, penetration depth for the selected material will be on the top of quality parameter list. Cure depth can be determined by the energy of the light to which the material is exposed. However, this energy can be controlled by:

- Adjusting the power of light source.
- Adjusting the exposure time.

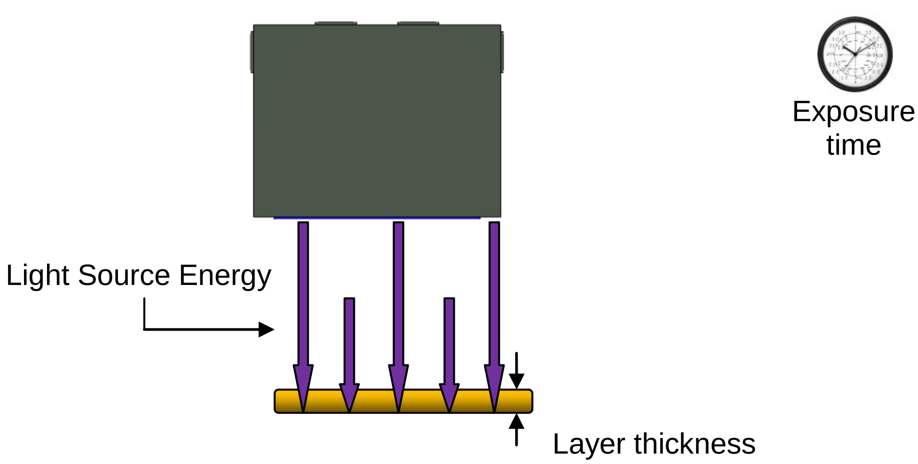


Figure 5.2 UV Curing Process

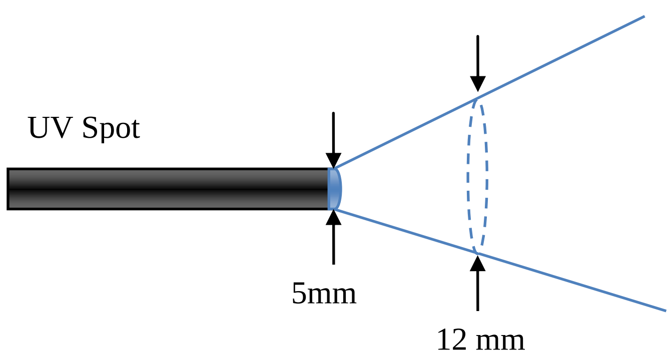
The parameters like light source power and exposure time also depend on the properties of the selected material, as shown in figure 5.2. Different composition of photopolymer will require different curing strength and time. Thus to have control and improve the quality of the cured layer, it is important to adjust the light parameters for each layer when different materials are used.

If the UV – curing process parameters are not closely monitored or adjusted for different materials, overexposure will result in over curing into the preceding layer which may have been intended to remain uncured. This problem can be controlled by decreasing the penetration depth and increasing the photo-initiator concentration. This reduced penetration depth will allow most accurate control of the polymerisation process and minimal over cure, however, this will lead to increased building times (F. Melchels et al, 2010).

5.4 M^2-3D Printer - UV light selection criteria

UV light selection depends mainly on the material properties. During the exposure process UV light needs to be controlled or its parameters need to be readjusted as explained earlier, depending on the penetration depth of the material and layer thickness. So it is important to identify the penetration depth and layer thickness before the UV exposure strength is calculated. Greater control on the UV laser light will make the machine more flexible.

Quality of UV light depends on its relative intensity which further depends on the distance between the UV source and the objects under observation. UV light intensity decreases as the distance increases between the UV source and the object under observation. This happens due to the increase in the area covered by the UV light which is shown in figure 5.3.



Distance	Intensity %
0 mm	100%
5 mm	69%
10 mm	43%
13 mm	18%
25 mm	6%

Table 5.2 UV light intensity

Figure 5.3: Quality of UV light

M^2-3D Printer - Curing process selection for photo polymers:

Development in solid free form fabrication techniques have increased the use of RP&M technology and has resulted in development of more sophisticated techniques to produce objects within hours with high resolutions. Each technology may require different setup for each part produced with respect to its size and shape. However, each technique has a lower limit in size of the smallest detail it can produce. The relation in the resolution and the size of item is critical. The higher the resolution with which a part is build, the smaller will be its maximum size (F. Melchels et al, 2010).

Most of the commercial fabrication techniques can build parts with smallest details between 50µm to 200µm whereas, commercially available SLA setup can even build objects with a lower resolution accuracy of 20µm (Maruo, 2002). As mentioned above the setup of the fabrication techniques and the size of the object can limit the lowest resolution which can be achieved.

There are number of different curing processes available for curing photopolymers. Digital light processing (DLP) is one of them, where the material is cured layer by layer with z-axis moving upwards to cure the next layer. Resolution of 50µm in x-y axis and 30µm in z direction can be achieved using DLP technology. However, UV curing process involves photo curing of polymers layer by layer by moving laser beam on the liquid surface and can achieve higher resolutions of 5µm in x-y axis and 10µm in z direction (Liska et al, 2007).

5.5 M^2-3D Printer – Design

M^2-3D Printer layout shown in figure 5.4, consists of four major system assemblies, nozzle deposition apparatus, feeding apparatus, z-axis and pipe hanger. These component assemblies consist of many sub assemblies which are shown in appendix D. M^2-3D Printer comes with a unique Nozzle deposition system which consists of seven nozzles designed to support more than two build materials. The nozzle deposition system is connected with the material feeding apparatus by the material and pipe hanger. The nozzle system has the ability to move in x-y direction, whereas the z-axis is lowered by the elevation mechanism after a deposited layer is cured.

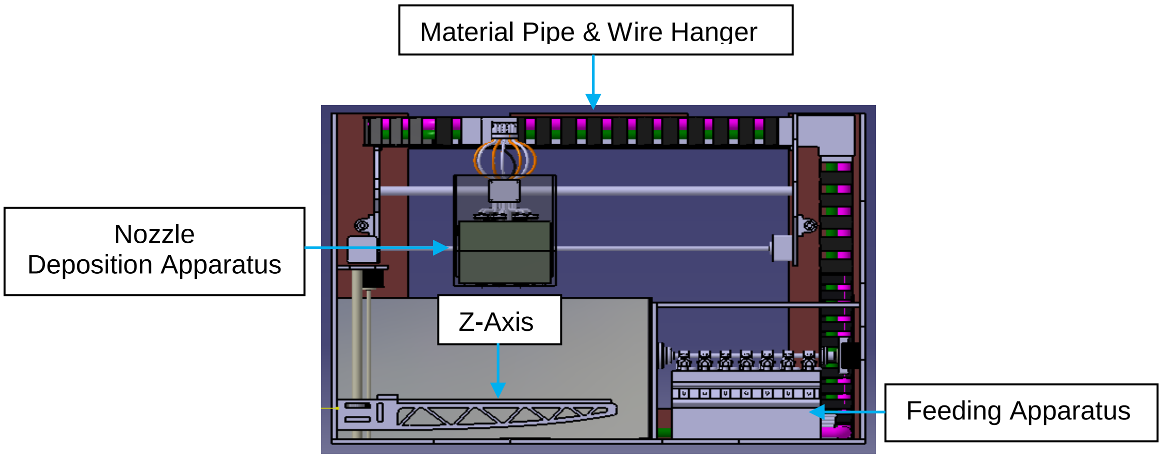


Figure 5.4: M^2-3D Printer Layout

5.5.1 Nozzle Deposition System

Nozzle deposition apparatus is an innovative system which consists of seven nozzles designed to support more than two build and support materials. Nozzle apparatus also includes a UV light which is used as a curing device. Complete apparatus is shown in figure 5.5. Some of the main components of the apparatus are:

- Multi-material deposition head is equipped with seven nozzles.
- Nozzle rotation/selection is smooth which is controlled with one servo motor.
- To reduce the curing time an off the shelf UV light is integrated into the deposition apparatus.
- An off the shelf UV spot light is integrated to improve the control, accuracy and precision with regards to curing process.

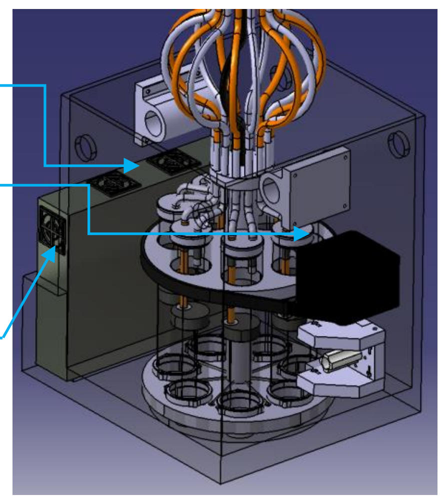


Figure 5.5 Multi-material deposition apparatus

A complete Nozzle is shown in figure 5.6 which consists of three sub assemblies, which are as following:

- Top cover is a snap fit assembly with material and air pressure tube access. Consists of three rubber seals which seal the pressure chamber.
- Multipurpose Pressure plate assembly design is used for feeding the material into the tube chamber and to exert pressure onto the material during the deposition process. Pressure plate assembly consists of a material access door which opens during material feeding process. Door closes when pressure is exerted on the pressure plate.
- Deposition control assembly consists of an electro magnet system which when activated can deposited material continuously or in drop formation.

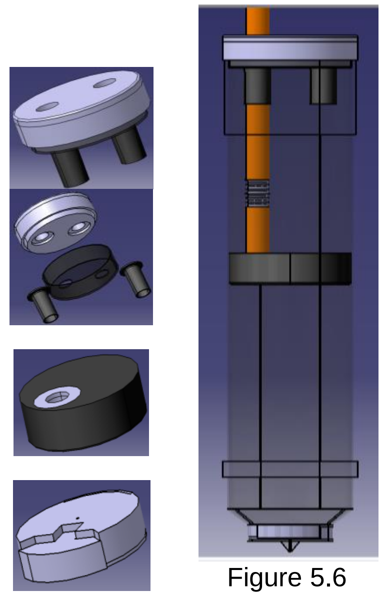


Figure 5.6
Nozzle & sub assemblies

Material Pressure Plate Assembly:

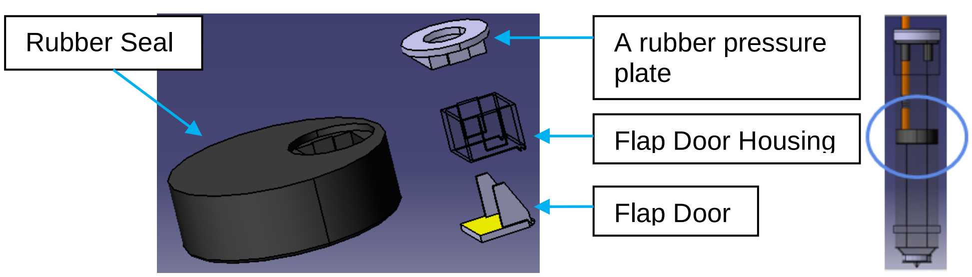


Figure 5.7 Material Pressure Plate Assembly

Exploded view of pressure plate assembly can be seen in figure 5.7. Working principle of pressure plate is to exert pressure on the material during the time of material deposition. However, pressure is released from the plate assembly when material is being feed into the nozzle chamber. This process is done in three steps:

1. Material is pumped into the nozzle from the feeding apparatus through material pipe which is connected with the nozzle pressure plate as shown in figure 5.8. This exerts the pressure on the flap door (as shown in figure 5.8), which opens when the pressure exerted from point “A” is greater than point “B” as shown in figure 5.8.

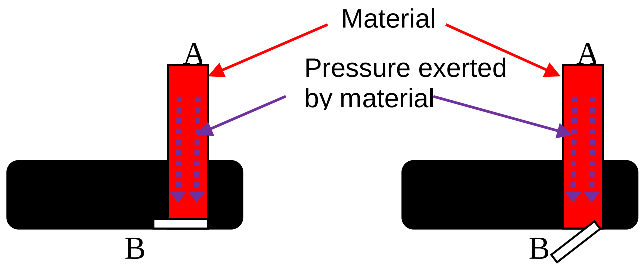


Figure 5.8 Working principle of pressure plate

2. When material deposition process begins, feeding apparatus is switched off which releases the pressure exerted on the door previously. At the same time air pressure is exerted on the pressure plate from point A as shown in figure 5.9 which builds up an equal pressure in material chamber (at point B). Pressure developed in material chamber closes the material flab door, which seals the material feeding tube excess to the material chamber.

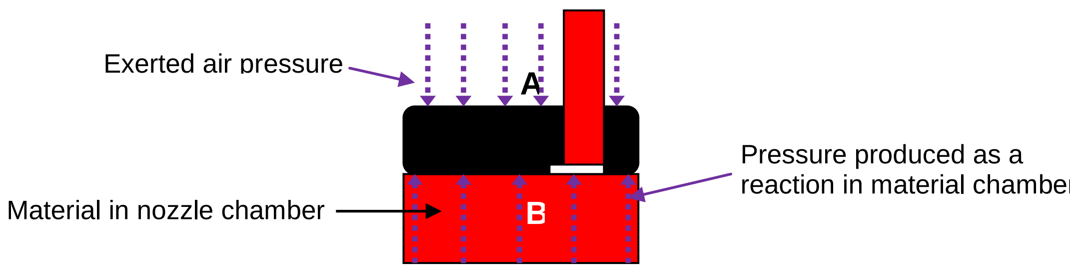
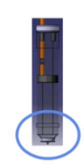


Figure 5.9 Working principle of pressure plate

Deposition Control Assembly:



Deposition control assembly is a unique deposition controller which is operated by an electro magnet. Electro magnet is charged to deposit material and in idol position it works as a stopper. Deposition control consists of seven parts (see figure 5.10):

- There are three material access holes one each on housing cover, main housing and deposition trigger.

- Springs push the trigger away from the housing cover hole when electro magnet is not activated.

- When electro magnet is activated trigger moves towards the magnet. During this process three holes are aligned and deposition of material occurs.

- This control has the ability to perform drop and continuous deposition accurately and preciously.

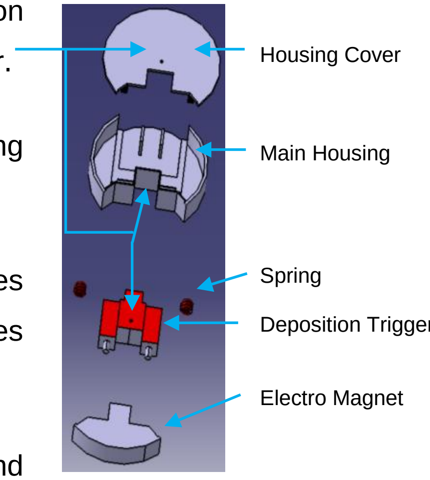


Figure 5.10 Deposition Control Assembly

UV Curing light:

M^2-3D Printer's nozzle deposition apparatus comes with two commercially available, off the shelf UV curing lights. M^2-3D Printer system uses photopolymer materials which come with different photoinitiator properties. It's important to understand that when a 3D object is being fabricated with the help of multi-materials, this challenges the curing capabilities of an AF system.

All though M^2-3D Printer is not using functionally graded materials but it has the capability to deposit more than two build materials in a same layer. This unique feature of M^2-3D Printer challenges its curing capability, especially when material deposition is done to achieve high resolution. It is important to keep in mind that higher the resolution size is, smaller will be the deposition material size. To achieve higher resolution, M^2-3D Printer can deposited material as small as 10µm in x-y axis and 10µm in z axis. However, the quality of resolution mainly depends on the parameters of curing process.

Parameters affecting the quality depend on material properties and their reaction to the curing source. If the material's viscosity rating is low then the time of deposition and curing process needs to be short and efficient. As a delay in curing process with materials with low viscosity will cause problems of material movement or drag on the build platform. For this reason the material deposition and curing speed needs to match.

Delay in curing may result in a problem of material movement which may result in decreased material thickness in z-axis. This problem can be controlled or eliminated by understanding material properties such as viscosity and photoinitiator strength. This problem can be removed if the material deposition speed and the time of polymerisation are significantly reduced so that deposition speed is equal to curing speed.

Deposition flow Rate = Material polymerisation speed

Material flow rate can be calculated which is explained later however, material polymerisation speed includes the factor of area of exposure and intensity of UV light. To increase the curing speed, M^2-3D Printer is equipped with two UV light sources (see figure 5.11). Main UV light source of nozzle deposition apparatus is used to cure instantly a large about of material volume, as shown in figure 5.12. It can speed up the curing process when a large amount of a material is deposited and requires an instant cure. However, in the case of multi-material deposition, each material will have different UV intensity requirement to cure and can prove difficult to manage the curing intensity preciously for each material. It is important to understand that if a material exposure time and intensity is not controlled, issues of over cure will occur.

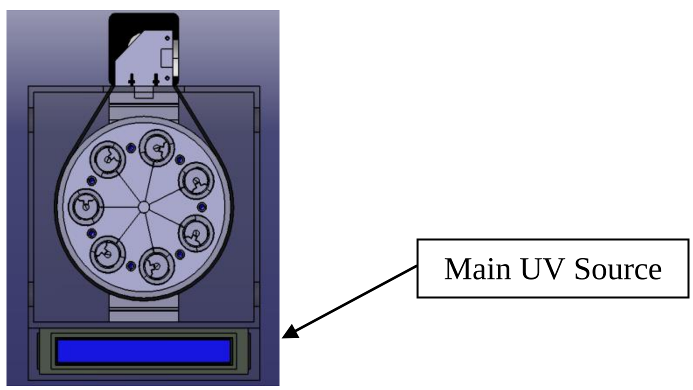


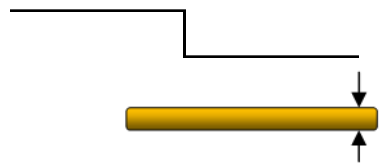
Figure 5.11 Main UV source

Let's consider if a layer of single material (Accura 40) is deposited on the build platform as shown below. UV light intensity is adjusted by considering the materials photoinitiator value and material thickness. Let's suppose if 3dsystems "Accura 40" material is deposited continuously in a straight line. The deposited volume has the depth or thickness of 10µm, whereas, the commercial UV intensity required for curing material depth of 0.17mm is 20.9mJ/cm^2 approximately.

So the UV intensity required to cure "Accura 40" will be:

$$\frac{Layer\ thickness\ of\ deposited\ material}{Given\ Penetration\ depth\ of\ material} = \frac{Required\ energy\ to\ cure\ deposited\ matreial}{Given\ Energy\ of\ Critical\ exposure}$$

Layer thickness of deposited material = L_d = 10µm



Required energy to cure deposited material = X

Given Penetration depth of build material = P_d =17mm

Given Energy of critical exposure = E = 20.9mJ/cm^2

$$\frac{L_d}{P_d} = \frac{X}{E}$$

$$\frac{10\mu m}{170\mu m} = \frac{X}{20.9mJ/cm^2}$$

$$\text{Required energy} = X = 1.23mJ/cm^2$$

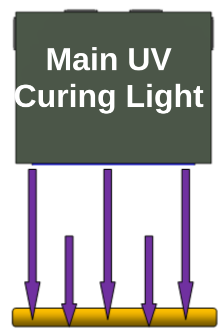


Figure 5.12 Main UV source

To control the UV curing intensity for multi-materials, M^2-3D Printer nozzle deposition apparatus is also equipped with a spot UV light source for precision curing of a small volume deposition. UV spot light is specifically integrated into the nozzle deposition system to speed up curing process by aiming the curing source to a specific material volume (see figure 5.13). It is an ideal curing source when multi-material deposition is done in drop formation and requires instant curing by adjusting the curing intensity for each material.

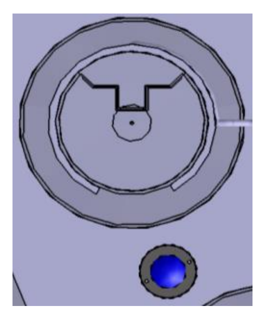


Figure 5.13 Spot UV source

Let's consider if a layer of multi-materials (Accura 40, 55 and 60) is deposited on the build platform as shown below. UV spot light intensity is adjusted by considering the materials photoinitiator value and material thickness. Let's suppose if 3dsystems "Accura 40, 55 and 60" materials are deposited continuously in a straight line for 10mm one after another and have material thickness of 10µm each, whereas, the commercial UV intensity required for curing material selected materials are presented in table 5.3:

Table 5.3 UV light intensity

Material	Penetration Depth (Dp)	Critical Exposure (Ec)
Accura 40	0.168-.173mm	20.1-21.7 mJ/ cm^2
Accura 55	0.132mm	7.4 mJ/ cm^2
Accura 60	0.16mm	7.6 mJ/ cm^2

And the UV intensity required for curing deposited layer of multi-materials calculated using the same equation is shown in table 5.4

Table 5.4 Required UV light intensity

Material	Penetration Depth (Dp)	Critical Exposure Limit (Ec)
Accura 40	10µm	1.23 mJ/ cm^2
Accura 55	10µm	0.56 mJ/ cm^2
Accura 60	10µm	0.48 mJ/ cm^2

UV spot light will be more practical for instant curing a low volume deposition layer of multi-material with average material length of 10mm, as it will give more control on preciously adjusting UV intensity and exposure time for each deposited material volume one by one. A graphical representation of the process is shown in figure 5.14.

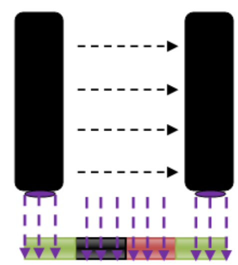


Figure 5.14 Graphical representation of UV-process

5.5.2 M^2-3D Printer - Process

Pre process:

A 3D model is designed in a CAD environment using engineering drawing software such as CATIA, SolidWorks or PRO/E, which is saved in a IGS format (see figure 5.15).

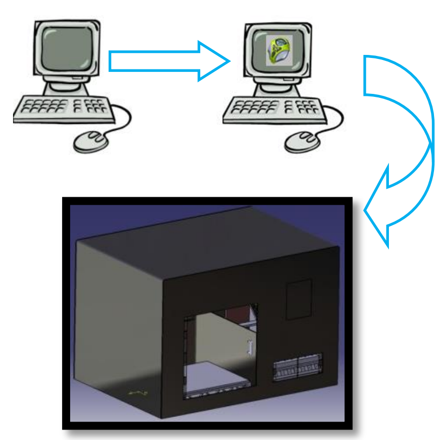


Figure 5.15 M^2-3D Printer design

CAD model is then tarnsfered into proposed M^2-3D Printer software, which uses a direct slicing algorithm technique where the developed slicing algorithm can mix together all segments of the cut layer by calculate start and end points of every segments. After finding the sequence of the segments, the algorithm can generate a closed NURBS curve to represent the contour of the cut layer based on Open CASCADE foundation.

Build Process:

1. Feeding apparatus is switched on to start pumping the material from the Feeding tanks to material deposition nozzle chambers. Each feeding pipe is dedicated to a specific material, its one end is connected to the material source tank and other is connected to the deposition nozzle pressure plate.

   Feeding apparatus pumps the material with the help of a crank shaft attached to the dedicated pumps. Feeding apparatus is switched off when deposition material nozzle chamber is full. A graphical representation of the process is shown in figure 5.16.

   Note: The detailed working of feeding apparatus is explained earlier in feeding apparatus design

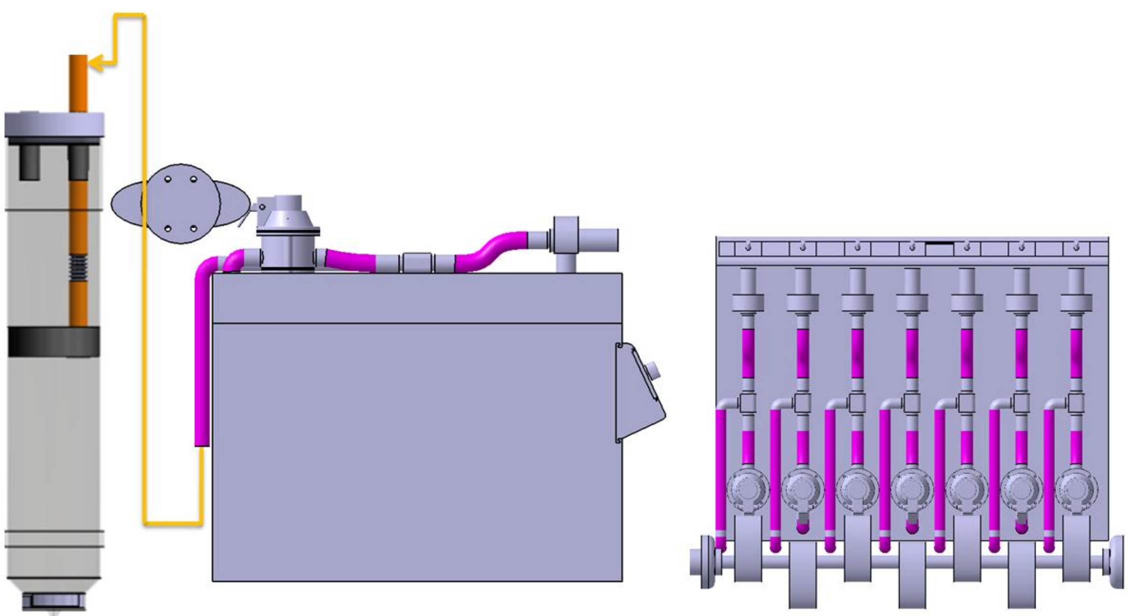


Figure 5.16 Feeding process

2. Deposition apparatus is initiated to start the deposition process after the material chambers of each nozzle is filled with the desired multiple materials and support material.

   Air compressor is switched on and a constant pressure on the nozzle pressure plate is maintained. The required pressure for each nozzle needs to be controlled and can be calculated by using the following equation derived from Poiseulle's law:

$$Pressure = P = \frac{8V\eta l}{\pi t r^4}$$

   The deposition flow rate is controlled by the pressure exerted on the pressure plate. The pressure of each nozzle depends on the material properties and the geometry of nozzle tip. So each nozzle's pressure is adjusted according to the required flow rate, as shown in figure 5.17.

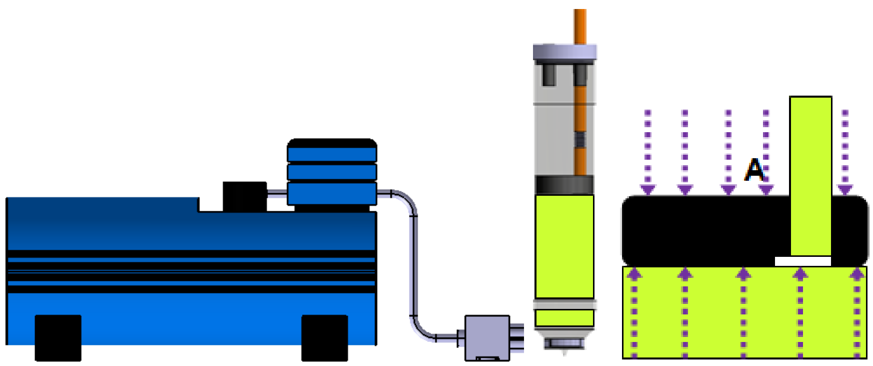


Figure 5.17 Feeding process

3. Z axis is adjusted for the first deposition by moving closer to the deposition nozzle apparatus (see figure 5.18). The movement of z axis is controlled by a servo motor which moves the z axis upward or downward.

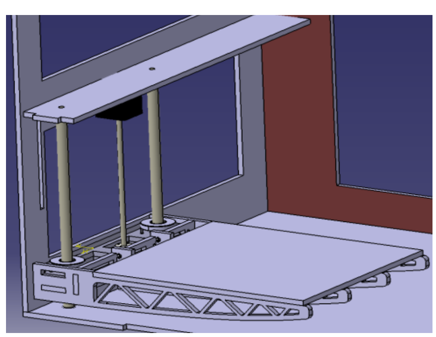


Figure 5.18 Z-Axis

4. Nozzle apparatus (see figure 5.19) is adjusted for the first deposition to begin by selecting the desired material nozzle. Seven nozzles are mounted on a rotation tray which is connected to a servo motor. The servo motor can rotate the nozzles 180^0 clockwise and anti clockwise. For nozzle selection an algorithm is developed which is explained in the software chapter.

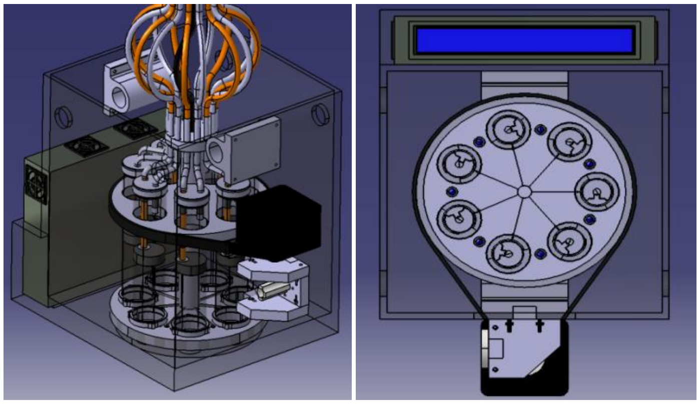


Figure 5.19 Nozzle Apparatus

5. Deposition control is actuated after the z axis is adjusted and nozzle is selected for the first material deposition for continues or drop deposition. Deposition control actuation is predefined when the material tool path is defined during pre processing.

Deposition control makes it possible to control the material deposition quantity precisely. It is important to understand the flow rate is controlled by the pressure exerted by the pressure plate however, the deposition mode (continuous or drop) is controlled by the deposition control assembly. For quality and precision, both pressure mechanism and the deposition control need to work in perfect coordination.

In the figure5.20, material is being deposited continuously in a straight line by activating the deposition control.

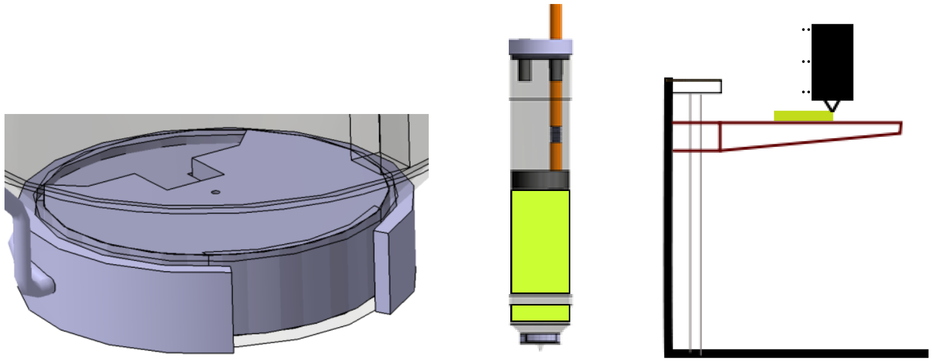


Figure 5.20 Continuous material deposition.

6. Material depositing process is followed by the curing process which is done layer by layer. However, curing process needs to be adjusted for every material in a layer, when multi-materials are deposited. Material curing process can be done by using either Main UV source or UV spot light, depending on the material quantity, geometry and area which need to be cured.

When multi-materials are deposited in small quantity and more frequently then it is impossible to use a main UV light sure for curing as different materials will require different UV laser intensity depending on the material properties and photo initiator strength, so for this reason UV spot light is used. UV spot light process is slow as compared to Main UV light source but it is more precise and easy to control (see figure 5.21).

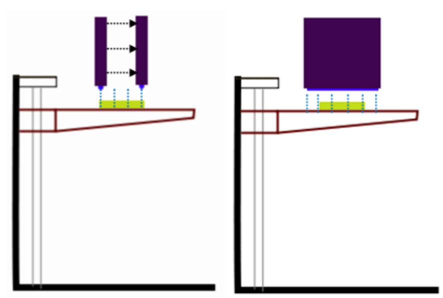


Figure 5.21 Curing process

Working Example:

Scenario in figure 5.22 shows that a single material layer is deposited and cured by both UV lights. It is clear that the area covered by the Main UV light source is much bigger as compared to UV spot light so there will be a major difference in time of curing process in the two approaches.

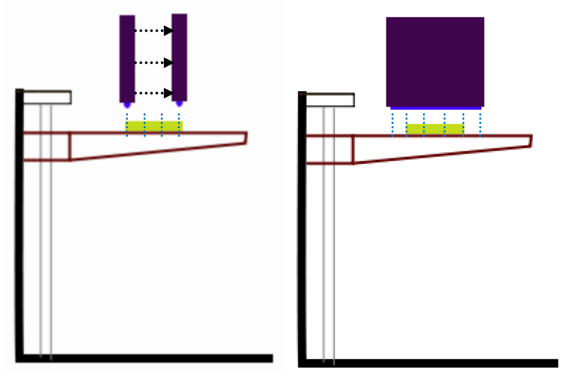


Figure 5.22 Curing process

However, when more than two materials are deposited in a same layer one after another as shown in figure 5.23 then it will be impossible to use main UV source to cure as different materials will require different UV intensity to cure. In this case Main UV cure may result in either over curing a material and at the same time under cure another material in the same layer. This will result into a layer which is imperfect and has structural and geometrical defects. To resolve this issue an integrated UV spot light is used which may increase the time of curing process but will give better control and accuracy when curing multi materials in a same layer.

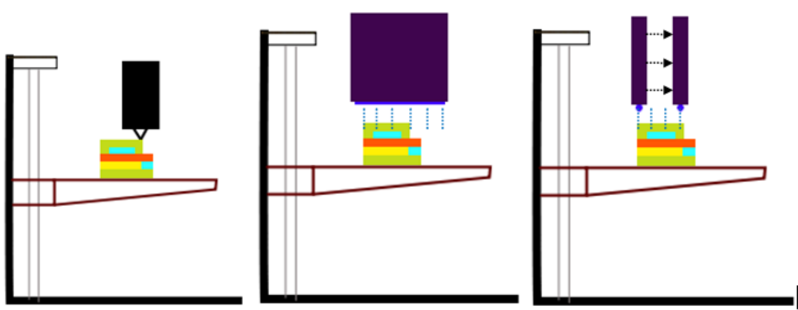


Figure 5.23 Curing process

When first layer is cured, z-axis moves downward to allow the next layer deposition to begin and repeat the cycle until the fabrication of an object is completed, as shown in figure 5.23.

Post Process:

When the fabrication process is completed, model is removed from the machine for post processing, which involves chemical cleaning and rinsing, support structure removal and final UV curing. Support structure is used to support the build structure of the fabricated object where its geometry consists of overhangs and undercuts. However, structure removal can be a tedious and time consuming process. After the support structure removal, in some case post curing is down to improve the integrity of the structure. After the final cure, sometimes hand finishing may need to be done for appearance and functional purposes.

5.6 Working Principle and Quality Control

The proposed M^2-3D Printer system process is more flexible as it is composure of SLA and FDM technology in principle. However, M^2-3D Printer process is fundamentally based on the same principles as of SLA process. So overall the process is based on the following principles:

- Parts are built from photo curable liquid resins, which are extruded from the nozzle deposition system onto the build platform one by one and cured when exposed to the UV light.
- The build is done layer by layer, where each layer when cured is lowered by the elevation mechanism.

Quality Control:

The parameters which influence performance and functionality of the fabricated objects in M^2-3D Printer system include:

- Physical and chemical properties of resins
- Curing speed and UV intensity
- Collaboration between the deposition and curing system

For the better quality and control of fabrication, it's important to understand the properties of resins as the curing speed and UV intensity also directly depends on them. When material properties are known, then the UV intensity can be calculated by using the following equation presented by EIT, Inc (eit.com, 2011).

$$Intensity\left(\frac{\mathrm{mW}}{\mathrm{cm2}}\right) = \frac{Energy(\frac{\mathrm{mJ}}{\mathrm{cm}^2})}{Time\ (s)}$$

To increase the collaboration between the deposition and curing system, flow rate, deposition pressure and volume needs to be controlled precisely. This can be calculated using following formulas derived from Poiseulle's equation:

$$\text{Volume} = V = \frac{\pi t P r^4}{8\eta l} \qquad \text{Pressure} = P = \frac{8V\eta l}{\pi t r^4} \qquad \text{Flow rate} = \frac{V}{t} = \frac{\pi P r^4}{8\eta l}$$

5.8 Case Study

Material selection:

Photopolymer materials are selected for the proposed multi-material nozzle system. There are number of photopolymers available in industry, mainly produced by 3D Systems, Amber Composites and Huntsman. All photopolymers are in liquid form however, materials produced by each company are designed for a specific purpose with different physical and mechanical properties. These materials differ with respect to their density, viscosity, penetration depth and cured/mechanical properties. Therefore, a material selection table is formed to compare the selected photopolymer materials.

Table 5.5 Photopolymer material comparison (3DSystems.com,2010)

Material	Colour	Density @ 25 ^{0}C	Viscosity @ 30 ^{0}C	Penetration Depth (Dp)	Critical Exposure (Ec)
Accura 10	Clear Amber	1.1 g/cm^3	485 cps	0.127mm	13.2mJ/ cm^2
Accura 25	White	1.14 g/cm^3	250cps	0.107mm	10.5 mJ/ cm^2
Accura 40	Clear Amber	1.1 g/cm^3	485 cps	0.168-.173mm	20.1-21.7 mJ/ cm^2
Accura 45	Clear Amber	1.14 g/cm^3	475 cps	0.13mm	7.4 mJ/ cm^2
Accura 50	Opaque natural or Opaque Gray	1.15 g/cm^3	600 cps	0.114mm	9.0 mJ/ cm^2
Accura 55	White	1.13 g/cm^3	155-185 cps	0.132mm	7.4 mJ/ cm^2
Accura 60	Clear	1.13 g/cm^3	150-180 cps	0.16mm	7.6 mJ/ cm^2
Accura Amethyst	Purple	1.1 g/cm^3	350cps	0.094mm	14.4 mJ/ cm^2
Accura Bluestone	Opaque Blue	1.7 g/cm^3	1200-1800cps	0.104mm	6.9 mJ/ cm^2
Accura CeraMAX	Opaque White	1.59 g/cm^3	1500-2000cps	0.145mm	7.2 mJ/ cm^2
Accura PEAK	Amber	1.32 g/cm^3	605cps	0.142mm	11.5 mJ/ cm^2
Accura Xtreme	Grey	1.13 g/cm^3	250-300cps	0.104mm	11.7 mJ/ cm^2

In the above table the penetration depth and critical exposure values will not be constant and will change depending on the layer thickness, part geometry. It is important to note that materials are compared not on the bases of their applications but on the sole bases of their general properties which will be later shortlisted after driving the formulas to identify material compatibility to the selected apparatus. 3D Systems have proposed a material selection guide which is shown below in table 5.6:

Table 5.6 Accura Stereolithography Material Selection Guide (3DSystems.com, 2010)

	Accura® 25	Accura® Xtreme	Accura® 55	Accura® 60	Accura® 48HTR	Accura® Amethyst™	Accura® PEAK™	Accura® CeraMAX™	Accura® Bluestone™
	Plastic	Plastic	Plastic	Plastic	Plastic	Material	Plastic	Composite	Composite
Material Property									
Accuracy	****	****	****	***	****	*****	****	*****	*****
High Temperature					****		****	*****	*****
Moisture Resistance		***	****	****			*****	*****	*****
Optical Clarity				****	***				
High Stiffness (Flex Modulus)						***	****	*****	*****
High Elongation	****	*****	***	***					
High Impact Strength	***	****							
Opacity	*****	*****	*****					*****	*****
Color	White	Grey	White	Clear	Clear Amber	Purple	Amber	Off-white	Blue
"Simulant" Characteristics									
Polypropylene	*****	*****							
ABS		*****	*****						
Polycarbonate				*****					
Recommended Applications									
Investment Casting/QuickCast				*****	***				
Jigs/Fixtures/Tools			****	***	***		****	*****	*****
Master Patterns for RTV	****	****	*****	*****	***		****		
General Purpose Models	****	****	****	*****	****				
Snap Fit Testing	*****	*****	***	***					
Injection Molding/Direct AIM							****	*****	*****
Automotive/Under-The-Hood					****		*****		
Wind-Tunnel					***		****	*****	*****
Jewelry Manufacturing						*****			
Thermally Resistant Components					***		****	*****	*****
Abrasion Resistant Components								****	****

For the case study five materials which are selected from the tables 5.6 are presented in table 5.7:

Table 5.7 Selected materials

Material	Colour	Density @ 25 ^{0}C	Viscosity @ 30 ^{0}C	Penetration Depth (Dp)	Critical Exposure (Ec)
Accura 25	White	1.14 g/cm^3	250cps	0.107mm	10.5 mJ/ cm^2
Accura 40	Clear Amber	1.1 g/cm^3	485 cps	0.168-.173mm	20.1-21.7 mJ/ cm^2
Accura 55	White	1.13 g/cm^3	155-185 cps	0.132mm	7.4 mJ/ cm^2
Accura 60	Clear	1.13 g/cm^3	150-180 cps	0.16mm	7.6 mJ/ cm^2
Accura Xtreme	Grey	1.13 g/cm^3	250-300cps	0.104mm	11.7 mJ/ cm^2

Curing Process selection:

For the time being the critical parameters (i.e. material flow rate per second, pressure etc) for deposition are ignored but will be discussed later in fluid dynamics chapter. With the help of the deposition apparatus four layers of material will be deposited on top of each other one by one. Each material exhibits different properties of viscosity, penetration depth and critical exposure limits. So the selected curing process will need to be adjusted for each layer before the curing process can begin.

UV light curing process is selected for the selected materials. The UV light intensity will be adjusted for each material. For the purpose of case study, the object is a simple rectangular block as shown in figure 5.24. With the help of material deposition system first layer of Accura 40 is deposited.

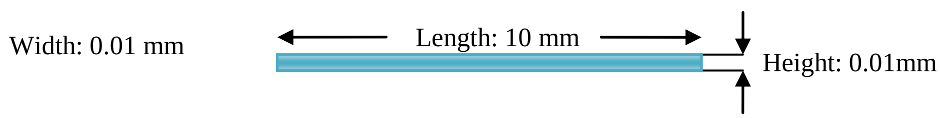


Figure 5.24 Accura 40 deposited material

Polymerisation Process:

UV light distance is adjusted, considering material thickness. The distance between the UV light source and the material layer is less than 0.5mm. So the intensity of UV light is above 98%.

$$Intensity\left(\frac{\mathrm{mW}}{\mathrm{cm2}}\right) = \frac{Energy(\frac{\mathrm{mJ}}{\mathrm{cm^2}})}{Time\ (s)}$$

Energy required when layer thickness is 10µm is calculated by using the following equation:

$$\frac{Layer\ thickness\ of\ deposited\ material}{Given\ Penetration\ depth\ of\ material} = \frac{Required\ energy\ to\ cure\ deposited\ matreial}{Given\ Energy\ of\ Critical\ exposure}$$

$$\frac{L_d}{P_d} = \frac{X}{E}$$

$$\frac{10\mu\mathrm{m}}{127\mu\mathrm{m}} = \frac{X}{13.2\mathrm{mJ/cm^2}}$$

$$\text{Required energy} = X = 1.04\mathrm{mJ/cm^2}$$

Table 5.8 Energy required for the selected materials

Material	Penetration Depth (Dp)	Critical Exposure Limit (Ec)
Accura 25	10µm	0.98 mJ/ cm^2
Accura 40	10µm	1.23 mJ/ cm^2
Accura 55	10µm	0.56 mJ/ cm^2
Accura 60	10µm	0.48 mJ/ cm^2
Accura Xtreme	10µm	1.13 mJ/ cm^2

Fluid Dynamics:

Rate of flow of liquid through a capillary tube of radius “r” and length “l” can be calculated by using equation 1 derived from Poiseulle’s law:

$$V=\frac{\pi t P r^4}{8\eta l}=\frac{\Delta P}{8\eta l/\pi t r^4}=\frac{\Delta P}{R} \leftarrow \text{Equation 1}$$

P = Pressure difference ΔP

R = Fluid resistance (R $=8\eta l/\pi r^4$)

Rate of flow per second is calculated by changing equation 1.

$$V=\frac{\pi \Delta P t r^4}{8\eta l} \qquad \leftarrow \text{Equation 2}$$

Table 5.9 Equation Symbols

	Symbols	Units
Volume	V	m^3(Meter)
Pi	π	
Pressure	P	Pa (Pascal)
Time	T	S (Second)
Viscosity	H	ps (Poise second)
Length	L	m (Meter)
Radius	R	m (Meter)

As the fluid or material is going from applied pressure to atmospheric pressure, therefore, we can ignore the pressure change. So

$$\Delta P = P$$

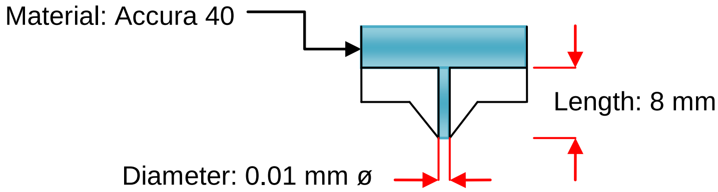
So equation 2 is rearranged to calculate the pressure required to deposit a certain amount of volume per second.

$$\text{Volume} = V = \frac{\pi P t r^4}{8\eta l} \qquad \leftarrow \text{Equation 2}$$

$$\text{Pressure} = P = \frac{8V\eta l}{\pi t r^4} \qquad \leftarrow \text{Equation 3}$$

Where as to calculate the flow rate per second equation will become

$$\text{Flow rate} = \frac{V}{t} = \frac{\pi P r^4}{8\eta l} \qquad \leftarrow \text{Equation 4}$$

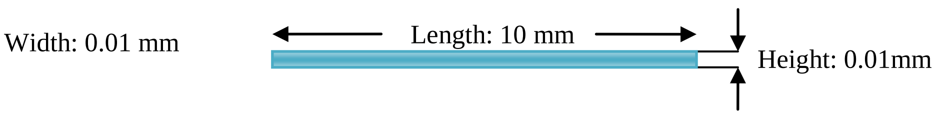


Length = l = 8mm = 0.008m

Radius = r = 0.005mm = 5×10^{-6}m

Viscosity = η = 485cps = 4.85ps = 0.485 Pa.s

If the volume dispensed in a straight line has the following measurements the;



Volume in meter^3= V = l x w x h

$$V = (0.01\text{m}) \times (1\times10^{-5}\text{m}) \times (1\times10^{-5}\text{m})$$

$$V = 1\times10^{-12}\text{m}^3$$

As we are dispensing material into atmospheric pressure, so we assume there won't be any changes in pressure. So using equation 3;

$$\text{Pressure} = P = \frac{8V\eta l}{\pi t r^4} \qquad \leftarrow \text{Equation 3}$$

$$P = \frac{8 \times (1 \times 10^{-12}\,\text{m}^3) \times (0.485\,\text{Pa.s}) \times (0.008\text{m})}{3.14 \times (1\text{ s}) \times (6.25 \times 10^{-12}\,\text{m}^4)}$$

$$P = \frac{3.104 \times 10^{-14}}{1.96 \times 10^{-21}}\,\text{Pa}$$

$$P = 15836734.69\text{ Pa}$$

Converting Pascal into Bar:

$$P = \frac{15836734.69}{100{,}000}\,\text{Bar}$$

$$P = 158.4\text{ Bar}$$

Chapter 6 – Software Development of M^2-3D Printer

In this chapter, some algorithms will be developed to support the design of M^2-3D Printer for multi-material RP&M processing. It gives an introduction about STL format file and NURBS curve. A NURBS-based slicing algorithm is developed to represent the boundary contours of the sliced layer in RP&M technology to maintain the geometrical accuracy of original CAD model. In addition, a nozzle change algorithm for fabrication of two-material object in RP&M technology is also developed in this chapter. The developed software can be used to reduce the build time of fabrication and guide the fabrication process of two material objects in the designed M^2-3D Printer.

6.1 STL Format File and its Problems

STL format file is the de facto standard widely used in RP systems which was originated by the 3D Systems Company in USA in 1989. It is a triangular representation of a 3D surface geometry, where surface is tessellated into a series of small triangles facets. Each facet is described by a perpendicular direction and three points representing the vertices of the triangle. Figure 6.1 shows a STL format model of human head.

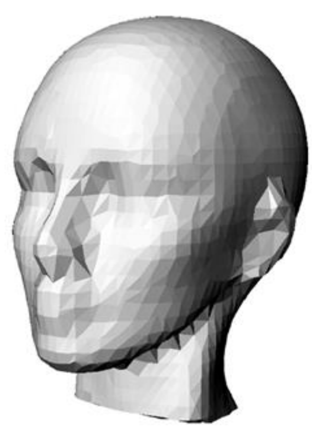


Figure 6.1 A STL format model of human head

The STL file has two formats: (a) ASCII format, (b) Binary format (shown in Figure 6.2). Compared with binary format, ASCII format is human readable but the size of file is larger than binary format.

(a) ASCII format

solid name

facet normal n_i n_j n_k
outer loop
vertex $v1_x$ $v1_y$ $v1_z$
vertex $v2_x$ $v2_y$ $v2_z$
vertex $v3_x$ $v3_y$ $v3_z$
endloop
endfacet
…

endsolid name

(b) Binary format

UINT8[80] – Header
UINT32 – Number of triangles

foreach triangle
REAL32[3] – Normal vector
REAL32[3] – Vertex 1
REAL32[3] – Vertex 2
REAL32[3] – Vertex 3
UINT16 – Attribute byte count
end

Figure 6.2 The two formats of STL file

STL file provides a simple method to represent the 3D CAD model and has been used by most single material RP&M systems in recent years. However, there are many types of errors in STL files such as holes, missing, gaps, overlapping and degenerate facets, etc. In addition, STL is inherent inaccuracy in terms of geometrical representation and it does not contain topological data, so it is difficult to represent accurate CAD models and hard to be used to represent the multi-material object in RP&M technology (Chua, Leong& Lim, 2010). So, there is a need to develop a method to support multi-material fabrication in RP&M technology.

6.2 NURBS Curve

NURBS are mathematical representations of 3D geometry that can accurately describe any shape from a simple 2D line, circle, arc, or curve to the most complex 3D organic free-form surface or solid. Figure 6.3 shows a NURBS curve with 8 control points. A NURBS curve is defined by its order, a set of weighted control points, and a knot vector:

(1) The control points determine the shape of the curve.
(2) The knot vector is a sequence of parameter values that determines where and how the control points affect the NURBS curve.
(3) The order of a NURBS curve defines the number of nearby control points that influence any given point on the curve.

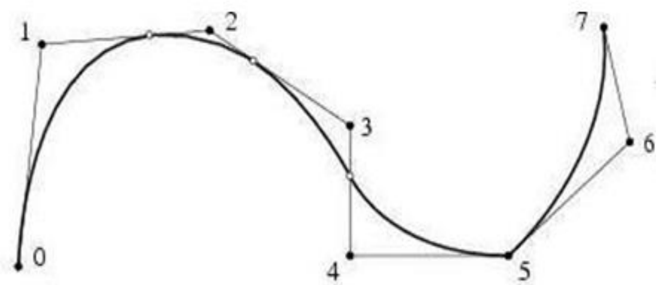


Figure 6.3 A NURBS curve with 8 control points

Compared with STL format file, NURBS – based curves have some advantages (showed in Table 6.1):

Table 6.1 The comparison between STL file and NURBS

STL	NURBS
Large storage space	Small storage space
Inherently inaccurate	Accurate
Hard to represent multi-material model	Can be used to represent multi-material model
Simple	Complex

As STL does not contain topological data and only a facet model derived from precise CAD models. It needs several times large storage space for a complex accuracy CAD model compared with NURBS. Meanwhile, STL file is inherently inaccurate as it is an approximate model, but NURBS is a mathematical model which offers great precision for freeform shape model. In addition, STL file is quite hard to represent multi-material model, but NURBS can be used to represent multi-material model easy. However, compared with STL file, NURBS is much more complex.

In this thesis, a method to use NURBS curve instead of STL format file to support multi-material RP technology is developed. Figure 6.4 shows the comparison between traditional RP process and the developed method. In the traditional method, it slices a STL model which transform from the original CAD model to get a 2D cross-section. This can be used to generate tool-path for the RP&M systems. In the developed method, it directly sliced the CAD model instead of the STL file conversion and NURBS (Non-Uniform Rational B-Spline)-based curve are introduced to represent the boundary contours of the sliced layers in RP&M to maintain the geometrical accuracy of original CAD model and to support the multi-material RP&M technology.

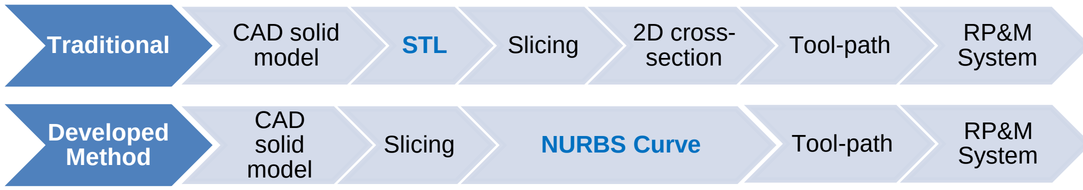


Figure 6.4. The comparison between traditional RP&M process and the developed method

6.3 A NURBS-based slicing algorithm

The developed NURBS-based slicing algorithm is based on the C++ programming language in an open-source CAD kernel system - the Open CASCADE. Open CASCADE Technology is a software development platform freely available in open source, which includes components for 3D surface and solid modelling, visualization, data exchange and rapid application development (opencascade.org, 2011). Figure 6.5 shows the main process of the developed algorithm.

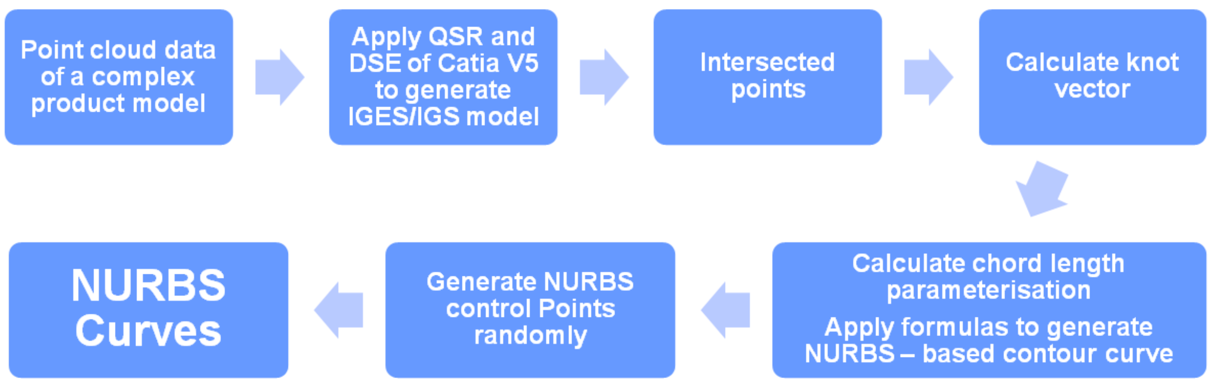


Figure 6.5 The flow of generating the NURBS-based contour curve.

- First, in the developed method, the point cloud data from a complex product model is reconstructed as an IGES/IGS model using the Quick Surface Reconstruction (QSR) and Digitized Shape Editor (DSE) modules in CATIA V5™. The reconstructed model is then read into the developed software platform.
- Then, a container is created to envelop the model, and the shortest edge of the enveloping box is determined as the orientation direction (Z-axis) to minimize the build time.
- After that, a series of sliced layers perpendicular to the orientation direction are set. Intersected points are generated between the slicing layer and the contour surface

of the model. The knot vector and control points are calculated based on the obtained intersected points.

- Finally, in order to establish a NURBS-based contour curve on the boundary between the sliced layer and the model ($C^{i,1}$), formulas (1) and (2) are applied to generate NURBS-based contour curve (Piegl, et al., 1997).

$$C^{i,j}(u) = \sum_{i=0}^{n} w_i N_{i,p}(u) C\_P^{i,j} \quad (1)$$

$$N_{i,0}(u) = \begin{cases} 1 & u_i \le u \le u_{i+1} \\ 0 & \text{otherwise} \end{cases}, \text{ and } N_{i,p}(u) = \frac{u-u_i}{u_{i+p}-u_i} N_{i,p-1}(u) + \frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}} N_{i+1,p-1}(u) \quad (2)$$

Where $C^{i,j}$ represents the jth contour curve in the ith RP layer; u is the parametric variable ($u=[0,1]$); w_i is the weight associated with control points; $C\_P^{i,j}$ is the control point; p is degree. Table 6.2 shows the detailed steps of the developed NURBS-based slicing algorithm.

Table 6.2. The steps of slicing algorithm

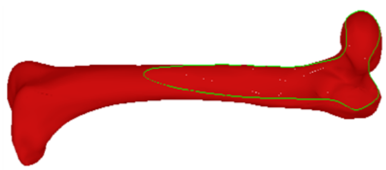
Steps	START
1.	Read a CAD model (IGS/IGES format)
2.	Make a container to accommodate the CAD model
3.	Determine the direction of slicing *(the longest segment of the CAD model)*, and set it to be Z-axis
4.	Along the Z-axis, slice the model with a uniform thickness, and get all the layers $(L_0, L_1, \ldots L_n)$ of the model
5.	Get the contour segments of the first layer (L_0)
6.	Explorer all the segments of the (L_0) to get the number of the segments (N_m)
7.	Select a segment randomly as the start segment (S_0) and find the start point $(P_{0,s})$ and the end point $(P_{0,e})$ of (S_0)
8.	Explorer all the segments (S_j) except the selected one and find a segment with start point $(P_{1,s})$ equals to $(P_{0,e})$. Named it as the second segment (S_1) $(j = 0,1,2, \ldots m)$
9.	Loop this process of step 8 until all segments along the sequence from start to end of the layer (L_0) are found
10.	Join all the segments of the (L_0) to generate a closed NURBS curve $(C_{0,0})$
11.	Loop the process from step 5 to step 10 to obtain all closed NURBS curves $(C_{i,0})$ for the CAD model $(i = 0,1,2, \ldots n)$
	END

An example to illustrate the developed slicing algorithm:

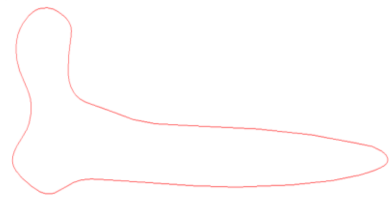
A tibia model of human right leg is used to illustrate the developed slicing algorithm. The length, width, height and volume of the tibia model are 405.29mm, 106.96mm, 98.249mm and 471600mm^3 respectively. The process for the NURBS-based contour curve generation is shown in Figure 6.6.

(a) An tibia model for RP tool-path generation

(b) An enveloping box for the model and a sliced layer



(c) The cross-section segments



(d) A NURBS-based contour curve generated by the slicing algorithm

Figure 6.6 An example to illustrate the developed slicing algorithm.

6.4 A Nozzle Change Algorithm for Two-material Object

The normal manufacturing processing for the fabrication of two-material object with RP&M machines are shown in Figure 6.7. It uses additive manufacturing method from bottom to top layer by layer to complete the object. For example, in Figure 6.7(c), firstly, it fabricates material A by nozzle 1 along the tool-path, then nozzle is changed from 1 to nozzle 2 and its positioned in the right location for the fabrication of material B. After the layer is finished, nozzle is changed to nozzle 1 to fabricate the material A on the next layer In Figure 6.7(b), and then its changed back to nozzle 2 to fabricate material B, layer by layer until the fabrication of an object is completed.

When the object is composed by different materials, the RP&M machine have to change the different nozzles to fabricate different materials in every layer. This slows the fabrication process due to the time required for nozzle change and its positioning at the right location. This also decreases the surface quality because the fabrication processing has too many start and end points, which will increase staircase problem and will cause warpage of the fabrication object (Kou and Tan, 2009). In this project, a nozzle sequence algorithm is developed based on the C++ programming language and the Open CASCADE software develop platform. It can be used to control the above designed M^2 – 3DP RP&M machine to fabricate the two-material object with the least changeover of the nozzles. Figure 6.8 shows the flowchart of the nozzle change algorithm.

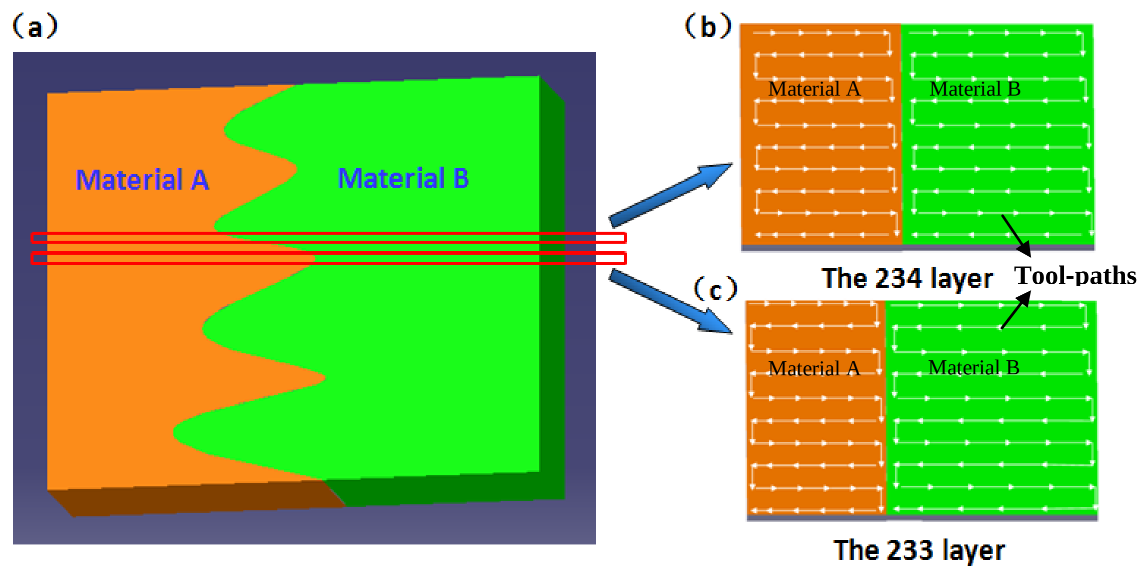


Figure 6.7 The processing for the two-material objects fabrication in RP&M

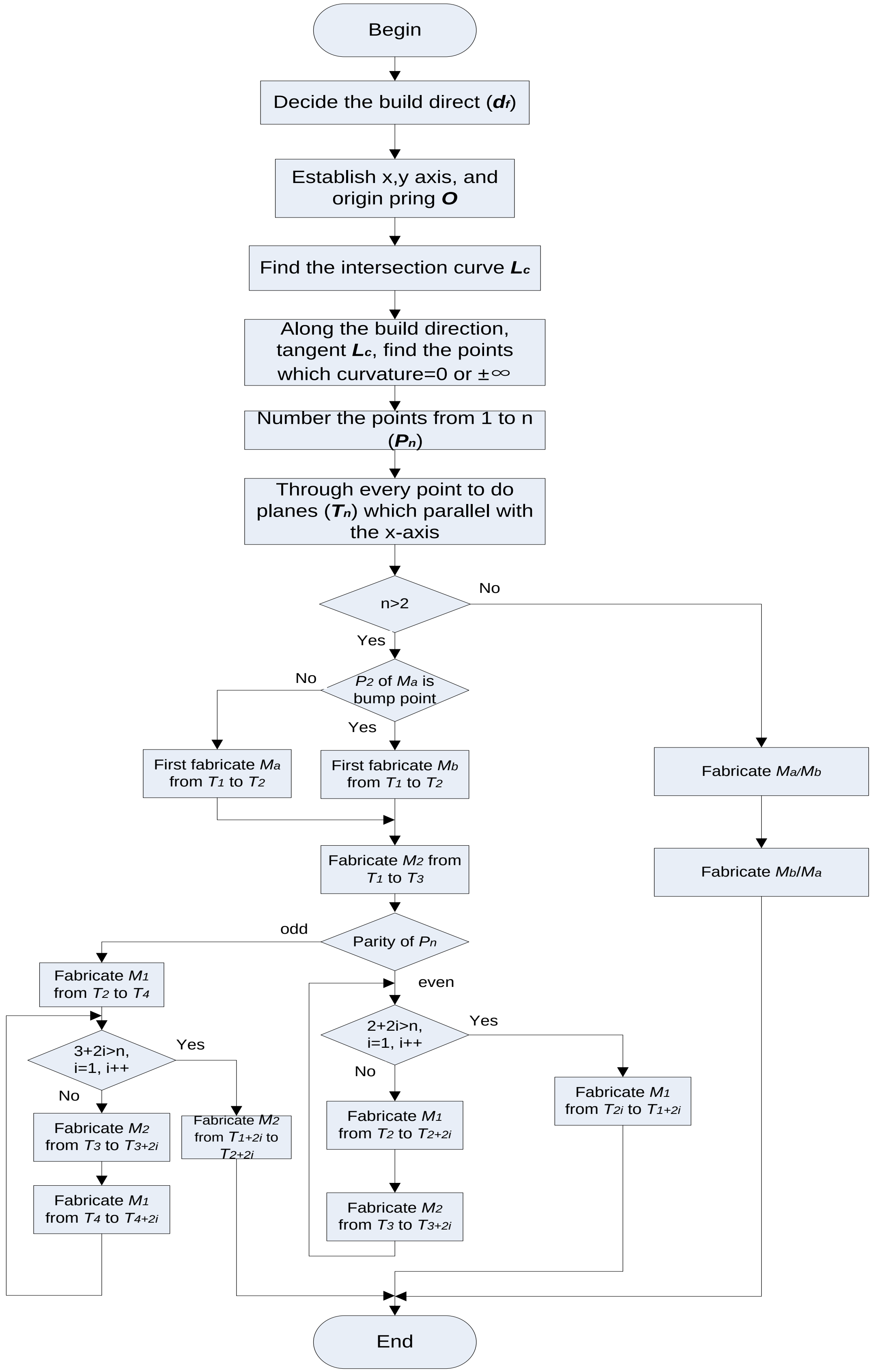
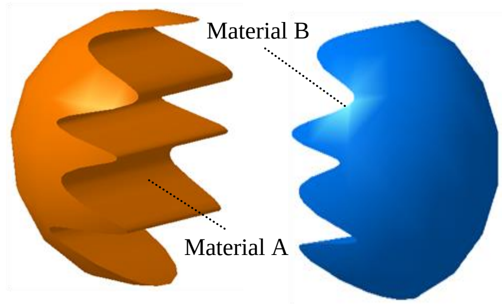


Figure 6.8 The flowchart of the nozzle change algorithm

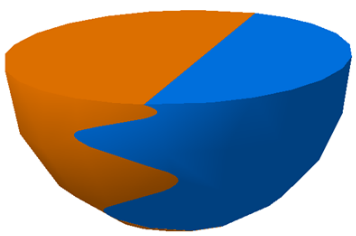
Compared with the traditional method:

The ball showed in Figure 6.9 with two different materials is used in this comparison. The diameter of the ball is 20cm. The thickness of every layer for RP&M system is 0.2mm. So the ball has 1000 layers totally.

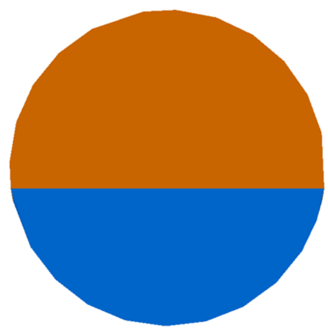
(a) An ball model with two different materials



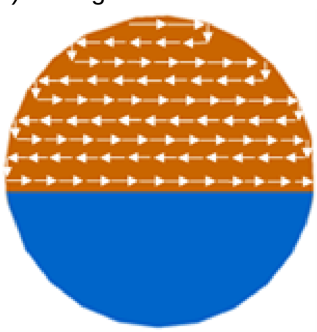
(b) The two parts of the ball



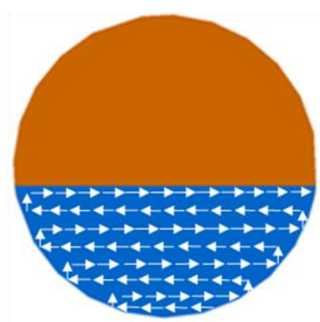
(c) Slicing the ball for one layer



(d) Contour of the layer



(e) Tool-paths generated for the material A



(f) Tool-path generated for the material B

Figure 6.9 An example to illustrate the nozzle change algorithm.

The format to calculate the totally build time is given as follows:

$$T_t = T_c + T_p + T_f \qquad (3)$$

Where T_c is the total time spent to change different nozzle, T_p is the total time spent for nozzle positioning, and T_f is the total time spent for fabrication. They can be calculated using following equations:

$$T_c = N_c \times t_c; \quad T_p = N_p \times t_p; \quad T_f = N_f \times t_f; \qquad (4)$$

Where N_c is the times of the nozzle change, N_p is the times of the nozzle positioning, and N_f is the times of the nozzle fabrication; t_c is the time spend to change a nozzle, t_p is the time spend to position a nozzle, and t_f is the time spend to fabricate one material part of the layer.

We assumed that $t_c = 60$ seconds, $t_p = 45$ seconds, $t_f = 30$ seconds. Figure 6.10 shows the fabrication processing for the ball in the developed nozzle change algorithm. The Table 6.3 shows the build time comparison between traditional processing and the developed change nozzle algorithm.

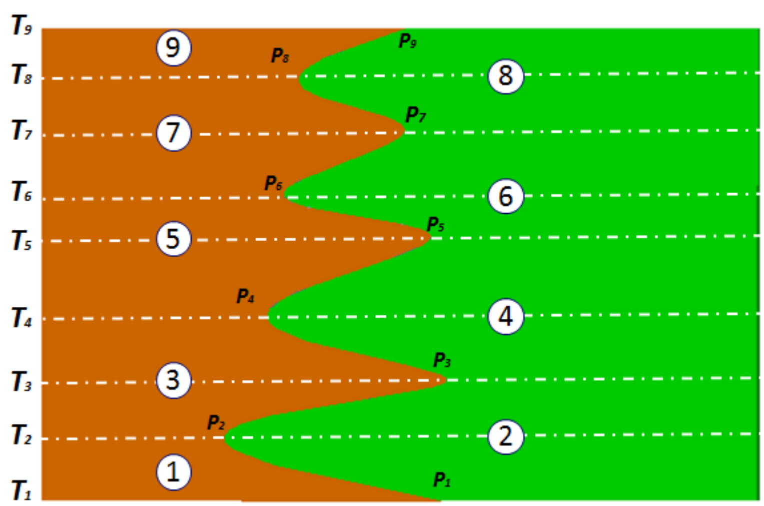


Figure 6.10 The fabrication processing for the ball in the nozzle change algorithm

Table 6.3: Build time comparison between traditional processing and the developed change nozzle algorithm

	The traditional fabrication processing	Using developed algorithm processing
N_c	1999	8
N_p	2000	9
N_f	2000	2000
T_c	1999×45=119940s	8×60=480s
T_p	2000×45=90000s	9×45=405s
T_f	30×2000=60000s	30×2000=60000s
T_t	269940s	60885s
Reduce	269940 – 60885 = 209055s	

Compared with traditional method for fabrication the ball, the developed nozzle sequence algorithm can reduces 209055 seconds. It is about $\frac{209055}{269940} \times 100\% = 77.4\%$ of the total fabrication time. In addition, it can also improve the surface quality of fabrication as it has less start and end of the nozzle change, which causes staircase and warage problem of fabrication of RP&M system.

Conclusion

The major focus of the dissertation is on the feasibility study of developing a unique multi-material nozzle deposition system which is flexible, accurate and can handle up to seven materials with controllable deposition. By evaluating all the findings with respect to the design of a multi-material nozzle deposition apparatus, its suitability to handle more than two materials, slicing and controlling algorithms, it is concluded that the selected proposed multi-material nozzle deposition system design is feasible for multi-material deposition of more than two materials and can be further developed to be used in the proposed M^2-3D Printer system. Comparison of existing multi material deposition system research with the proposed feasibility model of M^2-3D Printer is presented in table 7.1 (see page 79). Developed multi-material slicing and its nozzle control algorithm will reduce the processing time, data storage space and overall improve the quality of fabricated objects in the proposed M^2-3D Printer system. With the reference to the aims and objectives set out at the start of the project are completed at the end of the dissertation. The objectives included:

- ***To analyse and evaluate existing commercially available RP&M systems:*** RP&M systems research has been carried out mainly with the help of research papers, articles, reports and company websites. The literature review and its analysis conclude that applications of the most RP&M systems are either limited by the material choice and its properties or by its fabrication process itself.

- ***To analyse and evaluate existing research on multi-material RP&M systems:*** Present research on multi-material RP&M systems has been carried out mainly with the help of research papers, articles, and published reports. The literature review and its analysis conclude that the current research being done in this field has been focused on developing a multi-material deposition apparatus which can be used to deposit up to two materials or to deposit FGM materials. Most of the RP&M systems presented need further development to improve the process quality, control and repeatability.

- ***To analyse and evaluate the need of multi-material RP&M system with respect to related industries:*** The literature review and its analysis of the technologies, industrial trends, and research and development of RP&M shows that there is a growing interest from number of industries in multi-material RP&M system. There is a demand of more capable RP&M systems which can fabricate functional models from different materials. It will reduce the manufacturing cost and open doors for more complex, low volume product design and production.

- ***To review and analyse existing deposition apparatus design:*** Research analysis of the commercial market and the current research being done has clearly suggested that there is a need of Multi material RP&M system. It is concluded that commercial market of RP&M has no feasible solution available for multi material fabrication, whereas, recent research has gained some progress in the field of multi material fabrication of components from two materials but there is no deposition apparatus designed to deposit more than two materials.

- ***To produce a research gap analysis:*** Literature review is critically analysed to develop an understanding of issues related to the current RP&M technology, its industry trend and current research and development. The analysis are made and concluded to establish the current research gaps and topic of proposed research (See chapter 3 for details).

- ***To produce design specifications for the key components of the proposed multi-material RP&M machine:*** The proposed M^2-3D Printer system, consists of four major components, feeding apparatus, material delivery and flow system, deposition apparatus and build platform. All the components are designed to work with photopolymers materials. The key specifications of material disposition system are set by understanding the photopolymer materials.

- ***To design a nozzle of "M^2-3D Printer" for a controlled and accurate deposition:*** Nozzle design of deposition apparatus can build objects with a lower resolution of 10µm. It comes with a unique deposition controller which is operated by an electro magnet for controlled and accurate deposition.

- ***Multi material nozzle deposition apparatus design:*** A concept model of multi-material deposition apparatus is designed which can deposit more than two build materials. Photopolymer is the material choice which can be deposited in a continuous or drop format from the design apparatus. Flow rate and volume can be controlled by using the presented formulas for accurate deposition and to minimise the over/under fill issues. Deposited material can be fabricated by two UV curing options (Major cure or spot curing). The right choice of UV curing source and its set parameters affect directly the quality of fabrication. Formula is used to set UV parameters to gain more control and to improve its curing quality (See chapter 5 & appendix D for design details).

- **To conduct detailed design of feeding apparatus for the proposed *M^2-3D Printer:*** Feeding apparatus design comes with seven tanks for different materials. Material is feed to the Nozzle apparatus by pumping the material from the tanks, through flow pipes. Off the shelf pressure control valves are used to control the pressure in the flow pipes See chapter 5 & appendix D for design details).

- ***Algorithm design for better slicing and control of the Nozzle system:*** A detailed literature review of the available RP&M system, its processes and software has identified many problems such as accuracy, quality and process repeatability. It is concluded that STL file format is designed to represent one material type CAD models, comes with inherent issues of inaccuracy with respect to dimensional representation and requires large storage space for complex CAD model representation. Therefore a NURBS based slicing algorithm is developed for multi-material representation of CAD model to improve the quality of the RP&M components in terms of better geometrical representation of multi material objects. Developed NURBS-based slicing algorithm can maintain the geometrical accuracy of original CAD model and to support multi-material RP technology. In addition, a nozzle change algorithm was also developed to reduce the build time of fabrication and to support the design of M^2-3D Printer.

Table 7.1 Multi Material RP&M Technology Comparison with proposed feasibility model of M^2-3D Printer

Multi Material RP&M Technology Comparison	More than Two Material Deposition	Two Material Deposition	FGM Deposition	Under- fill Problem	Over-fill Problem	Print Quality	Number of Nozzles	Material Choice
Jafari and Han et al (2000) FDMC system	N	Y	N	3	3		Four	2
Yang and Evans (2004) FGM powder deposition apparatus	N	N	Y		3	2	One	
Khalil and Sun's (2005) Multi-material FDM system	N	Y	N	3	3		Four	2
Weiss and Amon (2005) fibrin based scaffolds RP system	N	Y	N				Four	2
Liew et al (2001 & 2002) dual material fabrication method	N	Y	N			2		
Ram et al (2007) UC processing method	N	Y	N			2		
Beal et al (2004) X graded powder deposition system	N	N	Y			1		
Mazumder et al. (2003) FGM fabrication method	N	N	Y			1		
Chiu and Yu (2008) direct digital manufacturing methodology	N	N	Y			1		2
Morvan et al (2001) heterogeneous flywheel fabrication by LENS	N	N	Y			1		
Kieback et al (2003) FGM fabrication on powder based 3DP system	N	N	Y			1		
Kieback et al (2003) FGM fabrication on SLS system	N	N	Y			1		
Kieback et al (2003) FGM fabrication on FDM system	N	N	Y			1		
Kieback et al (2003) FGM fabrication on SLA system	N	N	Y			1		
Syed I (2011) Feasibility Design of M^2-3D Printer	Y	Y	N	1*	1*	4*	Seven	4

Range (1Low – 5 High)
Range increases from 1 low to 5 High
S-M = Single-Material
Y = Yes, N = No
* = Needs to be tested physically.

Note: Columns are left empty where no information is available from literature sources.

Future work and recommendations:

The further work should be carried out in future research and development of the presented concept of multi-material nozzle deposition system to support a fully functional multi-material 3D printer ("M^2-3D Printer"). Presented research can be used as a feasibility study for the proposed M^2-3D Printer system so more research needs to be carried out in implementation of this concept design into a working prototype model. More research should be carried out in developing algorithms for the multi-nozzle control and positioning for accurate and precious deposition.

The research areas which need further research and development are:

- First prototype needs to be manufactured for the physical testing of multi-material nozzle deposition system which can fabricate objects with more than two materials.
- Further develop an algorithm for the better control of multiple nozzle system which can help improve the fabrication quality and process time.
- A better statistical quality and control data needs to be developed with respect to the current RP&M systems which can be used as a benchmark for the manufacturing industry.
- A wide range of materials need to be developed which can be used as an alternative to the materials used in conventional manufacturing.
- A better statistical data with respect to testing and quality needs to be developed for the available variety of RP&M materials which can be used as a benchmark for the manufacturing industry.

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Appendix A – Prototyping

A.1 Types of Prototypes

For contemporary product development processes, six general classes of prototypes are typically used (Otto & Wood, 2001):

1. Proof of concept models: They are usually fabricated from simple, readily available materials, they focus on a component or subsystem of the product. They are constructed usually during concept selection and product embodiment. The general question proof of concept answer is whether the imagined physics of the concept on the paper indeed actually happen and what any unforeseen physics might be.
2. Industrial design prototypes: They demonstrate the look and feel of the product. In general they are initially constructed out of simple materials such as foam or foam core and seek to demonstrate many options quickly.
3. Design of Experiments (DOE) experimental prototypes: DOE experimental prototypes are focused physical models where empirical data is sought to parameterise, layout, or shape aspects of the product.
4. Alpha prototypes: The alpha is the first system construction of the subsystems that are individually proven in the subsystem DOE prototyping and design. Alphas also usually include some functional features for testing and measurements of the product system.
5. Beta prototypes: Beta prototypes are the full scale functional prototypes of a product, constructed from the actual materials as the final product.
6. Preproduction prototype: These prototypes are used to perform a final part production and assembly assessments using the actual production tooling.

A.2 Roles of Prototypes

The prototypes play key roles in the product development process which include the following (Chua, Leong& Lim, 2003):

- Experimentation and learning: Prototypes can be used to help the thinking, planning, experimenting and learning process while designing the product.
- Testing and proofing: Prototypes can also be used for testing and proofing of ideas and concepts relating to the development of the product.

- Communication and interaction: Prototypes also serve the purpose of communication information and demonstrating ideas, not just within the product development team, but also to management and client.
- Synthesis and integration: Prototype can also be used to synthesise the entire product concept by bringing the various components and sub assemblies together to ensure that they will work together. This helps in the integration of the product and surface any problems related to putting the product together.
- Scheduling and markers: Prototyping also serves to help in the scheduling of the product development process and is usually used as markers for the end or start of the various phases of the development effort.

Appendix B – Literature Review Extended

B.1 Historical development of RP Technology

Table B.1 Recent Developments of Rapid Prototyping and related technologies (Wohlers Associates,2008 and Chua, Leong & Lim, 2003).

Years	Technology
2008	Solidscape Introduced T76 precision wax printing
	Optomec Released its new LENS MR-7 with fiber laser, dual powder feeder & integrated thermal imager for process monitoring
	3D Systems introduced iPro 9000 SLA Centre as a replacement to Viper Pro
	MTT Technologies released a larger selective laser melting machine SLM 250-300
	Z Crop Released 24bit colour printer ZPrinter650
	EOS unveiled a new large frame, high temperature, laser sintering platform EOSINT P 800
2007	3D Systems released V-Flash 3D printer & the next version of its Multi-Jet modelling machine, the ProJet HD3000
	Stratasys launched the new Dimension Elite 3D printer
	Solidscape released to market specific version of T66 Machine • D66 – Digital Dental Modeling system • R66 – For jewellery applications
	Z Crop introduced a truly office friendly ZPrinter 450
	Arcam introduced its larger build volume A2 electron beam melting (EBM) machine
	Stratasys announced its FDM 200mc, FDM 360mc, FDM 400mc & its large frame FDM 900mc
	Voxeljet introduced its VX500 system, a smaller version of the VX800
2006	Object Geometries introduced its Eden350/350V platform
	3D Systems announced its Vision DP (dental professional) system
	Stratasys introduced the Dimension 1200BST and SST systems
	EOS introduced Formiga P 100 laser sintering system
	EOS also introduced EOSINT P 390 & EOSINT 730
	Voxeljet Technology introduced its VX800
	MTT Technologies introduced its new SLM ReaLizer 100 selective laser melting machine
2005	Z Corp released its latest colour 3D printing system, the Spectrum Z510
	3D systems unveiled the Sinterstation Pro
	Object Geometries introduced the Eden500V
	MTT Technologies introduced the SLM ReaLizer 100
2004	Stratasys introduced the “Triplets” which consists of three variations of the FDM Vantage machine
	Envisiontec introduced the Vanquish photopolymer based system
	3D systems introduced its dual-vat Viper HA stereolithography system for hearing aid industry.
	Solidscape introduced the T66 Benchtop & T612 Benchtop systems
2003	Z Crop introduced its ZPrinter 310 system

	Solidscape introduced its T612 system for making wax patterns for investment castings
	3D Systems began to sell its In Nision 3D printer
	EOS introduced its EOSINT M 270 direct metal laser sintering machine
	Trumpf introduced its TrumaForm LF and TrumaForm DMD 505 machines
2002	Stratasys introduced its Dimension product
	Envisiontec GmbH began to sell its prefactory & Bioplotter machines
	Solidscape introduced its T66 product
	Phenix Systems of France sold its first Phenix 900 System
	POM began to sell its direct metal deposition machine
	Menix, Co., Ltd. Of Korea introduced its first VLM300 variable lamination machines
2001	Object Geometries began to sell a beta version of its Quadra 3D printer
	Stratasys began the commercial shipment of its FDM Titan
	Z Crop. Introduced its Z810, a system that prints parts in a 500 x 600 x 400 mm build volume.
	Generis GmbH of Germany Commercialised its large GS 1500 system used to produce sand cores and molds for metal castings.
	EOS announced its DirectSteel 20-V1 peoduct, a steel based powder consisting of particles 20microns
2000	Sanders Design International developed Rapid ToolMaker (RTM)
	Object Geometries of Israel announced Quadra
	Precision Optical Manufacturing (POM) announced direct metal deposition (DMD)
	ZCorp. introduced its Z402C machine, world's first commercially available mutli-colour 3D printer
	Stratasys introduced Prodigy, a machine that produces parts in ABS plastic
1999	3D Systems introduced: • ThermoJet a faster & less expensive version of Actua 2100 • SLA 7000 system
	Roders began to sell its controlled metal build-up (CMB) machine
1998	Autostrade introduced its E-DARTS stereolithography system
	Optomec commercialised its laser-engineered net shaping (LENS) metal powder system.
1997	AeroMet developed a process called laser additive manufacturing (LAM)
1996	Stratasys introduced the Genisys machine, which used an extrusion process similar to FDM
	3D Systems sold its first 3D printer Actua 2100
	Z Crop. Launched its Z402 3D printer
	BPM Technology sold Personal Modeler 2100 commercially
1995	Japan's Ushio (now called Unirapid Inc.) sold its first stereolithography machine
1994	Solidscape launched ModelMaker machine
	EOS commercialised a EOSINT machine based on laser sintering technology
1993	Soligen commercialised direct shell production casting (DSPC)
1992	DTM commercialised Selective laser sintering (SLS)
	Teijin Seiki launched Soliform stereolithography system

1991	Stratasys commercialised fused deposition modelling (FDM)
	Cubital launched solid ground curing (SGC)
	Helisys commercialised laminated object manufacturing (LOM)
1990	Electro optical systems (EOS) sold its first Stereos stereolithography system
	Quadrax introduced the Mark 1000 SL system
1988	3D Systems commercialised first stereolithography machine SLA-1

B.2 Classification of Rapid Prototyping Processes

Usually RP systems are classified according to different methods used. The three famous classifications of RP process are given by Burns, Jerome, Kochan and Chua.

Categorisation of RP&M process by Kochan & Chua:

Kochan and Chua (1995) classify RP&M process by the initial form of its material and method. They have grouped the RP&M processes under solid, liquid and powder. However under each group the RP&M processes are further classified into the different methods adopted which includes (Cornelius & Leondes, 2003):

- Lamps
- Holography
- Masked lamp
- And joining
- Cutting and gluing
- Melting and solidifying
- Single or dual laser beams

Burns Classification:

According to M. Burns (1993) RP processes can be classified into additive and hybrid processes. Additive process is further characterised under different techniques used by the RP&M systems such as (Cornelius & Leondes, 2003):

- Laser curing,
- Laser sintering, and
- Masked lamp curing,
- Droplet deposition

Adhesion of cut sheet such as laminated object manufacturing (LOM) is characterised by Burns as a hybrid subtractive/additive process because the contour of the cross section and unwanted parts are cut by laser after being bonded to the previous layer.

Jerome's Classification:

Jerome L Johnson (1994) classified the RP&M process according to the method of controlling layer fabrication. The interaction of raw material mass m and energy W produces the physical layer in a total variation occurring as (Cornelius & Leondes, 2003):

Jerome explains the equation in two terms:

1. ***(mW)**: First term represents a process where a uniform mass ***m*** is selectively activated, removed, or bonded by a variable energy ****W*** controlled by the layer description. Under this variable energy process molecular bonding, particle bonding and sheet lamination can be classified.
2. ***m*W + W*m*** : Second Term represents process where layer information controls a variable mass ****m*** acted on by a control energy *W*. Under this variable mass process droplet deposition, particle deposition and melt deposition car classified.

B.3 3D Systems' Stereo lithography Apparatus (SLA)

Advantages of SLA:

Key advantages and features of SLA system are (3Dsystems.com, 2011)

- SLA systems can be used continuously and unattended round the clock
- SLA systems are available with different build size configurations:

  Small – 250 x 250 x 250 mm
  Large – 737 x 635 x 533 mm
- SLA systems generally have good accuracy and can achieve excellent part feature details and definition.
- SLA can obtain good surface finish with minimum post process finishing requirements
- A wide range of materials are available from general purpose to specialty materials for specific applications
- SLA systems comes with Automatic material refill and levelling

Images removed

Figure B.1 Viper SLA system *(3Dsystems.com, 2011)*

Figure B.2 Viper Pro SLA system *(3Dsystems.com, 2011)*

Disadvantages of SLA:

Requires support structures: Structures which overhang and undercuts must have supports, however, removing supports is a time consuming and delicate task (See figure B.3).

All SLA fabricated objects require post processing task which include:

- Cleaning
- Post Curing
- Finishing

Figure B.3 Fabricated object (additive3d.com, 2011)

Applications of SLA:

Table B.2 Applications of SLA

Models	For conceptualisation For Packaging For Presentation	Image removed	**Prototypes**	For Design, For analysis, For verification For functional testing
Parts	For prototype tooling For low volume production tooling	Figure B.4 Viper System (3Dsystems.com, 2011)		
Tools	For fixture design For tooling design For production tooling	**Applications of SLA** (Chua, Leong& Lim, 2010)	**Patterns**	For investment casting For sand casting For molding

Custom Turbines:

3D Systems iPro 9000 SLA capability helped Tushino Power Machine Tools to convert the design of their customised turbines into a master pattern casting. This enabled (Tushino Power Machine Tools) to print QuickCast patterns that reduced the production cost and time of customised turbines and improved the operating efficiency to +20% (Ashrapov, 2010). The QuickCast SL master pattern, produced with Accura 60 SLA material is a pattern that weights just 70 Kg (Shown in figure 1.9), while the final cast model weighs 1990 Kg (shown figure B.5) (3DSystems.com, 2011).

Figure B.5 Accura 60 SLA material pattern

Figure B.6 final cast model

SLA technology is now being used in jewellery manufacturing industry to produce high resolution parts used for jewellery design validation, communication, aesthetics and as direct patterns for flask casting (gizmag.com, 2011).

Image removed

Figure B.7 Jewellery Design (gizmag.com, 2011)

B.4 Cubital's Solid Ground Curing (SGC)

Cubital's RP technology creates highly physical models directly from computerised data files. Solid ground curing (SGC) like SLA use ultraviolet light to selectively harden photosensitive polymers. But unlike SLA, SGC cures an entire layer at a time. Figure B.8 depicts solid ground curing, which is also known as the solider process (Palm, 2002).

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Figure B.8 Schematic diagram of solid ground curing (stereolithography.com, 2011)

Process:

- First, photosensitive resin is sprayed on the build platform.
- Then machine develops a photomask of the layer to be built. This photomask is printed on a glass plate above the build platform using an electrostatic process similar to that found in photocopiers.
- The mask is then exposed to UV light, which only passes through the transparent portions of the mask to selectively harden the shape of the current layer (see figure B.8).
- After the layer is cured, the machine vacuums up the excess liquid resin and sprays wax in its place to support the model during the build.
- Top surface is milled flat, and then the process repeats to build the next layer.
- When the part is complete, it must be de-waxed by immersing it in a solvent bath.

Material:

Cubital's SGC system uses several kinds of resins, as shown in figure B.9:

- Liquid and cured photopolymer resins are used as build or primary materials.
- Water soluble wax is used for building support structure or secondary material.

Image removed

Figure B.9 Cubital's Solimer resin (eng.nus.edu.sg, 2011)

Software:

CAD model is transferred into Cubital's Solider Data front end (DFE) workstation mainly in STL format. Cubital's DFE software has edit and file manipulation capabilities where CAD model can be rendered for visualisation purpose, searched and corrected of flows. This software can prepare in adequate STL files for processing on any RP system. Some of the key features of DFE software are shown in figure B.10

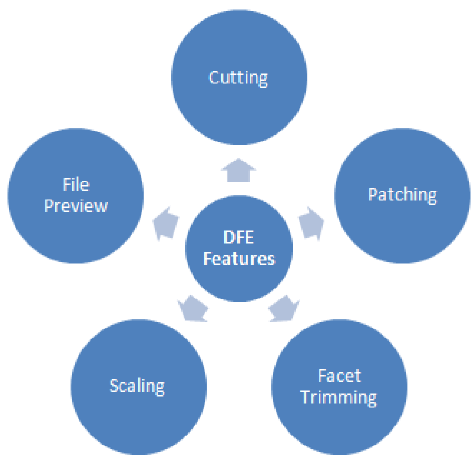

Figure B.10 Features of Cubital's Solider of DFE software

Advantages of SGC:

Key advantages and features of Cubital Ltd.'s Soldier 5600 stereolithography system are (3Dsystems.com, 2011):

- Parallel Processing: Point by point curing is a slow and time consuming process, where as Soldier system can cure the whole cross-sectional layer area instantly, which can help reduce the production time and cost significantly.

- Self supporting: Unlike the SLA systems, Solider systems' solid modelling environment provides an unlimited geometry, where solid wax supports the part in all dimensions.
- Solider systems' have good fault tolerance, where changeable layers:
  - Allow job changing during a run.
  - Make it possible to erase faulty layers.
- Instant cure of a whole cross-sectional layer minimises the shrinkage effect and minimises the development of internal stresses which result in high structural strength and stability.
- Solider system produces parts which exhibit unique properties (shown in figure B.11).

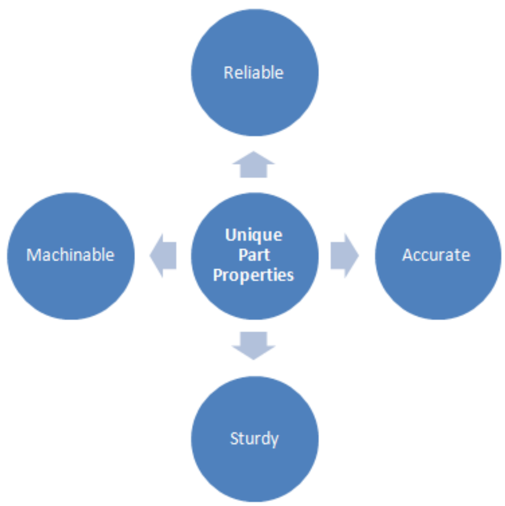

Figure B.11 Solider Part Properties

Disadvantages of SGC:

- Solider system requires large physical space (see figure B.12).
- Solider system generates high noise level.
- Sporting wax gets stuck in corners and is difficult to remove from parts with complex dimensions

Image removed

Figure B.12 Cubital's Solider 5600 (eng.nus.edu.sg, 2011)

Applications of SGC:

Table B.3 Applications of SGC

Models	For conceptualisation For Presentation	Images removed	**Prototypes**	For Design, For analysis, For verification For functional testing
Parts	For prototype tooling For low volume production tooling	Figure B.13 (turkcadcam.net, 2011)	**Patterns**	For investment casting For sand casting For molding
Tools	For fixture design For tool free manufacturing For production tooling	Figure B.14 (Kasetsart University, 2011) **Applications of SGC** (Chua, Leong& Lim, 2010)		

B.5 D-MEC's Solid Creation System (SCS)

The D-MEC's solid creation system is based on the principle of polymer curing by ultraviolet light and manufacturing by layering. The basic operation and techniques used are very similar to 3D System's SLA unit.

Process: The complete process cycle of SCS system comprises of five steps, which are:

- 3D CAD model is generated using available CAD packages.
- SCS software is used for CAD model slicing and support structure generation.
- UV laser scans the resin surface to draw the cross sectional shape based on the data (figure B.15).
- After a layer is cured, elevator descends to start the scanning process for the next layer (figure B.16).
- Prototype model is completed after repeating the scanning and elevating process, and then elevator is raised to start the post curing treatment.

Images removed

Figure B.15 SCS Process (d-mec.co.jp, 2011)

Figure B.16 SCS Process (d-mec.co.jp, 2011)

The parameters which affect performance and functionality of the machine are:

Table B.4 SCS Process Parameters (Source: Chua, Leong& Lim, 2003)

Parameters	
➢ Scanning pitch	➢ Step period
➢ Step size	➢ Scanner delay
➢ Jump size	➢ Jump delay
➢ Scanning pattern	➢ Resin's properties

Material: SCS system uses UV curable resins which are initially in liquid state. SCS-1000HD to SCS-9000 machines use epoxy resins provided D-MEC Corporation, which are highly recognised by the industry.

High toughness Resins

SCR710, SCR720, SCR735, SCR11120 & SCR9120

Figure B.17 Dehumidifier(total 5 parts)

Super Heat Resistant Filler Resin

SCR802

Figure B.18 Aluminum wheel (1/2 plated)

High Precision and High Resolution Resin

SCR751 & SCR950

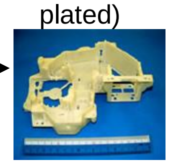

Figure B.19 Lost wax master

Software:

SCS system requires files in D-MEC's slice data format (SCDB) which is prepared by using Magics and SolidWare software (see figure B.20 and B2.1). Magics software is produced by Materialise Corporation, which is used:

- ➢ To display and measure STL
- ➢ To correct and edit STL
- ➢ For support creation
- ➢ To prepare SCDB file format

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Figure B.20 Magics Software (d-mec.co.jp/eng, 2005)

Figure B.21 Solid Ware Software (d-mec.co.jp/eng, 2005)

D-MEC's Solid Ware software requires SCDB file, which offers to:

- Browse slice data.
- Autometically detect layers with error.
- Provides option of adding, combing and delting lines.
- Merging two or more models.

Advantages of SCS:

Key advantages and features of D-MEC's SCS systems are (d-mec.co.jp/eng, 2011):

- D-MEC SCS systems come with large build volume which makes it possible to produce large prototypes.
- High accuracy models can be produced with 0.04mm repeatability.
- D-MEC system come with a wide range of materials, as shown in figure B.22:

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Figure B.22 Variety of Resins (Chua, Leong& Lim, 2010)

Disadvantages of SCS: SCS models requires support structures to support objects with overhang and undercuts, however, removing supports is a time consuming and delicate task which leads to a post processing process of cleaning. Some of the object may also require post curing to ensure structural integrity.

Applications of SCS:

Table B.5 Applications of SCS

Models	For conceptualisation For Presentation For process planning	Images removed Figure. B.23 Light cover (d-mec.co.jp/eng, 2011)	**Prototypes**	For Design, For analysis, For verification For functional testing
Parts	For low volume part production Figure B.25 Projector Body (d-mec.co.jp/eng, 2011)	Figure. B.24 Large manifold (d-mec.co.jp/eng, 2011) **Applications of SCS** (Chua, Leong& Lim, 2010)	**Patterns**	For investment casting For sand casting For molding

B.6 Cubic Technologies' Laminated Object Manufacturing (LOM)

This method is often applied to large models that require particularly robust properties. Surface finishing by hand is needed to remove layer steps. The models can be used for visualization, replication masters and patterns, particularly sand casting. A variation on this method permits manufacture of low cost, hand assembled plastic parts using sheet cutting technology, but necessitates considerable hand finishing to conceal or remove stepping. The LOM process consists of three phases:

- Pre-Processing
- Building Process
- Post-Processing

Process: In pre-processing, slice layer data file of STL CAD model is prepared by using LOMSlice software, this process is explained in detail under the software topic below (see figure B.26).

The building process consists of following steps (Chua, Leong& Lim, 2010):

- LOMSlice creates a cross section of the 3D model by measuring the height of the horizontal layer. Software then images the crosshatches which define the out perimeter and convert the excess material into a support structure.

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Figure B.26 LOM Process (msoe.edu, 2011)

- Laser beam then cuts the cross section outline, crosshatches and model's perimeter.
- Platform then descends with the stack of previously formed layer. Then a new section of material advances on top of the previous layer and then laminated with the stack by a headed roller in a single reciprocal motion.
- This sequence is repeated until a all the layers are built, which ends up with a complete prototype in rectangular block.

The main parameters which influence performance and functionality of the parts are shown in figure B.27:

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Figure B.27 Performance and functionality parameters (Chua, Leong& Lim, 2010)

Material: Material in LOM system is used in sheet form, which is cut by a high precision laser according to the cross section projected for each layer. This ability if LOM system makes it possible to increase the range of materials which can be used. The main feature for any material to be used in LOM system is to be available in a sheet form with adhesive backing. Whereas, Kraft paper with a polyethylene based heat seal adhesive system is the most popular, cost effective and widely available material. Other ranges of materials which can be used in sheet form are shown in figure B.28

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Figure B.28 Variety of Resins (Chua, Leong& Lim, 2010)

Software:

A 3D CAD model is generated and transferred into LOMSlice software provided by the LOM systems (see figure B.29). LOMSlice is used to pre-process the STL file and control the LOM machine. Some of the automated features of LOMSlice include:

- View STL Model.
- Sorting input data.
- Creating secondary data structures.

Image removed

Figure B.29 The main Lomslice screen(mne.psu.edu, 2011)

Whereas, following functions have to be done manually on LOMSlice:

- Orienting.
- Translation.
- Mirroring
- Scaling
- Merging

Advantages of LOM:

Key advantages and features of LOM systems are:

- LOM systems come with fast build time as it only scans the outline cross section of the each layer to be cut. Layers with considerably large thickness cut as fast as the layers with small thickness which makes it possible to build large and bulky parts.

Figure B.30 LOM-1015Plus (itgo.com, 2011)

- LOM systems can produce parts with high accuracy and precision (better than 0.127 mm).
- LOM system come with a wide range of materials as any material in sheet form can be used.
- LOM can produce parts with no or minimum shrinkage which does not affects the model.

Disadvantages of LOM:

- When different material layers or layers of different thickness are being used in a model, it is important to adjust the laser power precisely as it can over cut or under cut a layer.
- Fabrication of thin walls: The process is not well suited for building parts with delicate thin walls.
- Integrity of prototype entirely depends on the adhesive strength of the glue used.
- Removal of supports is the most labour intensive process in post processing as shown in Figure B.31

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Figure B.31 Support Removal process (Chua, Leong& Lim, 2010)

Applications of LOM:

Table B.6 Applications of LOM

Models	For conceptualisation For Packaging For Presentation	Images removed Figure B.32 LOM-2030H (multistation.com, 2011) **Applications of LOM** (Chua, Leong& Lim, 2010)	**Prototypes**	For Design evaluation, For analysis, For verification For basic testing
Patterns	For investment casting For sand casting For molding For injection Moulding		**Tools**	For tooling design Figure B.33 Engine Block (cubictechnologies.com , 2011)

B.7 Stratasys' Fused Deposition Modelling (FDM)

Advantages of FDM:

Key advantages and features of FDM systems are:

Images removed

- Fabrication of functional parts: FDM models made from ABS and ABSplus materials can be used to produce fully functional parts which in some cases have the strength of moulded parts (see figure B.34).
- Minimal wastage: FDM models are fabricated by depositing semi melted material only where build and support material is required, therefore material wastage is very low.
- Ease of support removal: With FDM's break away support system (BASS) and WaterWorks Soluble Support System, support material can be easily broken off or washed away (see figure B.35).
- Ease of material change: Build and support material are available in spool and cartridge form which can be easily changed (see figure B.36).
- FDM 900mc and Maxum offer a large build volume, which can be used to fabricate large models or multiple parts at the same time.

Figure B.34 Functional Parts (itgo.com, 2001)

Figure B.35 Support material (pddnet.com, 2010)

Figure B.36 Material Spool (makerbot.com, 2011)

Disadvantages of FDM:

The three most common problems in FDM system are (Chua, Leong& Lim, 2010):

- The typical build material comes with a diameter of 1.27mm, which sets a limit on the part accuracy.
- Building speed of FDM is slow as compared to other AF processes, the material properties of plastics make it difficult to speed up the extrusion process or flow rate of materials.
- Unpredictable shrinkage and distortions caused by rapid freezing is a common problem in FDM models, which can be limited by controlling the process parameters.

Applications of FDM:

Table B.7 Applications of FDM

Models	For conceptualisation For Presentation	Imnages removed	**Prototypes**	For Design evaluation, For analysis, For verification For functional testing
Patterns	For vacuum foaming For investment casting For sand casting For moulding	Figure B.37 3D Production system (stratasys.com, 2011) **Applications of FDM** (Chua, Leong& Lim, 2010)	Figure B.38 Conceptualisation and functional Model (dimensionprinting.com, 2011)	

B.8 3D Systems's Selective Laser Sintering (SLS)

SLS Materials:

- Polyamide: This material is used to create rigid and rugged plastic parts for functional engineering environments. The trade name for this material is "DuraForm".
- Thermoplastic elastomer: Flexible, rubber like parts can be prototyped using SLS. Trade named "SOMOS 201", the material produces parts with thigh elongation. The material is impermeable to water and ideal for sports shoe applications and engineering seals.
- Polycarbonate: These are suitable for creating concept and functional models and prototypes, investment casting patterns for metal prototypes and cast tooling, masters for duplication processes, and sand casting patterns.
- Nylon: It is one of the most durable rapid prototyping materials currently available in the industry, and it offers substantial heat and chemical resistance. It is durable, resistant to heat and chemicals, and is excellent when fine detail is required.
- Metal: This is a material where polymer coated stainless steel powder is infiltrated with bronze. Trade named "LaserForm ST-100" exhibits high durability and thermal thermal conductivity and can be used for relatively large scale production tools.

- Ceramics: Trade named "SandForm Zr" and "SandForm Si", these use zircon and silica coated with phenolic binder to produce complex sand cores and molds for prototype sand castings for metal parts.

Advantages of SLS:

Table B.8 Advantages of SLS (Todd Grimm, 2004, User's Guide to Rapid Prototyping)

Stability	Plastic material: The plastic prototypes produced in SLS are dimensionally stable once they are removed from system and cooled. The prototypes will not shrink, warp, or distort as long as excessive heat is avoided. Metal material: The parts produced are dimensionally stable once fully infiltrated. Dimensional accuracy can be degraded if care and caution are not exercised during the furnace cycle, where binder is burned off and bronze is infiltrated.
Feature Definition	For SLS devices the spot size of laser dictates the minimum feature size. The laser has a diameter of 0.46mm but due to the nature of the technology, surrounding material often fuses to the part even if the laser does not directly contact it. This yields a typical minimum feature size of 0.64mm. In terms of metal parts, from the machine and prior to infiltration, the green part has little strength. Therefore, evacuating powder that surrounds small features can easily result in damage. So a minimum feature size for metal part or tool ranges from 0.76-2.54mm.
Machinability	SLS prototypes and tools produced in the thermoplastic and metal materials can be easily machined. However the machined area can melt if cutting speeds are too high, with the polyamide based DuraForm.
Environmental Resistance	SLS prototypes provide material properties similar to those of the thermoplastics on which they are based, including resistance to environmental exposure. The polyamide materials can withstand moisture, heat up to 163^{o} C, and many SLS materials are reporter to withstand exposure to chemical agents.

Process Time	The time for the SLS process is dependent on many variables, including part volume, build height, build style and material. There are gains in speed when multiple parts are constructed in one machine run.
Support Structure	SLS does not require any form of support structure. The powder that surrounds the sintered material acts a as a fixture by ensuring the prototype is a “cake”. When a build is complete, brushing, vibrating, or air blasting the cake will expose the prototype to complete all required processes.
Post Build Processing	The SLS prototype is enclosed in unsintered powder when removed from the system. The excess material is removed to yield the finished prototype, in most cases this process is completed quickly. The metal prototypes and tools are heated in a furnace over 24 hour period to burn off the binder and infiltrate with bronze.

Disadvantages of SLS:

Table B.9 Disadvantages of SLS (Todd Grimm, 2004, User’s Guide to Rapid Prototyping)

Dimensional Accuracy	SLS have reasonable accuracy, but the materials have shrinkages of 3.0 - 4.0%. The SLS process is less predictable and controllable since it relies on raising the temperature of the powders to just below their melting points. The results may vary with part geometry, size and operational conditions.
Surface Finish	Surface finish mainly depends on the powder particle size. With the finer powders, surface finish can be improved. However due to the sintering process of SLS, all surfaces demonstrate rough and porous qualities.
Feature Definition	For SLS devices the spot size of laser dictates the minimum feature size. The laser has a diameter of 0.46mm but due to the nature of the technology, surrounding material often fuses to the part even if the laser does not directly contact it. This yields a typical minimum feature size of 0.64mm. In terms of metal parts, from the machine and prior to infiltration, the green part has little strength. Therefore, evacuating powder that surrounds small features can easily result in damage. So a minimum feature size for metal part or tool ranges from 0.76-2.54mm.

Machinability	SLS prototypes and tools produced in the thermoplastic and metal materials can be easily machined. However the machined area can melt if cutting speeds are too high, with the polyamide based DuraForm.
Physical Size	The Vanguard si2 and its predecessor, the Sinterstation 2500 plus, provides a usable build envelope of 330 X 279 X 381 mm. However, the physical work envelope is larger than these specifications, but the usable work volume is limited by system operating parameters.

B.9 Z Corporation's three Dimensional Printing (3DP)

3DP creates parts by a layered printing process and adhesive bonding, based on sliced cross sectional data. Parameters that influence the performance and functions of the process are:

- The properties of the powder,
- The binder material and
- The accuracy of the XY table and Z-axis controls.

Table B.10 Advantages & Disadvantages of 3DP (Source: Chua, Leong& Lim, 2003)

Z Corporation's three Dimensional Printing (3DP)	
Advantages	**Disadvantages**
High speed	Limited functional parts
Versatile	Limited materials
Simple to operate	Poor surface finish
No wastage of materials	
Colour: Enables complex colour schemes in rapid prototyped parts	
No post curing required	
Large parts can be built	

B.10 Soligen's Direct Shell Production Casting (DSPC)

The principle of Soligen's DSPC is based on three dimensional printing. DSPC deposits liquid bind onto ceramic powder to form shells for use in the investment casting process. A technology invented, developed and patented by the MIT. Parameters that influence performance and function are:

- The layer thickness
- The binders pressure
- The powder's properties
- The pressure of rollers

Table B.11 Advantages & Disadvantages of DSPC (Source: Chua, Leong& Lim, 2003)

Soligen's Direct Shell Production Casting (DSPC)	
Advantages	**Disadvantages**
Patternless casting	Limited materials
Functional metal parts	
Net shaped integral molds	

B.11 Fraunhofer's Multiphase Jet Solidification (MJS)

The basic concept of the MJS process is comparable to the FDM process with regards to the deposition of low viscosity molten material layer by layer with a nozzle system. The main difference between the two processes is the raw material used to build the model and the feeding system. The parameters influence the performance and functions of this process are:

- The layer thickness
- The feed material

And the variables include:

- Chamber pressure
- Jet specification
- Operating temperature
- Machining speed
- Material flow
- Liquefied alloys or powder binder mixture

Appendix C – Research Analysis Extended

C.1 Challenges Related to RP&M Industry

Quality Standards Issues:

Quality or testing standards must be established for the RP&M systems. Specially how current additive processes and materials vary from system to system or from build to build, and standards to measure the quality of parts with respect to dimensional accuracy and material properties as they can be affected by the time lapse from when the part is build, tested and used. Currently few test results are published but to increase the confidence of the manufacturers, new testing and quality standards need to be defined

Fabrication Process Issues:

Mostly the additive processes used in the industry are designed for producing rapid prototypes. Whereas, same processes are used for the rapid manufacturing which face the problems like:

- Poor surface finish
- Tolerance control
- Poor process repeatability
- Fabrication capability with respect to material choice, as currently available RP systems can only fabricate with one build material.

Build Area/ Volume Issues:

RP&M systems produced by the manufacturers are mostly aimed for the prototyping market where build volume requirement is mostly small. Whereas, when the same machine is used for part production or RM, the build area limits the build size. Build volume also affects on the batch size which can be produced. Currently for small parts can be produced in considerable quantity per batch by using the ideal build orientations. Currently the largest machine has a build volume of 2100 x 640 x 600mm.

Process time:

Process time as compared to the conventional manufacturing is still considerably short. However, high speed additive fabrication regardless of build volume is an area still needs further development. Process time also includes the procedural demands of

AF processes, such as support structure removal. The support structure removal can increase the overall processing time when producing thousands of parts.

Quality control:

Some of the problems faced by the current RP&M systems explained above include issues with surface finish, tolerance control and process repeatability. Some of these issues are directly related to the materials used and the process of fabrication. The need of statistical data requirement for materials has been explained before. However, the need for in depth statistical data requirement for each system still needs to be developed. This data can not only identify the best practice to overcome the mentioned problems but can help identify developing issues.

Currently most of the work done by the researchers is focused on the control rather than on new processes. Like the conventional manufacturing processes, the principal for quality control with respect to process depends on the statistical process control and closed loop feedback subsystems. The development in enhanced process control will improve the quality of parts produced and boost the industries interest in adopting RP&M as a serious RM alternative.

RP&M Materials:

RP&M materials have gone through a lot of development in recent years. However, most of the materials still cannot be used as a possible alternative for majority of commercial products. Majority of materials are designed with respect to the RP&M system to produce prototypes.

Materials used for prototyping purpose have less requirements for example, surface finish, dimensional accuracy, mechanical and thermal properties etc. Whereas, RM requires more advanced materials which can satisfy the product standards so less materials can currently be used for commercial manufacturing.

C.2 Analysis of Current Research in Multi Material RP Technology

Jafari and Han et al (2000) developed a FDMC system at Rutgers University, which includes a novel deposition sub system, which can deposit up to two advanced ceramic materials. The deposition sub system shown in figure C.1 includes four deposition nozzles assembled for each material specifically, where two nozzles are used to deposit build material and two are used for support material deposition.

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Figure C.1 Deposition system of FDMC machine (Jafari & Han et al, 2000)

Although it's an advanced deposition system but it still comes with some issues:

- The deposition process is an open loop process due to which precise synchronisation between positioning and deposition sub system is not possible, the errors relating to this issue can be under-fills and overfills.
- Each deposition assembly is designed for a specific material so the material choice is very limited.
- Machine can use only two materials to fabricate an object.
- Limited choice of material also limits the use of machine to fabricate objects, currently it is being used to fabricate ceramic actuators and sensors.

Yang and Evans (2004) developed a unique powder deposition apparatus for fabrication of FGM objects by selective laser sintering, where the apparatus comes with only one deposition nozzle. A schematic diagram of powder delivery apparatus is shown in figure C.2. Overflow mass that continues to fall from the nozzle after vibration ceases can influence the deposition accuracy.

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Figure C.2 Schematic of a powder delivery apparatus for FGM fabrication (Yang & Evans, 2004)

Coventry University

Khalil and Sun's (2005) proposed Multi-material FDM system concept which compromises of four unique nozzles that can possibly be used for precious deposition of biopolymer and living cells, schematic diagram shown in figure C.3. The efficiency of deposition system is compromised due to the issues like deposition controllability, material structural and chemical properties. However, this precision can only be achieved if issues are overcome or minimised by selecting suitable materials, adjusting key process parameter settings regarding the toolpath and material deposition. Some general problems of layered manufacturing like under fills and over fills can be controlled by either designing advanced closed loop motion control or by detecting the defects at an early stage by analysing the layers online.

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Figure C.3 Schematic of multi-nozzle FDM system (Khalil & Sun et al, 2005)

Weiss and Amon (2005) developed a RP system to fabricate fibrin based scaffolds (see figure C.4). This method can only deposit two materials and is specifically designed for the bio medical fibrin based scaffold fabrication which needs to be further developed to be used on an industrial scale to develop new therapies.

Figure C.4 Multi-nozzle print head RP system for Multi-material scaffold fabrication (Weiss & Amon et al, 2005)

Liew et al (2001 & 2002) proposed a method for fabrication of dual material polymeric drug delivery devices. Delivery method is composed of two process models of SLS which can be integrated to form multi material fabrication technique as explained in literature review. Figure C.5 shows the layer produced by implementing the developed processes. However, success of the developed deposition system depends on the ability to incorporate a bioactive agent (a secondary support material) within a suitable biocompatible polymer which is a primary material, whereas, the toner detachment from the photoconductor directly affects the quality of powder deposition. The developed process is needs to be further developed as there are so many parameters affecting the quality of the biomedical fabricated structures.

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Figure C.5 Multi-material fabrication process (Liew et al, 2001 & 2002)

Ram et al (2007) examined the capability of ultrasonic consolidation (UC) and found that a lot of engineering materials can be bonded to alloy Al 3003 matrix with UC processing. The results suggested for the successful fabrication of part from metallic foils, it is important to set the process parameters for each fabrication considering the materials in use. The research done is aimed to show that multi material fabrication of materials which differ in the physical, chemical and mechanical characteristics is possible, however, more work needs to be done in defining the ideal process parameters for specific materials and there feasibility of Multi material fabrication using UC process.

Beal et al (2004) developed an X graded powder deposition system to fabricate some specimens with graded Cu within the H13 matrix. It is found that the dimensional accuracy of the X graded specimen are not good, whereas, the surface quality is very poor and the gradient is not continuous. More research needs to be done to remove the issues of surface quality, dimensional accuracy and best laser processing parameters need to be identified for each blend.

Mazumder et al. (2003) proposed a new method for design and fabrication of FGM objects with Direct Meta Deposition (DMD). The provided sample results show that overall powder mixture concentration is continuous. However, results also suggest that there are few points where the concentration changes suddenly. It is found that the surface quality is very poor and the gradient is not continuous. To improve this more research is need to be done on defining the process parameters for different powders. The error of powder mixer concentrations also needs to be addressed.

Chiu and Yu (2008) described a direct digital manufacturing methodology, which make it possible for fabrication of FGM prototype in 3D printing process. In this process, the binders used in the 3D printing system are diluted to different extents, which makes it possible to use the 3DP (3D Printing) system for FGM part fabrication with any major modifications. However, it also proposed that range of the binder concentration at present is very low which makes it impossible to fabricate an FGM object with a wide range of mechanical properties. There are also 3DP process performance issues which can result due to the change in the binder concentrations resulting into different viscosity values, which can cause problems such as clogging of printer nozzles and unstable binder droplets generation etc. Therefore, to improve the final quality of an FGM objects, the technical issues need to be addressed before the methodology can be implemented commercially.

Morvan et al (2001) fabricated a heterogeneous flywheel by LENS apparatus. However, the process planning stage was modified for the fabrication of an FGM object on a LENS apparatus. The fabricated flywheel indentified the quality issues and constraints such as thermal constraint build up and overheating of previously deposited layers which need to be addressed.

Kieback et al (2003) reviewed various available RP technologies to make FGM based products, such as the Powder based 3D Printer (3-DP), Laser Selective Sintering (SLS), Fused Deposition Modeling (FDM) and Stereolithography (SLA). The review presents further challenges such as repeatability of production processes when fabricating FGM parts, reliability of produced FGM parts, cost effectiveness of production process and the quality control which needs to be addressed to evolve the FGM applications.

Appendix D – Machine Design Snapshots

M²-3DP Machine Design

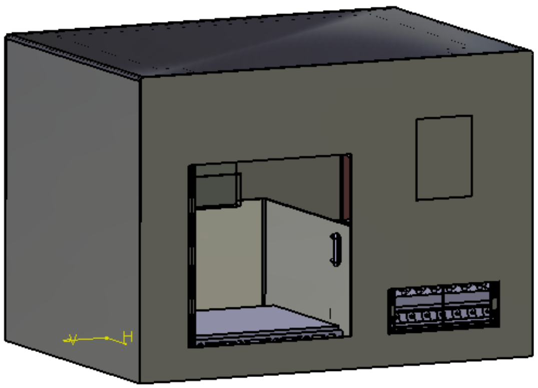

Figure D.1 M^2-3D Printer Machine Design

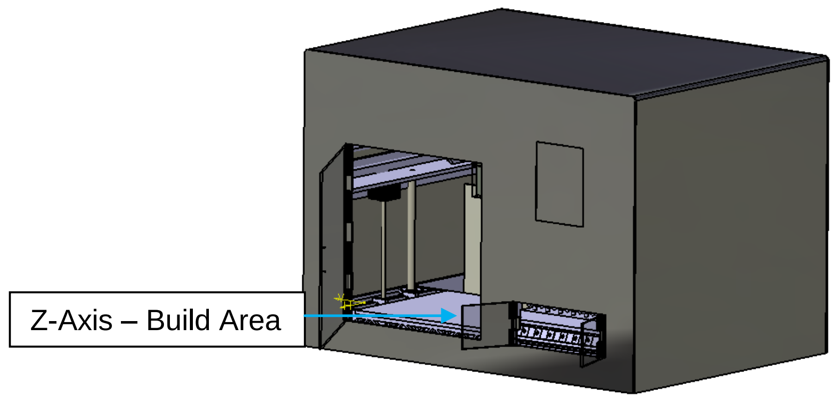

Figure D.2 M^2-3D Printer Machine Design

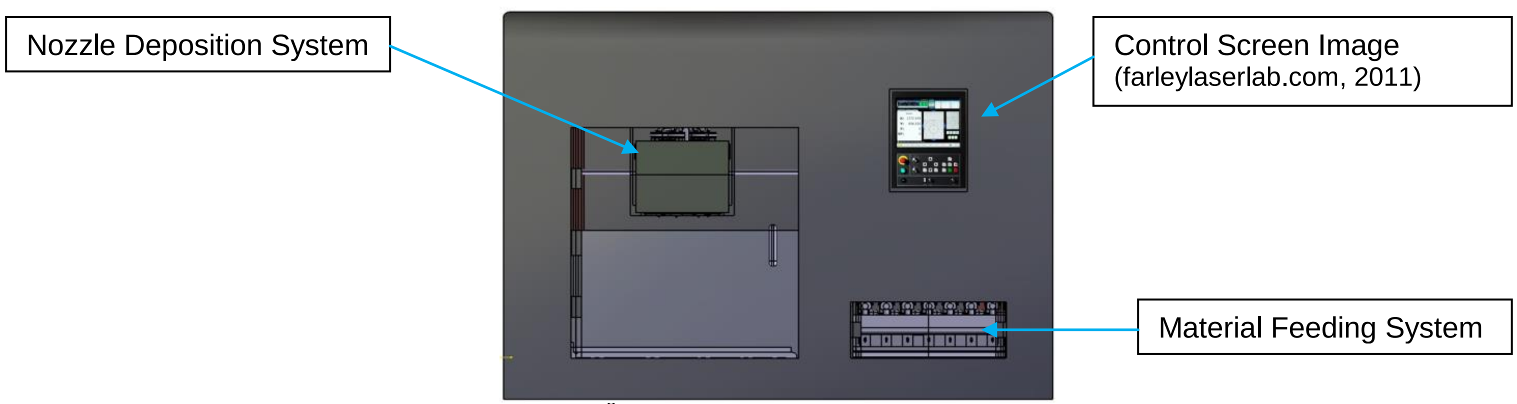

Figure D.3 M^2-3D Printer Machine Design – Front View

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M²-3DP Machine Design - Body Panels

Figure D.4 Front Panel Cover Assembly

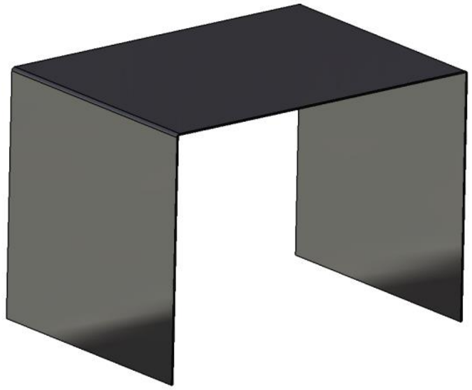


Figure D.5 Top Body Cover

Figure D.6 Back Panel Cover

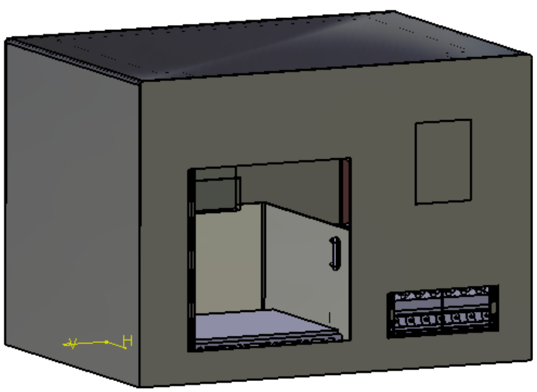


Figure D.7 Machine with Body Panel Covers

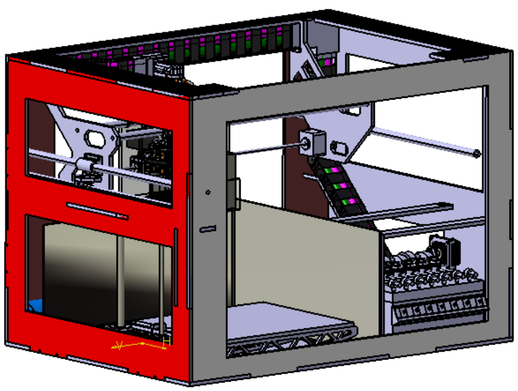


Figure D.8 Machine without Body Panel Covers

M²-3DP Machine Design - Body Panels

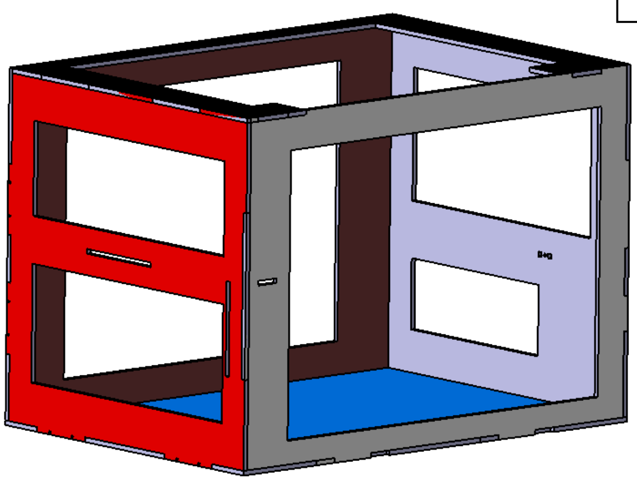


Figure D.9 Machine Structure Panel Assembly

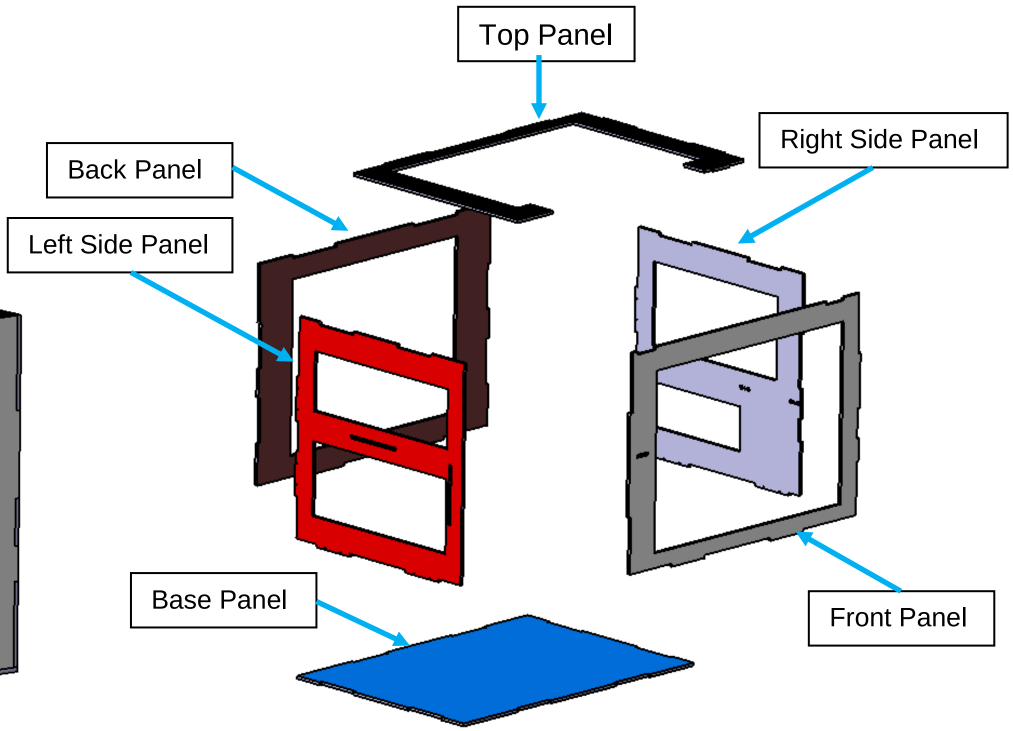


Figure D.10 Machine Structure Panels – Exploded View

M^2-3DP Machine Design - Layout

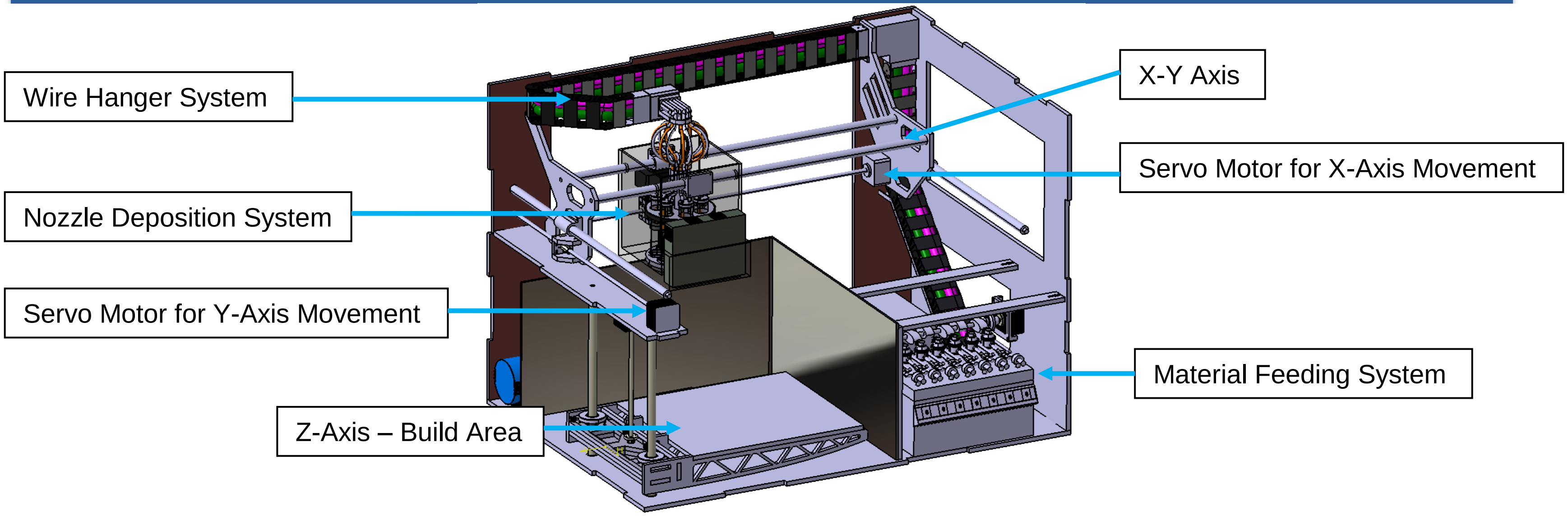


Figure D.11 M^2-3D Printer Machine Design Layout – Isometric View

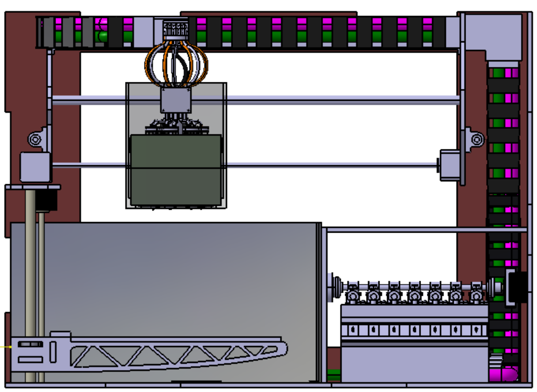


Figure D.12 M^2-3D Printer Machine Design Layout – Front View

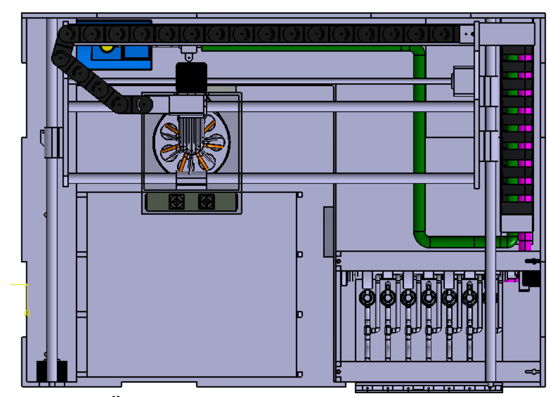
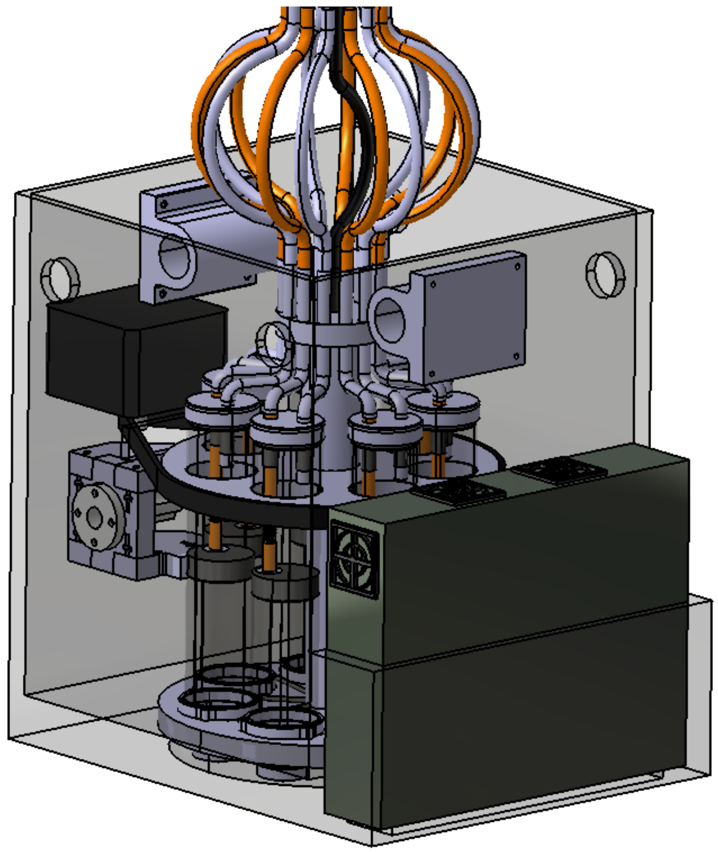


Figure D.13 M^2-3D Printer Machine Design Layout – Top View

M^2-3DP Nozzle Deposition Design



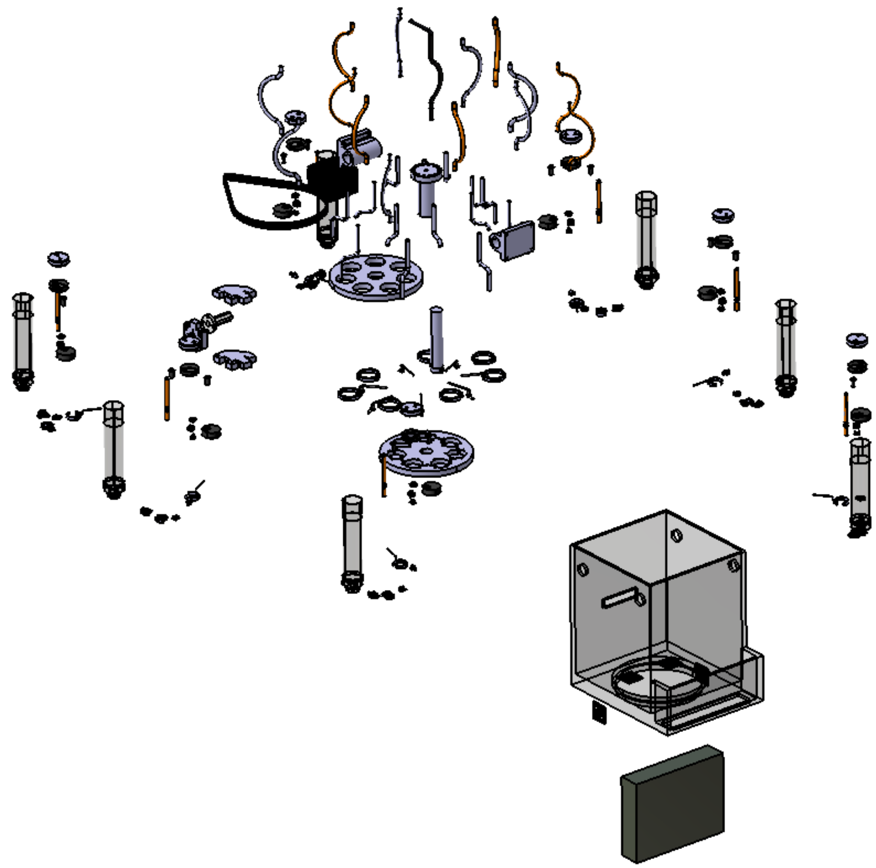


Figure D.14 M^2-3D Printer Nozzle Deposition System – Isometric View

Figure D.15 M^2-3D Printer Nozzle Deposition System – Exploded View

M²-3DP Nozzle Deposition Design

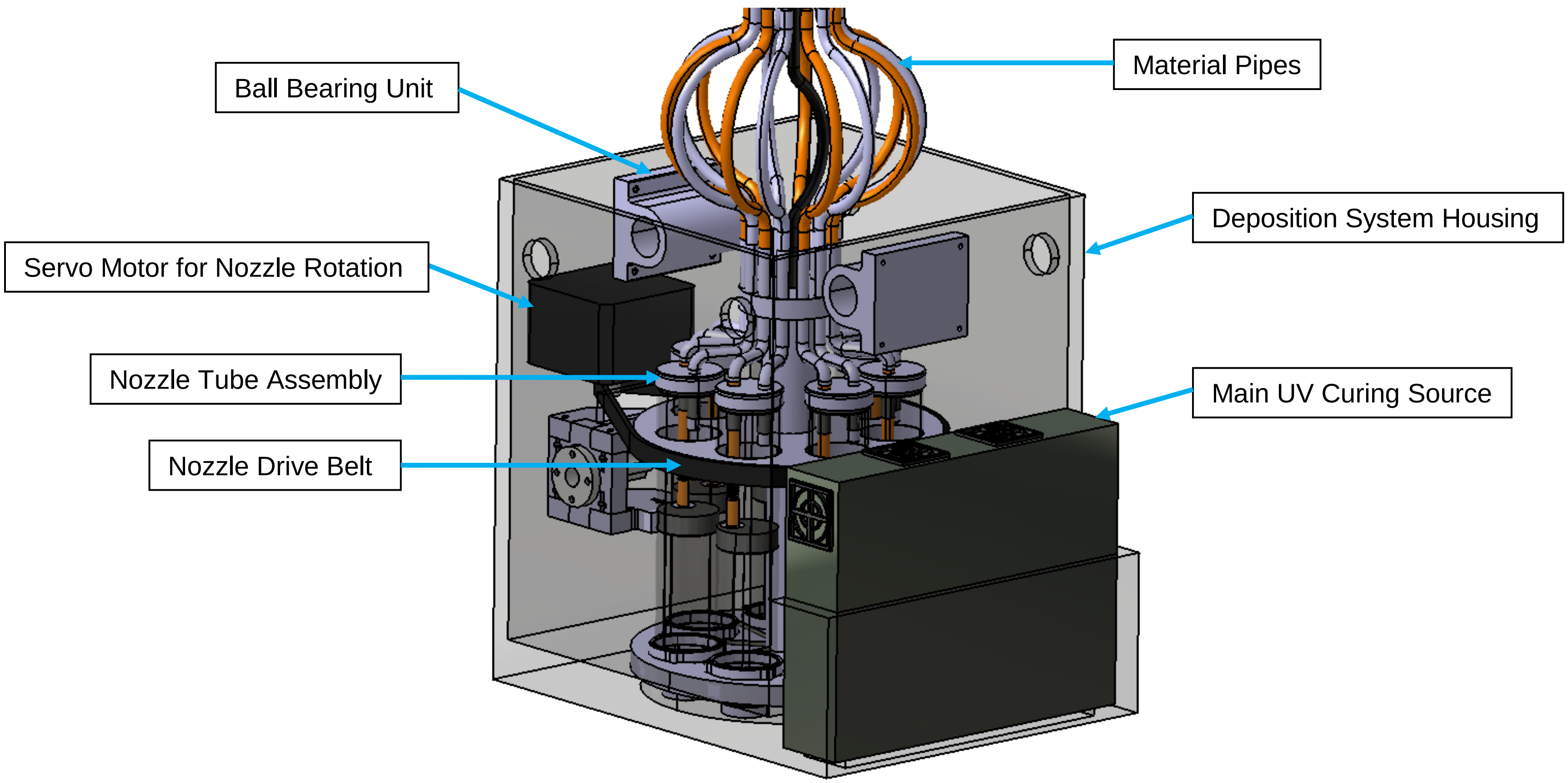


Figure D.16 M^2-3D Printer Nozzle Deposition System

M^2-3DP Nozzle Deposition Design

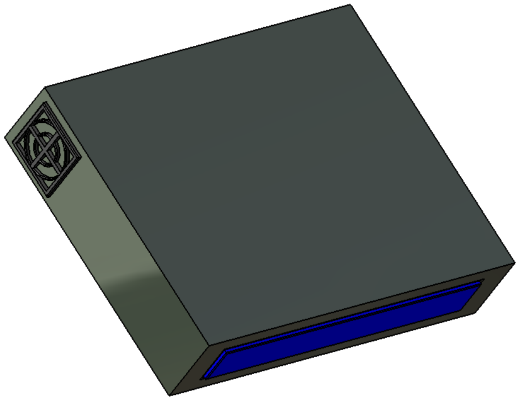


Figure D.17 Main UV Curing Source

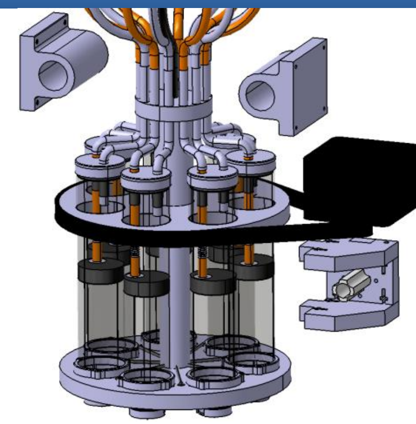


Figure D.18 Deposition System (without housing) – Isometric View

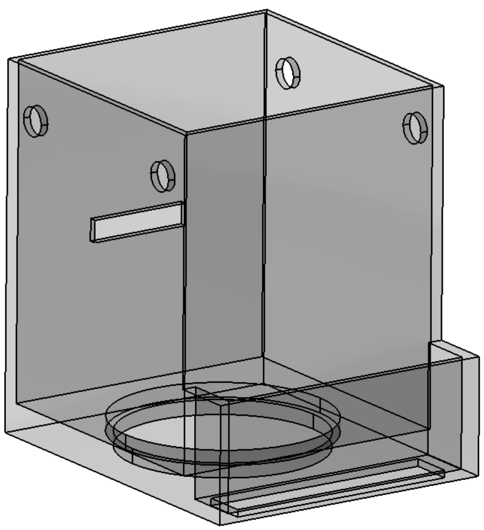


Figure D.19 Deposition System Housing

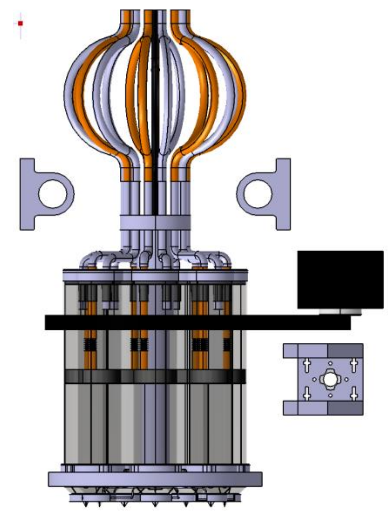


Figure D.20 Deposition System (without housing) – Side View

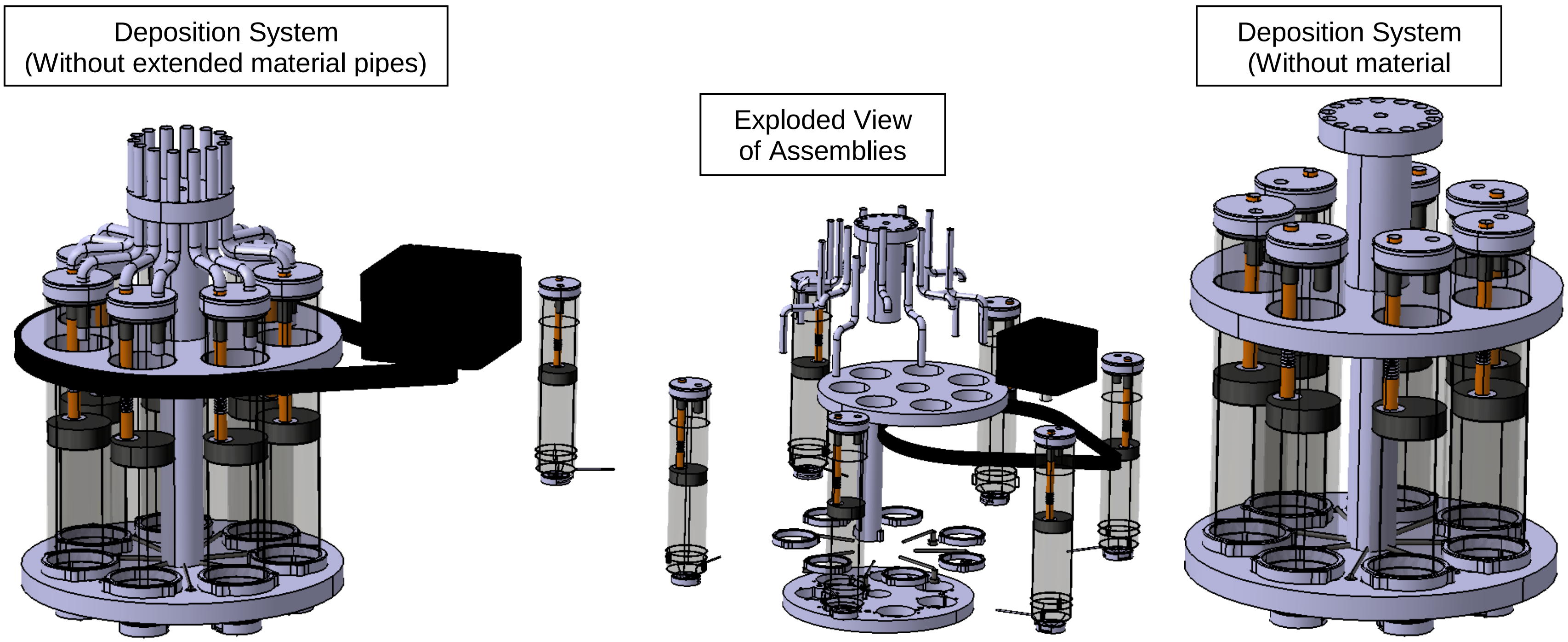


Figure D.21 Nozzle Deposition System

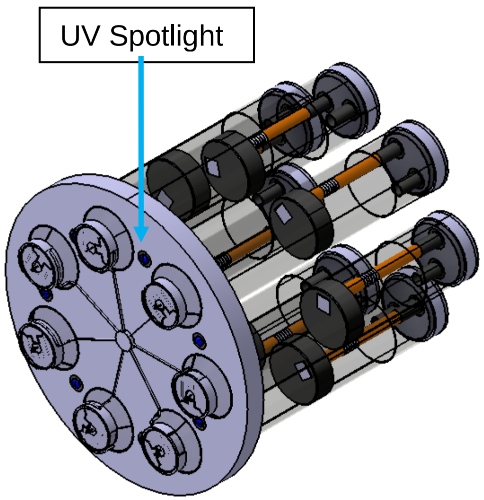


Figure D.22 Nozzle Deposition System

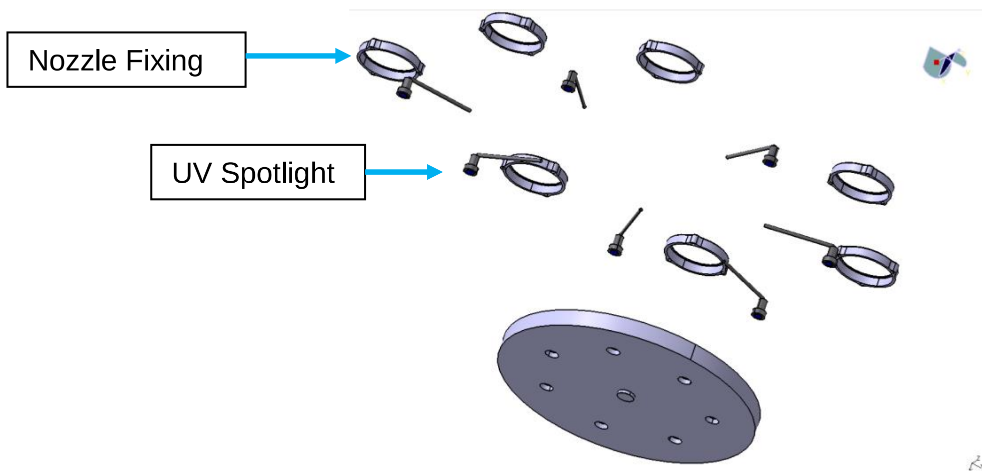


Figure D.23 Nozzle Fixing Plate – Exploded View

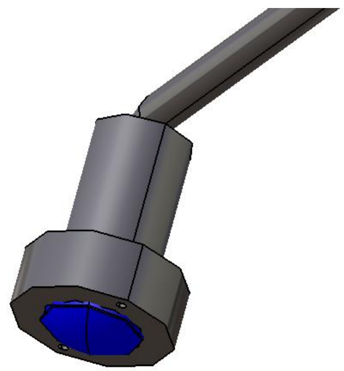


Figure D.24 UV Spotlight

M²-3DP Nozzle Deposition Design

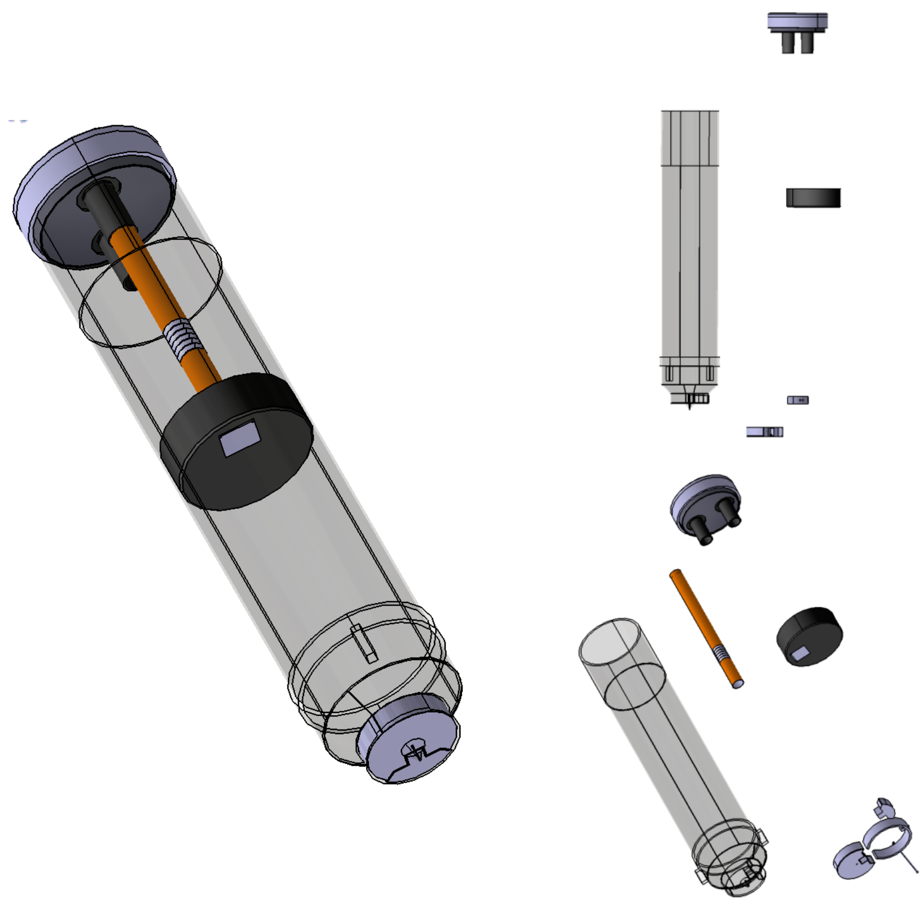


Figure D.25 Nozzle assembly & its Exploded View

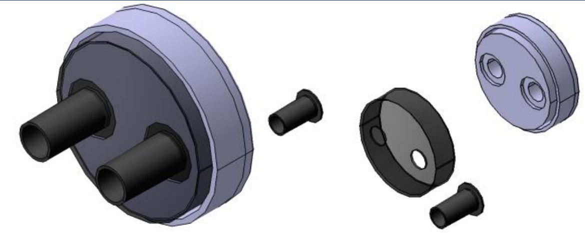


Figure D.26 Nozzle Cover Assembly

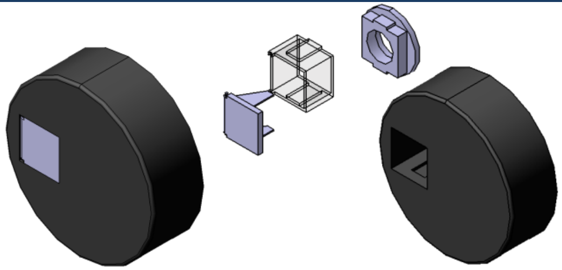


Figure D.27 Nozzle Pressure Plate Assembly

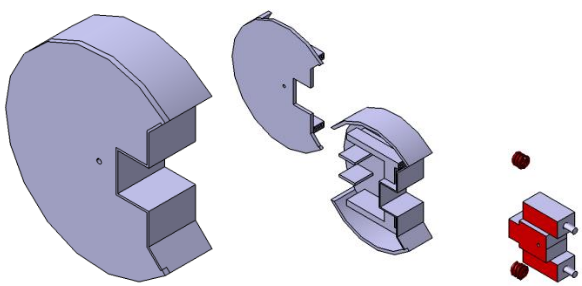


Figure D.28 Nozzle Flow Control Assembly

M²-3DP Nozzle Deposition Design

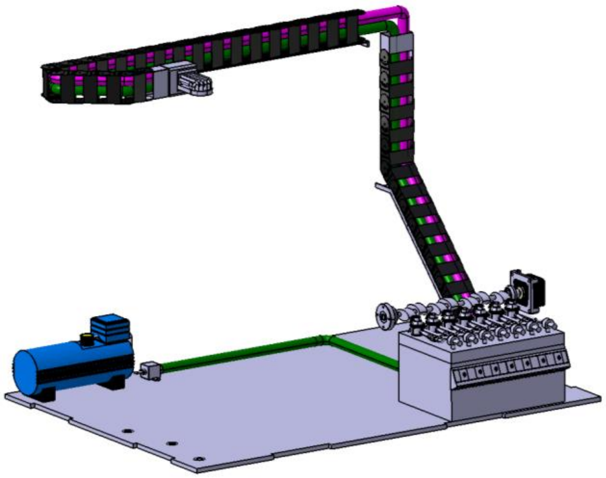


Figure D.29 Wire & Pipe Hanger Assembly

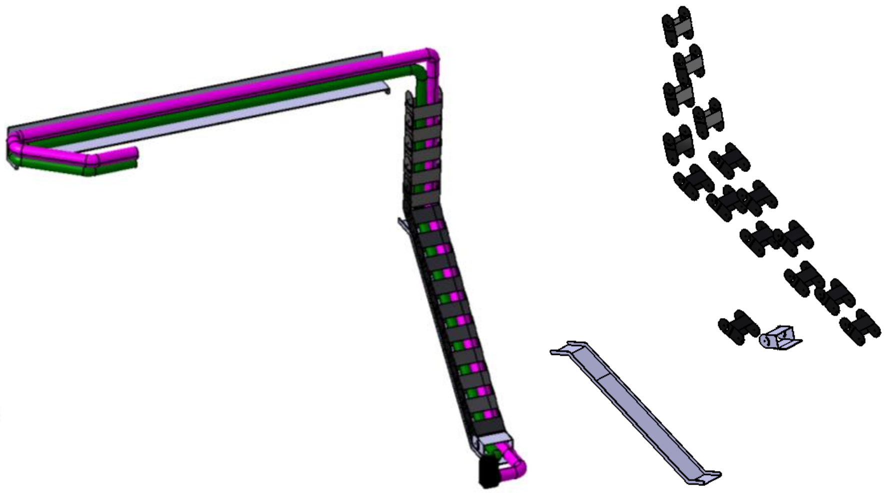


Figure D.30 Wire & Pipe Hanger Exploded View

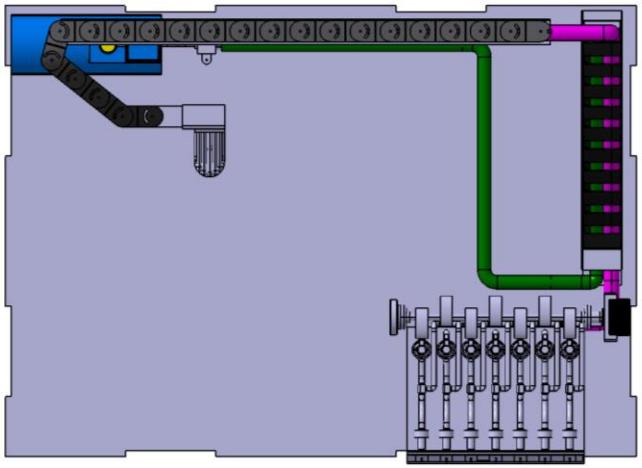


Figure D.31 Wire & Pipe Hanger Assembly Layout

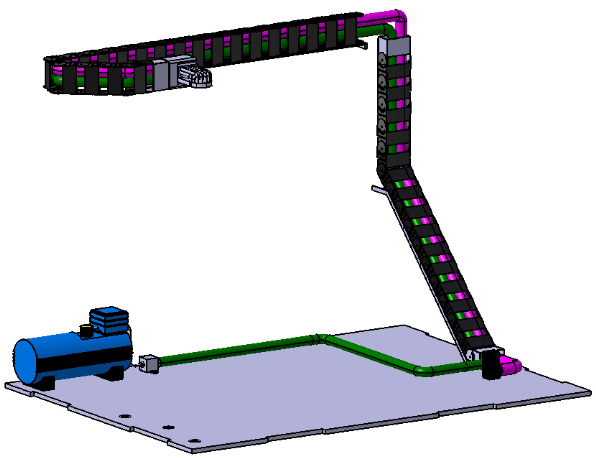


Figure D.32 Wire & Pipe Hanger Assembly

M^2-3DP Nozzle Deposition Design

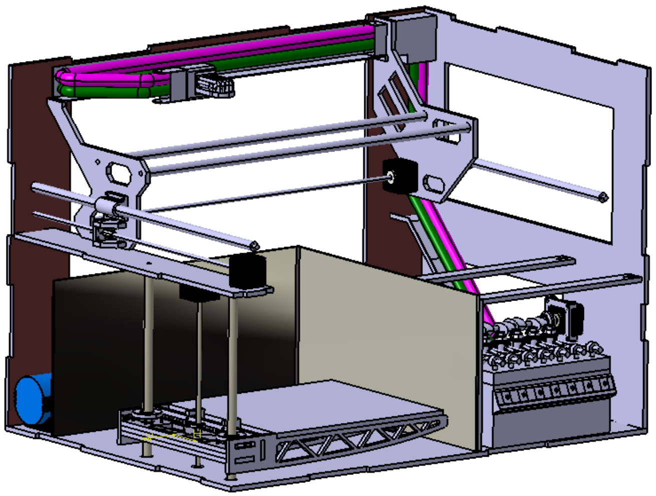


Figure D.33 M^2-3D Printer Machine Design

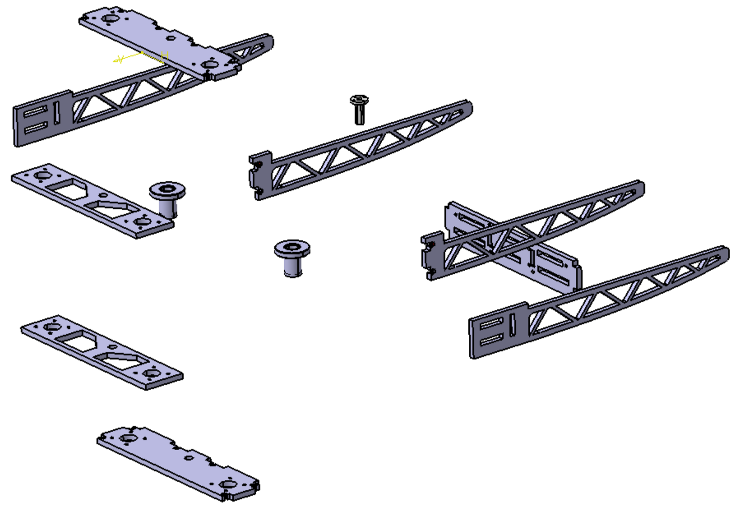


Figure D.34 Exploded view of Z-Axis

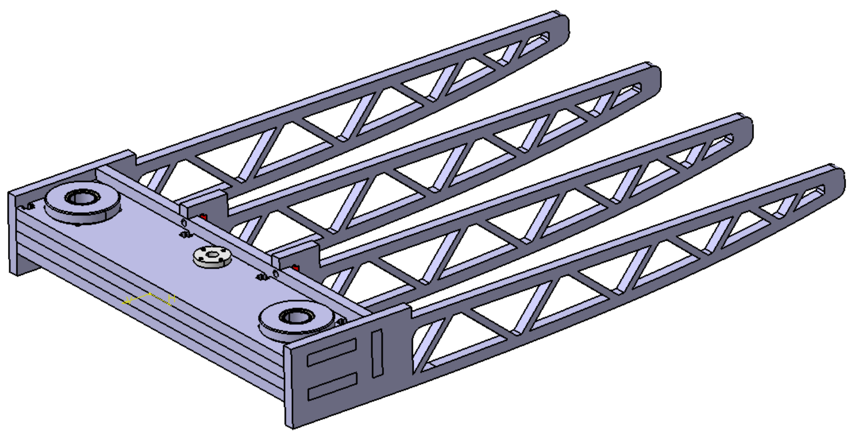


Figure D.35 Z-Axis Assembly

M^2-3DP Nozzle Deposition Design

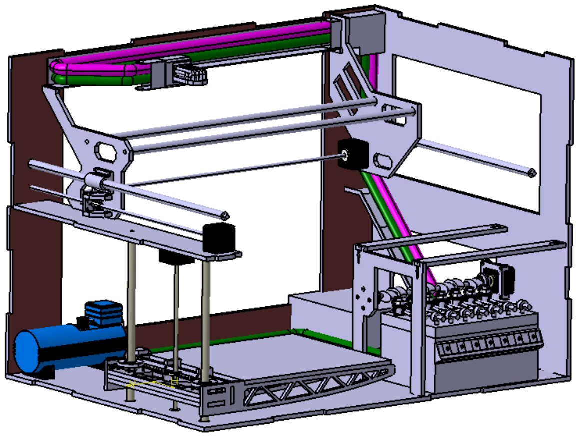


Figure D.36 M^2-3D Printer Machine Design

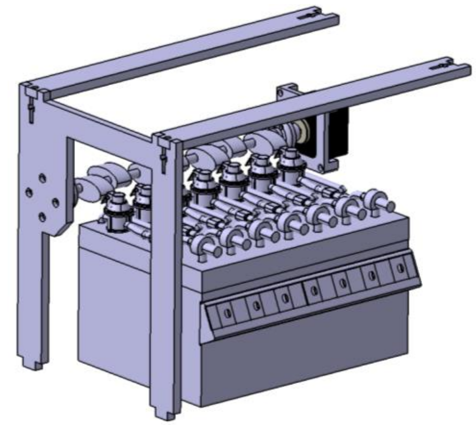


Figure D.37 Feeding Apparatus Design

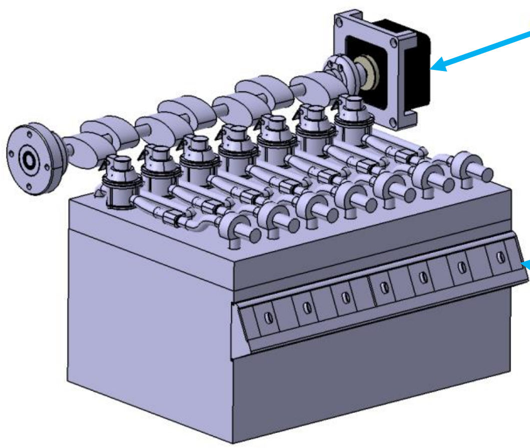


Figure D.38 Feeding Apparatus Design – Isometric View

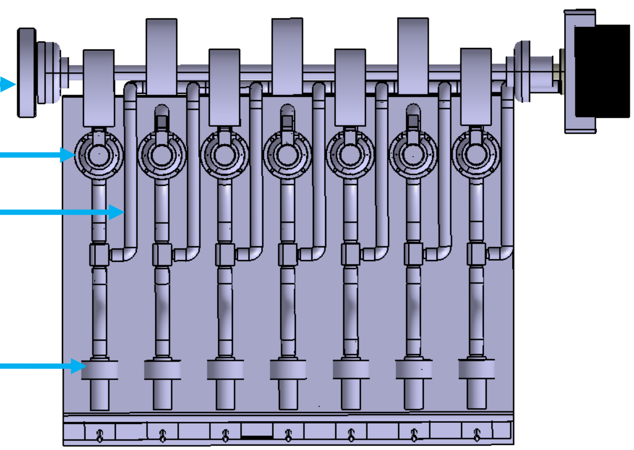


Figure D.39 M^2-3D Printer Machine Design

M²-3DP Nozzle Deposition Design

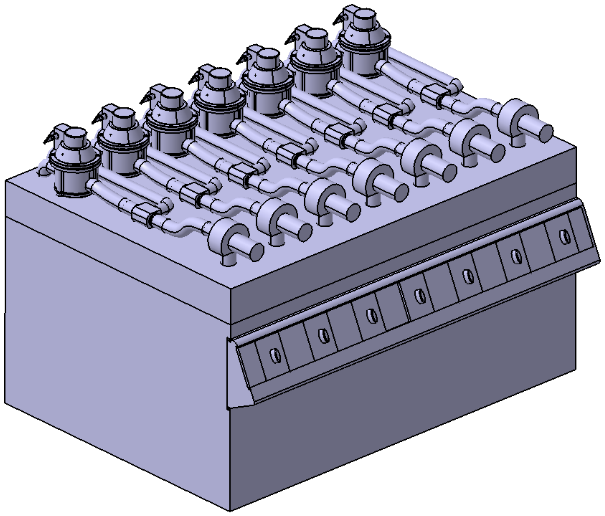


Figure D.40 Feeding Apparatus (Without Crankshaft)

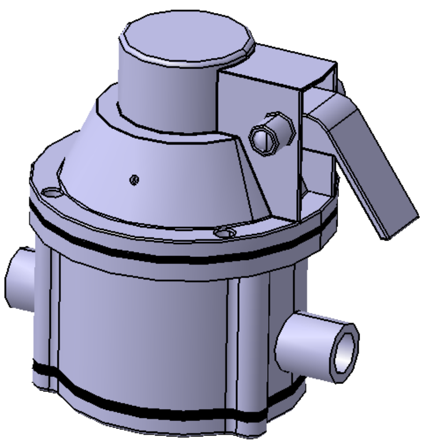


Figure D.41 Feeding Pump Assembly

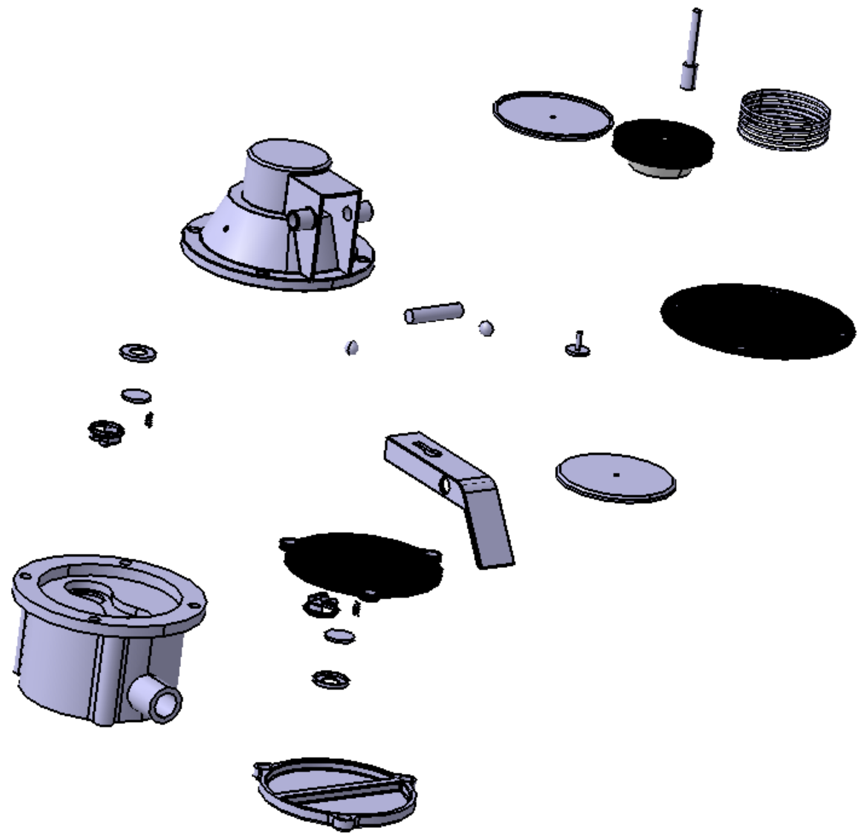


Figure D.42 Feeding Pump Assembly – Exploded View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