On the Development and Integration of Pneumatic Extrusion Module and a Methodology to Identify Process Parameters for Additive Manufacturing using Machine Learning

by

KASHISH DHAL

Presented to the Faculty of the Graduate School of The University of Texas at Arlington in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2018
ACKNOWLEDGEMENTS

I would like to thank my advising professor Dr. P. S. Shiakolas for his guidance, support, motivation and invaluable advice during the course of my master’s studies. I wish to thank Dr. Kamesh Subbarao and Dr. Tre Welch for their interest in my research and for taking time to serve in my thesis committee.

I would also like to extend my appreciation to lab-mates at Micro Manufacturing Medical Automation and Robotics Systems (MARS) laboratory including Tushar Saini, Ravi Patel, Samson Adejokun, Sudip Hazra, Parimal Patel, Henry Nguyen and Abdul Hafiz. I am especially grateful to Christopher Abrego and Dr. Prashanth Ravi for providing me the understanding of LabVIEW, mechatronics components and additive manufacturing. I wish also to thank Dr. H. Moon for providing access to her microscope.

I would like to thank Nordson EFD and Norland Products for providing samples of the needles and the material, NEA123T, used for the experiments. I would like to thank my uncles Dr. Harbans Lal and Swaran Saxena for encouraging and inspiring me to pursue graduate studies.

Finally, I would like to express my deep gratitude to my parents who have encouraged, inspired and sponsored me for my undergraduate and graduate studies. I am extremely fortunate to be so blessed. I am also extremely grateful to my brothers and sisters for their sacrifice, encouragement and patience. I also thank several of my friends who have helped me throughout my career.

May, 2018
ABSTRACT

On the Development and Integration of Pneumatic Extrusion Module and a Methodology to Identify Process Parameters for Additive Manufacturing using Machine Learning

Kashish Dhal, MS

The University of Texas at Arlington, 2018

Supervising Professor: Panos S. Shiakolas

Commonly used additive manufacturing platforms have a single extrusion module based on Fused Filament Fabrication (FFF) and their processing software generates G-code for this FFF module using defined process parameters. These platforms and software do not accommodate different processing modules such as viscous extruders or Direct Ink Writing (DIW).

This research is focused on the development of a Pneumatic Extrusion Module (PEM) capable of dispensing viscous materials such as gels or slurries controlled through a digital pneumatic valve. A PEM is developed, integrated and its performance is evaluated on a multi-modality additive manufacturing platform in the MARS Lab. The operation of PEM is controlled through an FPGA that communicates with the traditional G-Code for 3D printing in real-time. A methodology is developed for characterizing 3D printed strand width of a poly-urethane based photocurable resin based on process parameters, namely print speed and extrusion pressure using an Artificial Neural Network (ANN) model. During the additive manufacturing process,
in real-time and as instructed from the G-code, the PEM control pressure is evaluated using another ANN model. Using this methodology and the developed hardware tools 3D constructs have been successfully fabricated. The results of this research show that PEMs module can be successfully and seamlessly integrated on a multi-modality platform for the fabrication of multi-material constructs using different processing.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>3</td>
</tr>
<tr>
<td>1.4</td>
<td>4</td>
</tr>
<tr>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>1.6</td>
<td>5</td>
</tr>
<tr>
<td>1.7</td>
<td>6</td>
</tr>
<tr>
<td>1.8</td>
<td>7</td>
</tr>
<tr>
<td>2.1</td>
<td>13</td>
</tr>
<tr>
<td>2.2</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>16</td>
</tr>
<tr>
<td>2.5</td>
<td>17</td>
</tr>
<tr>
<td>2.6</td>
<td>19</td>
</tr>
<tr>
<td>2.7</td>
<td>19</td>
</tr>
<tr>
<td>2.8</td>
<td>21</td>
</tr>
<tr>
<td>3.1</td>
<td>23</td>
</tr>
</tbody>
</table>

**LIST OF ILLUSTRATIONS**

1.1 Stereolithography apparatus

1.2 DLP compromising of (a) tank containing resin, (b) light source, (c) mirror, (d) movable platform, and (e) tilting device which restores the uncured bottom layer

1.3 Fused Filament Fabrication (FFF)

1.4 Pneumatic dispensing of heated polymer (left) and photo curable resin (right)

1.5 Zero gravity printing

1.6 3D printed ceramic structure

1.7 Stepper (left) and piezoelectric (right) based extrusion systems

1.8 Solenoid based extrusion systems

2.1 General viscous extrusion approach

2.2 Rumba board, stepper motor driver and current viscous extrusion module

2.3 Multi-Modality 3D printer

2.4 Pressure control valve (left) and calibration curve (right)

2.5 Cross-section (left) and physical appearance (right) of Nordson EFD syringe

2.6 Syringe barrel holder (left) and LED and fan holder (right)

2.7 Aluminum tape covering UV rays (left) and Nichia LED (right)

2.8 Fully assembled PEM

3.1 LabVIEW VI for fluid dispensing
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>Strands printed at different pressure</td>
<td>24</td>
</tr>
<tr>
<td>3.3</td>
<td>Conversion of PWM signal into a number between 0 and 1</td>
<td>28</td>
</tr>
<tr>
<td>3.4</td>
<td>Frequency calculation of PWM signal on FPGA</td>
<td>29</td>
</tr>
<tr>
<td>3.5</td>
<td>FPGA VI to calculate extrusion feed rate</td>
<td>32</td>
</tr>
<tr>
<td>3.6</td>
<td>RT VI to initialise FPGA</td>
<td>32</td>
</tr>
<tr>
<td>3.7</td>
<td>Flow pattern inside the syringe and nozzle</td>
<td>34</td>
</tr>
<tr>
<td>3.8</td>
<td>LabVIEW VI for fluid dispensing</td>
<td>36</td>
</tr>
<tr>
<td>3.9</td>
<td>Mass flow rate vs nozzle diameter for toothpaste</td>
<td>37</td>
</tr>
<tr>
<td>3.10</td>
<td>Mass flow rate vs nozzle diameter for hair Gel</td>
<td>38</td>
</tr>
<tr>
<td>3.11</td>
<td>3D printed strand with NEA123T</td>
<td>40</td>
</tr>
<tr>
<td>3.12</td>
<td>ANN model for predicting strand width</td>
<td>41</td>
</tr>
<tr>
<td>3.13</td>
<td>MSE as a function of maximum number of iterations for different neurons</td>
<td>43</td>
</tr>
<tr>
<td>3.14</td>
<td>ANN performance with different number of hidden neurons</td>
<td>44</td>
</tr>
<tr>
<td>3.15</td>
<td>VI for training Artificial Neural Network</td>
<td>45</td>
</tr>
<tr>
<td>3.16</td>
<td>VI for strand width prediction</td>
<td>45</td>
</tr>
<tr>
<td>3.17</td>
<td>Execution, frequency calculations and condition to stop</td>
<td>47</td>
</tr>
<tr>
<td>3.18</td>
<td>FPGA VI communicating with ANN on Host (PC) in real-time</td>
<td>47</td>
</tr>
<tr>
<td>3.19</td>
<td>Host VI that communicates with ANN VI through shared library node</td>
<td>48</td>
</tr>
<tr>
<td>3.20</td>
<td>Overall process flow</td>
<td>49</td>
</tr>
<tr>
<td>4.1</td>
<td>ANN prediction over training dataset</td>
<td>50</td>
</tr>
<tr>
<td>4.2</td>
<td>ANN prediction over random dataset</td>
<td>51</td>
</tr>
<tr>
<td>4.3</td>
<td>Predicted strand width for varying print speeds and different constant pressures</td>
<td>52</td>
</tr>
<tr>
<td>4.4</td>
<td>Predicted strand width for varying extrusion pressures and different constant print speeds</td>
<td>52</td>
</tr>
<tr>
<td>4.5</td>
<td>Strand width greater than nozzle diameter</td>
<td>54</td>
</tr>
</tbody>
</table>
4.6 Strand width less than nozzle diameter .......................... 54
4.7 Unsuccessful print ...................................................... 55
4.8 Printed Scaffolds ....................................................... 57
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Electrical specifications of pressure control valve</td>
<td>16</td>
</tr>
<tr>
<td>3.1 Mass flow rate vs pressure input for the toothpaste (mg/s)</td>
<td>36</td>
</tr>
<tr>
<td>3.2 Mass flow rate vs pressure input for hair gel (mg/s)</td>
<td>37</td>
</tr>
<tr>
<td>3.3 Diameter of printed strand (mm)</td>
<td>41</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

**ACKNOWLEDGEMENTS** ................................................................. iii

**ABSTRACT** ........................................................................ iv

**LIST OF ILLUSTRATIONS** ..................................................... vi

**LIST OF TABLES** ...................................................................... ix

1. **Introduction** ........................................................................ 1

   1.1 Additive Manufacturing Technologies ............................... 1

      1.1.1 Stereolithography ..................................................... 1

      1.1.2 Digital Light Processing ........................................ 2

      1.1.3 Fused Filament Fabrication (FFF) ............................... 3

      1.1.4 Pneumatic Dispensing based AM ............................... 4

      1.1.5 Mechanical Dispensing based AM ............................. 6

      1.1.6 Other AM Techniques ............................................ 7

   1.2 Significance of Pneumatic Dispensing based AM ................. 7

   1.3 Scope of This Research .................................................. 10

2. **Pneumatic Extrusion Module Development** ......................... 12

   2.1 Current Extrusion Module and Proposed Pneumatic Extrusion Module 12

   2.2 Components of Pneumatic Extrusion Module ................... 15

3. **Integration of PEM to Multi-Modality 3D Printer and a Methodology to Characterize 3D Printed Strands** ................... 22

   3.1 3D Printing strands at a constant Pressure ..................... 22

   3.2 Coordinated Extrusion Feed ........................................ 24

   3.3 Co-ordinated Extrusion Module with RT Target ............... 27
CHAPTER 1

Introduction

1.1 Additive Manufacturing Technologies

Additive Manufacturing (AM), also referred to as three-dimensional (3D) printing, is a process that allows for customized fabrication of physical three-dimensional objects by adding the material in layers. AM has already been massively employed for rapid prototyping in the aerospace, manufacturing and medical domains. However, several methodologies are being investigated and developed for the transition of AM from rapid prototyping to rapid manufacturing. Several AM technologies that have emerged over the years work on the same basis of layered manufacturing but differ in the equipment, materials or the environment employed for fabrication\[13\]. To discuss how these processes differ some AM processes are described in the following sub-sections.

1.1.1 Stereolithography

First ever 3D printer was created by Charles (Chuck) Hull in 1984, he invented the Stereo-Lithography (SLA) process and patented this method and apparatus. In this process, an object was created by adding a layer on top of another layer by curing photo-polymers using Ultra Violet radiations. He defined this process as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed," \[14\] \[15\]. This process is presented in figure \[1.1\].
1.1.2 Digital Light Processing

Digital light processing (DLP) is an advanced form of SLA where selectively masked light source is utilized to cross-link a photo-resin in a layer-by-layer fashion instead of point-by-point [2]. Hence, the whole layer is developed in a single run as compared to SLA where only a point is cured at a time, and because of this, build time in DLP is less compared to SLA. This process is presented in figure 1.2.

Figure 1.2: DLP compromising of (a) tank containing resin, (b) light source, (c) mirror, (d) movable platform, and (e) tilting device which restores the uncured bottom layer [2]
1.1.3 Fused Filament Fabrication (FFF)

This process was introduced by Stratasys Inc., USA in 1990s under the name Fused Deposition Modeling (FDM) and is one of the most popular additive manufacturing technologies [16]. In this process, polymer filaments of the build material and the support material are fed into a computer controlled heated extrusion print head. Polymer filament is sandwiched between two wheels which pushes the filament whenever a command is issued from the computer. Filament is melted, extruded through the nozzle and then deposited on the bed. Materials that can be 3D printed using this process are wax-filled plastic adhesive, proprietary nylon, investment casting wax, etc. This process is presented in figure 1.3

Figure 1.3: Fused Filament Fabrication (FFF) [3]
1.1.4 Pneumatic Dispensing based AM

Pneumatic Dispensing based AM is a process where the material is filled inside a syringe and then pushed through a nozzle using compressed air. The extrusion rate can be controlled by varying the air pressure. After the material is dispensed, it is solidified and joined layer by layer to take a form of three-dimensional object. Solidification can be achieved by different methodologies based on the material and environment chosen for the 3D printing process [2].

A syringe can be filled with a polymer and then heated to melt the material. This molten material is then dispensed and when it is exposed to ambient temperature, it solidifies. This process is presented in figure 1.4.

If a viscous photo curable resin is used, then immediately after dispensing, the material is bombarded with light, which solidifies the material, as presented in figure 1.4.

![Figure 1.4: Pneumatic dispensing of heated polymer (left) [4] and photo curable resin (right) [5]](image)

If a chemically reactive polymer or bio-material is used, then it can be dispensed inside a liquid media. This liquid media serves two purposes, first is to provide the support for dispensing the material and secondly it can also provide a chemically
reactive environment where the dispensed material reacts with the environment and solidifies. This process can also be termed as Zero Gravity Printing as no support is needed and is presented in figure 1.5.

![Figure 1.5: Zero gravity printing](image)

This process can also be used to dispense viscous ceramic paste layer-by-layer finally taking a form of a three-dimensional object. In this process, the control of the rheological properties of the filament is essential to prevent deformation and sagging of the filaments after extrusion [7]. A 3D printed ceramic structure is presented in figure 1.6.

![Figure 1.6: 3D printed ceramic structure](image)
1.1.5 Mechanical Dispensing based AM

Similar to pneumatic dispensing, mechanical dispensing can also be applied to different areas. In these processes, the material is dispensed mechanically using actuators instead of compressed air [17], the commonly used actuators employed in these processes are stepper motors, solenoids or piezoelectric actuators. Afterwards, this dispensed material can be solidified using different methodologies as discussed in section 1.1.4.

In stepper motor based configuration, a screw is attached to the piston of the syringe which is filled with the material. When motor is actuated, the piston is pushed in the syringe and extrusion takes place. This process is presented in figure 1.7.

Piezo-electric actuators are most commonly used in inkjet printing, these actuators are placed inside the dispensing system, whenever a signal is commanded, due to vibrations a drop will be dispensed [18]. Multiple nozzles can be used to dispense the fluid using this setup. This process is presented in figure 1.7.

![Figure 1.7: Stepper (left) and piezoelectric (right) based extrusion systems](image_url)
Solenoid based configuration utilizes electrical signal to attract a magnet which is placed between a floating ferro-magnetic plunger and a ferro-magnetic ring. When solenoid is actuated, it results in opening of the valve [8]. The material is pushed continuously using compressed air and whenever the valve is opened fluid is dispensed. This process is presented in figure 1.8.

![Figure 1.8: Solenoid based extrusion systems](image)

1.1.6 Other AM Techniques

There are several other AM technologies such as powder bed fusion (SLS, SLM, EBM), directed energy deposition, material jetting, binder jetting and sheet lamination which are not being discussed as they are out of scope of this research.

1.2 Significance of Pneumatic Dispensing based AM

In section 1.1 various AM processes have been described to demonstrate how different equipment, materials, environment and methodologies can be employed to-
wards the fabrication of physical three-dimensional objects. However, each of these AM processes have advantages and disadvantages associated with it.

In SLA and DLP techniques, a laser controls the process, hence, high accuracy and a layer thickness of less than 10 µm can be achieved [19]. But these processes are restricted to photo-curable resins which are expensive and other materials cannot be printed on the same platform.

FFF technique can be used for any material available in the form of filament and can be melted inside the dispensing system (generally thermoplastics). The main advantages of this process are that no resins to cure, no chemical post-processing required, less expensive and smaller machine [20][21]. The disadvantages are low resolution and high build time (it is a slow process).

Dispensing based AM can be applied to larger variety of materials including rubbers, poly-urethanes, silicones, thermosets, inorganic and organic pastes, polymer latex, plastisols, biomaterials, hydro-gels and various functional polymers. It can also be used for dispensing biological materials such as living cells which cannot tolerate high processing temperatures and toxic monomers [2][22][23][24][25][26]. In these processes, different solidification methods can be employed as compared to FDM, SLA and DLP which are restricted to single solidification method. Although inkjet and SLA can be used for bio-printing but dispensing based AM is more efficient and cost-effective [27]. The disadvantage of these processes is low resolution as compared to SLA and DLP. The material is extruded through a nozzle and it becomes very difficult to extrude if the material viscosity is high and the nozzle diameter is less than 100 µm. When the nozzle diameter is decreased below 100 µm then the build time increases. If the nozzle diameter is increased above 100 µm, then the resolution decreases [2].
Since dispensing based AM can be applied to a wider domain ranging from cells to buildings, this process will be investigated further in this research. However, dispensing based AM can be controlled pneumatically or mechanically, which is described in section \[1.1\].

Mechanical dispensing based AM processes described in subsection \[1.1.5\] have certain drawbacks. The limitations associated with stepper motor based dispenser are delayed extrusion and oozing. Turning of the screw does not result in immediate material flow and also, when the motor is stopped, material flow does not stop immediately and keeps oozing due to pressure built up inside the syringe \[28\]. This poor control over the material flow results in poor print quality. Also, highly viscous materials such as ceramics slurries are hard to push using a motor and hence can not be controllably printed. Inkjet printing using piezoelectric actuators provides better control over the material flow, but is restricted to materials which can be dispensed using this setup, increases the bulkiness of print head and also the cost of the printer is high. Solenoid based dispensing can be applied to a wider range of materials because it uses mechanical displacement of magnet together with compressed air to push the material. But it does not have a good control over material flow as compared to pneumatic dispensing based systems because the flow is controlled by displacement as compared to pressure.

Pneumatic dispensing based AM systems have the advantage of allowing very rapid changes in pressure, and thus rapid starting and stopping of the material flow. Also, high viscosity materials can be pushed through the nozzle and printed using this process. Due to these reason, this system covers widest range of materials that can be printed including thermo-plastics (FFF), photo-polymers (SLA and DLP) and bio-materials. Apart from this, highly viscous materials such as ceramics slurries can be printed with good control over material flow.
1.3 Scope of This Research

Commonly used open source AM platforms have a single extrusion module, FFF and their processing software generates G-code for this module using defined process parameters. However, as described in section 1.2, FFF is limited only to the materials which can be processed in the form of filaments. On the other hand, dispensing based AM can be applied to wider range of materials but these open source platforms and software do not provide support for dispensing based modules. The currently available printer/software bundles for the dispensing based AM are cost-prohibitive and closed-source with limited customizability. Researchers tried to use these open source platform to build stepper motor based modules and successfully fabricated 3D structures [29][30]. However, a good control over the material flow and a good resolution cannot be achieved. To address this issue, other researchers tried to add special commands to G-code or algorithms in the controller to retract the plunger when dispensing is not required, which avoids overflow of the material [29][31]. However, adding these special commands and algorithms still can not lead to a print quality that can be achieved by pneumatic controlled extrusion with immediate pressure building and release. To develop a pressure controlled extruder/dispenser for any material, rheological properties and material characteristics are needed and if this information is available then material extrusion rate can be modeled as a function of input pressure. If multi-material printing is needed then remodeling and re-characterization will be required for each new material.

The objective of this research is to develop and integrate a PEM, capable of dispensing multi-materials as per commanded G-code from an existing multi-modality 3D printer. This PEM demonstrated better control over material flow with minimized delayed extrusion and oozing as compared to the stepper motor based module. The
purpose of adding a PEM to existing multi-modality 3D printer is that it can be used in combination with other different modules such as FFF to fabricate in-situ multi-material structures. This document describes the development of PEM and a methodology to identify the effect of controlled process parameters, namely print speed and extrusion pressure, on the width of 3D printed strands. However, the same characterization methodology can be applied to characterize other materials.

It is demonstrated in this research that instead of modeling the PEM with the rheological properties and material characteristics, multiple experiments can be performed and the results can be used to train an Artificial Neural Network (ANN). This ANN model can be used to predict the optimum values for effective printing in real-time with the PEM. The results of this research also show that PEMs can be successfully and seamlessly integrated on a multi-modality platform for the fabrication of multi-material constructs using different processing modalities.
CHAPTER 2

Pneumatic Extrusion Module Development

2.1 Current Extrusion Module and Proposed Pneumatic Extrusion Module

This section describes the working of an in-house multi-modality 3D printer developed in the MARS Lab. Furthermore, this information will be utilized to describe the approach for the development and integration of PEM to this in-house multi-modality 3D printer.

Three-dimensional geometries can be designed using CAD software and can be exported to .stl file format. The Slic3r software generates G-code from the .stl file. G-code is generated in such a way that extrusion feed is coordinated with the XYZ motion of the platform. Repetier Host software communicates this G-code to the Rumba board which is loaded with Marlin firmware. The Marlin firmware interprets the incoming G-code and generates PWM signal. This PWM signal is then sent to a driver which converts it into a form required by the actuators. In this 3D printer, bipolar stepper motors are used as actuators to control the motion of platform and extrusion. The driver converts this PWM signal into four signals, namely A1, A2, B1, and B2, which are then sent to the stepper motor. The actuation of the stepper motor can be used for the motion of the platform or extrusion. In the extruder, the stepper motor actuation results in the linear actuation of a screw. This screw is attached to a piston of the syringe filled with material. This piston is pushed inside the syringe, resulting in pressure built-up, and the extrusion takes place. The extrusion rate is governed by the frequency of the PWM signal generated from the Rumba board. This whole process is presented graphically in figures 2.1 and 2.2.
The limitations of this stepper driven module are delayed response and oozing which leads to poor print quality. To address these issues current module was replaced by PEM. A pressure control valve is used to regulate the syringe inlet pressure which
would be able to push the material by a piston, instead of a piston attached to stepper motor. The current multi-modality 3D printer integrated with the proposed PEM is presented in figure 2.3.

![Multi-Modality 3D printer](image)

**Figure 2.3: Multi-Modality 3D printer**

For developing PEM, it was proposed to use the step signals generated from the Rumba board as per commanded G-code. These signals can be used to control the output of the pressure control valve, the output pressure from which will further control the pneumatic dispensing. The Rumba board has a limited number of analog pins but none of the analog pins were available for use for the PEM. Even with the availability of analog pin, the firmware needs to be modified to program it from G-code, which was difficult. The proposed solution was to use the digital pins on the Rumba board for controlling the pressure control valve. However, the pressure control valve works on a command analog voltage signal ranging from 0 to 10 Volts,
a conversion was required from this digital signal to analog signal. Also, a calibration was required based on the characteristics of the material used for the dispensing.

As mentioned, the signals sent to the stepper motor are digital signals, i.e., in the form of pulses, and could not be used to control the pressure control valve. One approach was to provide a constant voltage signal to the valve while the pulses are being received from the board, but the issue encountered was pressure could not be varied during the print, and hence extrusion rate could not be controlled for different print speeds. The solution was to use one more controller which could convert the digital signal into an analog signal considering the calibration based on the material used for the printing. This thesis describes three approaches taken towards the development of PEM.

2.2 Components of Pneumatic Extrusion Module

For this research, BB1 Pressure Control Valve by Proportion Air was used. “This is a complete closed loop servo system consisting of valves, manifold, housing and electronic controls. Pressure is controlled by the use of two solenoid valves. One valve functions as inlet control, the other as exhaust. The pressure output is measured by a pressure transducer internal to the BB1 and provides a feedback signal to the electronic controls. The feedback signal is compared with the command signal input. A difference between the two signals causes one of the solenoid valves to open, allowing flow in or out of the system. Accurate pressure is maintained by controlling the two valves [10].” Pressure control valve and its respective linear calibration curve are presented in figure 2.4.
Table 2.1: Electrical specifications of pressure control valve [10]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUPPLY VOLTAGE</td>
<td>15-24 VDC</td>
</tr>
<tr>
<td>SUPPLY CURRENT</td>
<td>250mA reqd.</td>
</tr>
<tr>
<td>COMMAND VOLTAGE SIGNAL CURRENT</td>
<td>0-10 VDC</td>
</tr>
<tr>
<td></td>
<td>4-20mA Sinking</td>
</tr>
</tbody>
</table>

Using this pressure control valve, the output pressure is controlled based on the input pressure and commanded analog voltage signal. For this purpose, a LabVIEW VI [41] was developed to provide a user specified analog command voltage. Using the Express VI in myRIO [43], an analog voltage was sent to the pressure control valve. Based on the magnitude of the analog voltage, an output pressure was measured and the calibration curve provided by manufacturer was verified.

Since the extrusion pressure can be controlled from LabVIEW, the next step was to use this pressure to dispense materials. To dispense the material, 10 CC Optimum Syringe Barrel Systems by Nordson EFD [11] was used which is presented in Figure 2.5. It is a customized syringe with curvature at the nozzle entrance. This curvature decreases the turbulence in the fluid flow and there is minimum pressure
loss at the bottom of the syringe. The diagram on the left presents the cross-section of the syringe and the one on the right presents outer appearance. The black syringe was chosen to protect the material from UV radiations so that the material should not polymerize and clog inside the syringe barrel.

![Cross-section and physical appearance of Nordson EFD syringe](image)

Figure 2.5: Cross-section (left) and physical appearance (right) of Nordson EFD syringe [11]

The introduced fluid dispensing setup successfully dispensed fluids as a function of input pressure to the syringe from pressure control valve. The next step is to mount the syringe barrel on the printer head. Also, for the photo-polymerization module an Ultra-Violet (UV) source was installed on the same print head in such a way that maximum UV intensity can be captured for effective and efficient photo-polymerization. The function of the syringe barrel holder is to hold the barrel firmly on the print head to avoid movement or vibrations of the syringe which can bias the results of the experiments. To fulfill these desired functions, the syringe barrel holder was manufactured and installed on the print head. The photo-polymerization module was used to bombard UV radiations on the dispensed material. UV sources are expensive, to make a cost-efficient printer, specifically for high viscosity materials, a fixture was designed where an inexpensive LED can rest. This fixture was designed only for the purpose of photo-polymerizing strands in one axis. However, using the
same methodology, a fixture can be designed and UV sources can be installed for photo-polymerization in multiple axes.

While designing the fixture, the challenge was to keep a constant gap between the LED and nozzle, in an effort to photo-polymerize the material after it has been extruded a certain distance. A gap of 8 mm was kept so that the UV rays do not clog the nozzle, the slowest print speed in the experiments conducted was 100 mm/min which means UV radiations take maximum time of 4.8 sec to reach the material and it was observed that there was no spreading of the material in that duration.

Also, the gap between the print bed and LED should be consistent and minimum (to get maximum UV intensity). By using this fixture, UV intensity available to the dispensed material was constant and not a parameter for characterization during the different experiment runs. The developed fixture is presented in figure 2.6.

An aluminum tape was used to cover the LED inside fixture so that UV rays should not spread out from the fixture. This was done for two reasons, first, if UV rays are contained, it will be more intense, which was desired. Second, if UV is not contained, it can reach the nozzle resulting in clogging of the nozzle due to the photo-polymerization of the material inside the nozzle and could also reach a user which is very harmful. Concerning these issues, a single fixture was designed to contain both the LED and nozzle of the syringe. Also, the aluminum tape was used inside the holder to avoid UV spreading and reaching the nozzle. In this way, the nozzle was isolated from the UV light. This is further presented in figure 2.7.
The print surface was chosen in such a way that the printed material can be easily removed from the surface without any damage for characterization. Also, the surface should not absorb UV rays. It was observed that while using a 3M blue scotch tape as a print surface, the material took more time to photo-polymerize as compared to using an aluminum tape. The possible reason for fast photo-polymerization with this surface was that it would reflect the UV bombarded on it which in turn gives more UV exposure. Due to this reason, the aluminum tape was used as the print surface for rest of this research. LED used for this purpose was Nichia NCSU033B(T)
P33d21 [44] whose wavelength ranges from 360 to 370 nm. The minimum voltage required to actuate the LED is 3.3 Volts. The maximum current and power dissipation recommended by manufacturer is 0.7 Amps and 3.08 Watts respectively. To limit the power consumption, $P_{LED}$ by the LED, supplied current, $I_{LED}$ was limited to maximum value of 0.5 Amps and a resistor, $R$ of 1.5 Ω was used in series. The sum of voltage drop across the LED, $V_L$ and voltage drop across resistor, $V_R$ should be equal to total supplied voltage, $V$ and was measured to be 5.1 Volts.

$$V_R = R \times I_{LED} = 1.5 \Omega \times 0.5 \text{ A} = 0.75 \text{ V} \quad (2.1)$$

$$V_L = V - V_R = 5.1 - 0.75 = 4.35 \text{ V} \quad (2.2)$$

$$P_{LED} = V_L \times I_{LED} = 4.35 \times 0.5 = 2.175 \text{ W} \quad (2.3)$$

From equations 2.2 to 2.3, it can be observed that the actual power consumption of LED was less than the recommended maximum value by manufacturer. Hence, LED was protected from the damage caused by excessive power consumption and over heating. However, to be on the safe side, a heat sink was mounted on the back of the LED and a small 12 V fan was utilized to dissipate heat from the LED. The peak UV intensity available with this setup was measured using a Dymax radiometer, which has a least count of 1 mW/cm$^2$ at a distance of 0.5 mm from the fixture and was found to be 100 mW/cm$^2$.

The fully assembled PEM is presented in Figure 2.8.
Figure 2.8: Fully assembled PEM
CHAPTER 3

Integration of PEM to Multi-Modality 3D Printer and a Methodology to Characterize 3D Printed Strands

In chapter 2 a PEM was developed and mounted to the print head. This chapter describes three different approaches taken towards the integration of this developed PEM to the existing multi-modality 3D printer. After integration, strands were 3D printed using polyurethane based resin. Then a methodology was developed to characterize the 3D printed strand width for controlled process parameters, namely print speed and extrusion pressure.

3.1 3D Printing strands at a constant Pressure

As per section 2.2 the pressure control valve was programmed and calibrated using LabVIEW software and NI myRIO controller. The pressure output was used to dispense the material as instructed by the user. Using manufacturer provided calibration, pressure control valve was integrated with the Rumba board as a constant pressure device. The digital pins of the Rumba board can be programmed using G-code command as P0, P1 and P2 where these commands can be used to get high signal (5 Volts) at the corresponding pin and P9 command disables these three pins providing a output of 0 Volt on each pin. For this research, digital output from pin P2 was utilized for the actuation of pressure control valve. Whenever P2 is commanded, the pin corresponding to it turns high. When this pin is high, an analog voltage is sent from myRIO to the pressure control valve. For this purpose, 0-10 Volts command signal and ground was obtained from myRIO MSP C connector (Pin 4 and Pin 3
respectively). When the pressure control valve receives the voltage signal, the valve opens allowing pressurized air to pass through and push the syringe piston to dispense the fluid. myRIO will continuously send the signal while the pin is high. When P9 is commanded, the pin corresponding to it turns low and myRIO stops sending the signal to the pressure control valve.

Using manufacturer provided calibration, LabVIEW VI was used to calculate analog voltage from the desired extrusion pressure command. This analog voltage is calculated from predefined calibration gains obtained from manufacturer provided calibration curve presented in figure 2.4. So, instead of voltage command, a user can provide required dispensing pressure in LabVIEW VI, and the VI will be translate that pressure into a voltage and then send to the pressure control valve via myRIO. In this way, when myRIO receives a signal from Rumba board to actuate the valve, the extrusion pressure is governed by the user and material via a control in LabVIEW. The reason to have user controlled variable pressure is that different extrusion pressure is needed based on various print speed, and diameter. This completes the setup to have a user-defined varying and controlled extrusion pressure while printing. Figure 3.1 presents the block diagram of LabVIEW VI used for dispensing.

Figure 3.1: LabVIEW VI for fluid dispensing
This setup was then used to print strands at two random pressure values with a nozzle of diameter 0.41 mm and nozzle to bed distance of 0.4 mm. The resulting strands are presented in figure 3.2. The G-code used for printing these strands was:

P2; (actuates the pressure control valve)
G1 X50 F100; (command to move the platform to X= 50 mm with a print speed of 100 mm/min)
P9; (sends 0 Volt to the pressure control valve)

![Pressure = 60 PSI](image)
![Pressure = 95 PSI](image)

Figure 3.2: Strands printed at different pressure

One of the challenges faced with this printing was that Slic3r software does not generate G-code with P2 and P9 commands so there was a need for additional post processing software and user engagement to set the extrusion pressure. Due to these limitations, a PEM with coordinated motion was proposed.

3.2 Coordinated Extrusion Feed

There are four axes in this in-house 3D printer, namely X, Y, Z and E (Extrusion). In this context, E refers to the pneumatic extrusion through the controlled displacement of the syringe piston. The platform has motion in Z axis only during the layer change. However, while printing a layer there is no motion in Z axis. If a
user gives a command for the motion in X and E axes simultaneously with a specified print speed from the G-code and if the position movement specified in X and E axes are equal, then the frequency of PWM signal generated at pin corresponding to X and E will be same. By reading the frequency of PWM signal at pin corresponding to E, user can determine what print speed was commanded from the G-code. However, if an user gives a command for the motion in X and Y axes simultaneously with a specified print speed from G-code, then Marlin firmware will decompose the required print speed into X and Y components based on the position movement specified from G-code in these two axes for coordinated motion. If a user gives a command for the motion in X, Y and E axes simultaneously with a specified print speed from the G-code, then Marlin firmware will decompose the required print speed into X and Y components and the extruder feed rate will be calculated as per desired motion in different axes. If the displacement from one point to another in X and Y directions \( \sqrt{X^2 + Y^2} \) is equal to the position movement in the E (Extruder) specified in the G-code then the print speed will be replicated to the extruder pin as PWM signal. By reading the frequency of extruder pin PWM signal user can determine the print speed commanded from the G-code. If different amount of position movements is specified in X and Y as compared to E, then print speed can not be determined from extruder PWM signal. Lets consider this with two examples:

First Example: Current Position: X=0, Y=0, Z=0, E=0 and Command: G1 X100 E50 F600

In this command, the specified print speed (F) is 600 mm/min, print head has to move from X=0 to X=100 mm and the extruder has to move from E=0 to E=50 mm. If the extruder moves at same speed as print head moves in X axis then all the extrusion will occur when print head reaches X=50 mm and during the movement of print head from X=50 mm to X=100 mm there will not be any extrusion. So,
the Marlin firmware will reduce the extrusion speed by a factor of two which is 300 mm/min. The calculations for coordinated extrusion feed rate are illustrated below.

\[ \text{Extruder Feed Rate} = \left( \frac{\text{Extruder Movement}}{\text{XY axes Movement}} \right) \times \text{Print Speed} \quad (3.1) \]

\[ = \left( \frac{50}{100} \right) \times 600 = 300 \text{ mm/min} \quad (3.2) \]

So while acquiring the frequency of PWM signal, determined print speed will be 300 mm/min which is not correct.

Second Example: Current Position: X=0, Y=0, Z=0, E=0 and Command: G1 X100 E100 F600

In this command, the specified print speed (F) is 600 mm/min, print head has to move from X=0 to X=100 mm and the extruder has to move from E=0 to E=100 mm. Since the position movement in X and E are same, if extruder PWM signal is acquired it will give correct print speed of 600 mm/min. The same methodology can be applied to motion of multiple axes. The key point is that extrusion speed and printer speed are equal only when the position movement in X and Y is equal to E as commanded from the G-code.

While printing strands, platform movement is confined only to one axis and the equation 3.2 can be used to calculate print speed from the extruder PWM signal and the extrusion pressure can be manually controlled. However, while printing complex geometries such as circle or oval, the Marlin firmware breaks the geometry into multiple lines and hence manual calculation is not possible. In this case, the extruder feed is very important to consider because the thickness of strand being printed depends on the print head speed and extrusion pressure. If they are not coordinated then the material extrusion will vary due to which the printed geometry will be composed of strands of irregular sizes which further indicates poor print quality.
The Marlin firmware is capable of calculating coordinated feed for different axes based on G-code provided. So if one could utilize the same PWM signal generated from Rumba board to control the pressure then there is no need of writing a new firmware and hence open source firmware can be utilized for coordinated PEM development. For this, Slic3r settings were modified so that the generated G-code from .stl file has same extruder motion as the coordinated motion in X and Y axes. By doing this, print speed was replicated to the extruder feed.

3.3 Co-ordinated Extrusion Module with RT Target

The development of the hardware setup working on constant pressure was instrumental in printing straight lines at a constant print speed with user engagement. However, this setup could not work on coordinated motion when there is a need to vary the pressure during the printing of complex geometries. In existing 3D printer, Rumba board sends digital signal (pulses) to a motor driver which controls the extrusion stepper motor, and the extrusion velocity is governed by the frequency of the signal sent to the stepper. The challenge was to identify how to utilize the same signal, translate into an analog signal and then send to pressure control valve which could generate desired pressure. The NI myRIO has on-board Real-Time (RT) microprocessor which was utilized for data acquisition and to convert a PWM signal into an analog signal. The PWM signal was acquired by digital input pin (DI0) on MSPC connector of myRIO and then converted to a number between 0 and 1, where 0 is low signal and 1 is high signal. The Mean and Standard Deviation built-in VI which collects specified number of samples and returns the mean and standard deviation of those samples. This VI was successfully used to convert the pulses into a number between 0 and 1. However, there was a lag associated with this process, the reason being, it needs to acquire a few samples in order to calculate the mean. The more
samples give better result but adds more delay into the system as presented in the 3.3 where the red line represents the mean of the black PWM signal.

![Figure 3.3: Conversion of PWM signal into a number between 0 and 1](image)

This calculation takes 1 to 2 seconds time to execute and during that time no data is being captured, many data points are missed in that duration; this is referred to as undersampling, resulting in corrupted feed output. This delay was not acceptable and hence there was a need to investigate some other approach to address this issue. The digital signal has to be converted to analog signal in real time, i.e. whenever the digital pin sends signal there should be an analog signal available to be used immediately and with smallest delay.

3.4 Co-ordinated Extrusion Module with FPGA Target

A Field Programmable Gate Array (FPGA) is a chip containing many logic gates that can be re-wired in different configurations. The working of FPGA chip is described further. "FPGA chip is made up of a finite number of predefined resources with programmable interconnects to implement a reconfigurable digital circuit and I/O blocks to allow the circuit to access the outside world. FPGAs provide hardware-timed speed and reliability and have the same flexibility as a software running on a processor-based system, but it is not limited by the number of processing cores
available. Each independent processing task is assigned to a dedicated section of the
chip, and can function autonomously without any influence from other logic blocks.
FPGAs are truly parallel in nature, different processing operations do not have to
compete for the same resources. As a result, the performance of one part of the
application is not affected when you add more processing.”[45]

NI myRIO has an on-board FPGA chip which can be programmed using Lab-
VIEW Graphical Programming Language instead of writing low-level HDL codes.
As discussed, it has hardware timed speed and flexibility as a processor. So, it was
utilized to measure the frequency of the PWM signal generated from the board. This
FPGA controller has a clock of 40 MHz frequency which implies that it can run as
fast as 25 nanoseconds per loop iteration.

The PWM signal was acquired by digital input pin (DI0) on MSP C connector
of myRIO and FPGA was used to calculate the frequency. This FPGA was used to
capture the period between the two rising edges or two pulses and number of ticks,
where each tick is 25 ns. As soon as two rising edges are received, FPGA gives the
frequency. The signal sent by the Rumba board at 40 KHz had jitters[46] so the
maximum frequency was reduced to 3 KHz which is well below the frequency of FPGA
clock, as presented in figure 3.4.

![Figure 3.4: Frequency calculation of PWM signal on FPGA](image)

Figure 3.4: Frequency calculation of PWM signal on FPGA
This period can be converted back into print speed as commanded from G-code by the calculations and calibration according to equations 3.4 to 3.8.

\[
Period = \text{number of Ticks} \times 25 \times 10^{-9} \text{ sec} \tag{3.3}
\]

\[
Frequency = \left( \frac{1}{\text{Period}} \right) \text{ Hz} \tag{3.4}
\]

\[
Calibration \text{ factor} = \left( \frac{\text{Maximum Frequency}}{\text{Maximum Print Speed}} \right) = \left( \frac{3000}{600} \right) = 5 \tag{3.5}
\]

\[
Extrusion \text{ Feed} = \left( \frac{\text{Frequency}}{\text{Calibration factor}} \right) \tag{3.6}
\]

\[
= \left( \frac{1}{\text{number of Ticks} \times 25 \times 10^{-9} \times 5} \right) \left( \frac{\text{mm}}{\text{min}} \right) \tag{3.7}
\]

\[
= \left( \frac{8000000}{\text{number of Ticks}} \right) \left( \frac{\text{mm}}{\text{min}} \right) \tag{3.8}
\]

To stop the execution, standard deviation of the extrusion feed rate calculated by FPGA VI, was calculated over 100 samples. It was observed that when no PWM signal was commanded from the Rumba board, standard deviation of the extrusion feed rate was always less than 0.0001 but was greater than 0 due to the presence of noise. So, if the standard deviation calculated in the VI was less than 0.0001 then execution was stopped, as presented in figure 3.6.

Here, the PWM signals were acquired from the Rumba board and converted back into the commanded extrusion feed from the G-code. Also, as per the Slic3r settings the position movement in E was equal to the position movement in X and Y \((\sqrt{X^2+Y^2})\), which implies that the extrusion feed rate is equal to the print speed. These equations were used to successfully calculate the print speed commanded from the G-code. The calculated print speed is then used to calculate the analog voltage sent to the valve. However, a calibration from user was required to convert extrusion feed...
feed or print speed into analog voltage. For this purpose, two gains were provided by
the user to convert it into the voltage signal required by the pressure control valve,
these two gains were offset and multiplier. These gains are material specific and are
set manually based on requirements. The analog output channel on myRIO requires
a integer between 0 and +2047, based on that it linearly outputs a voltage between
0 and 9.995 Volts. For AI and AO channels on the MSP connectors, equations 3.10
to 3.11 can be used[47].

\[
\text{LSB Weight} = \left( \frac{\text{Voltage Range}}{2^{\text{ADC Resolution}}} \right) = \left( \frac{20 \text{ V}}{2^{12}} \right) = 4.883 \text{ mV} \\
\text{Maximum Positive Reading} = +2047 \times 4.883mV = 9.995V \quad (3.10) \\
\text{Maximum Negative Reading} = -2048 \times 4.883mV = -10.000V (3.11)
\]

where LSB stands for least significant bit, the smallest value myRIO can read.
With the aid of these two gains the extrusion feed which ranges from 0 to 600 mm/min
was converted into a number between 0 to 2047 as per the dispensing required for
that particular material. The working of FPGA and RT VI are presented in figures
3.5 and 3.6 respectively.
To program the FPGA, fixed point data type was used because floating point data type is not supported. “Fixed point is a format for representing numbers on digital processing devices. It is a data type used by hardware descriptive language
(HDL) to determine how to interpret bits in a memory location. A fixed-point number can be divided into two parts: an integer (which may contain a sign bit) and a fraction. The integer and fractional parts represent the portion of the number before and after the decimal point, respectively. In fixed-point representations, this point between the integer and fraction is called the radix point.” [48]

3.4.1 Execution Time

As described, FPGA was used because its execution time was less than that of the code executed on the Real Time Target or the OS. myRIO’s onboard FPGA runs on a clock of frequency 40 MHz which means each tick of clock is 25 nanoseconds. Most of the algebraic calculations such as addition, subtraction, division and multiplication can be performed on FPGA target in 1 tick. The execution time on the FPGA Target, RT Target, computer running LabVIEW and computer running MATLAB for simultaneous four calculations is presented in equations 3.12 to 3.15.

\[
FPGA \ Target = 1 \ tick = 25 \ ns \quad (3.12)
\]
\[
RT \ Target = 14058 \ ticks = 14058 \times 25 \ ns = 0.35 \ ms \quad (3.13)
\]
\[
Computer \ (LabVIEW) = 2987 \ ticks = 2987 \times 25 \ ns = 0.074 \ ms \quad (3.14)
\]
\[
Computer \ (MATLAB) = 0.889 \ ms \quad (3.15)
\]

3.5 Identifying Process Parameters

The FPGA controller discussed in section 3.4 was successfully able to control the PEM in coordinated motion with other axes employed in real time. However, an input or calibration from the user was required to convert the coordinated extrusion
feed into the pressure required for dispensing. This calibration could be identified by analyzing the process parameters and their significance.

With reference to the fluid dispensing syringe setup used for this study and presented in figure 2.5, the ratio of diameter of syringe barrel to nozzle is high and also there is a curvature in the syringe at the nozzle inlet which makes the fluid flow laminar inside the syringe. If a pressure is applied on the material filled inside the syringe then it is assumed that no pressure drop occurs across the syringe barrel, this implies that all the pressure drop occurs across the capillary (nozzle). Computational Fluid Dynamics (CFD) used by Nordson EFD to achieve the optimum laminar flow is presented in Figure 3.7

![Flow pattern inside the syringe and nozzle](image)

**Figure 3.7: Flow pattern inside the syringe and nozzle**

If no pressure drop occurs across the the syringe barrel, then the extrusion velocity of the material exiting the nozzle tip, \( \bar{V}_E \) is related to the pressure drop across the nozzle by capillary equation 3.16:

\[
\bar{V}_E = \left( \frac{R^2 \Delta P}{8 \eta_{app} L} \right)
\]  

(3.16)
With the aid of equation 3.16, the material flow rate, $Q$ can be calculated, which is given by equation 3.17:

$$Q = \text{Area of nozzle} \times \bar{V}_E = \pi \times R^2 \times \left( \frac{R^2 \Delta P}{8 \eta_{app} L} \right) = \left( \frac{\pi R^4 \Delta P}{8 \eta_{app} L} \right) \quad (3.17)$$

where $R$ is the radius of the nozzle, $\Delta P$ is the pressure drop across the syringe and nozzle, $L$ is the length of the nozzle and $\eta_{app}$ is the apparent viscosity of the material.

Using equation 3.17, the material flow rate is a function of four parameters. However, the dependence on each parameter is not linear. For Non-Newtonian fluids, apparent viscosity decreases with the increasing shear rate, the calculation of apparent viscosity is presented in the equations 3.18 and 3.19.

$$\tau = \left( \frac{R \Delta P}{2 L} \right) \quad (3.18)$$

$$\tau = \eta_{app} \times \dot{\gamma} \quad (3.19)$$

where $\tau$ is shear stress on the wall and $\dot{\gamma}$ is shear rate of the fluid on the wall. $\tau$ can be calculated using equation 3.18 and then using equation 3.19 the apparent viscosity can be calculated if the rheological data is available. Also, it can be observed that the apparent viscosity decreases with the increase in shear rate (or the shear force inside the nozzle) which is preferable because high viscosity may limit the flow through fine extrusion nozzle [49].

To confirm the relation described in the equation 3.17, an experiment was conducted with toothpaste of density 1.34 g/ml and hair gel of density 0.422 g/ml. A LabVIEW VI was developed to controllably dispense fluid from the syringe for a period of 10 seconds. For each pressure and nozzle diameter, the fluid was dispensed
three times, weighed and then the average mass flow rate was calculated in mg/s. For this experiment, it was assumed that the fluid is incompressible and the volume flow rate is directly proportional to the mass flow rate. The LabVIEW VI developed for this purpose is presented in figure 3.8.

Figure 3.8: LabVIEW VI for fluid dispensing

Tables 3.1 and 3.2 present the recorded data of mass flow rate with respect to different applied pressures and nozzle diameters for toothpaste and hair gel respectively.

Table 3.1: Mass flow rate vs pressure input for the toothpaste (mg/s)

<table>
<thead>
<tr>
<th>Nozzle Diameter (mm)</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.417</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.42</td>
<td>0.54</td>
<td>0.67</td>
<td>0.95</td>
</tr>
<tr>
<td>0.468</td>
<td>0.65</td>
<td>1.55</td>
<td>2.73</td>
<td>4.31</td>
<td>6.04</td>
<td>7.93</td>
<td>10.65</td>
</tr>
<tr>
<td>0.650</td>
<td>6.16</td>
<td>12.38</td>
<td>21.10</td>
<td>32.69</td>
<td>43.32</td>
<td>53.13</td>
<td>66.00</td>
</tr>
<tr>
<td>0.800</td>
<td>12.30</td>
<td>24.84</td>
<td>39.58</td>
<td>55.70</td>
<td>75.40</td>
<td>92.70</td>
<td>136.25</td>
</tr>
<tr>
<td>0.982</td>
<td>32.46</td>
<td>62.82</td>
<td>82.30</td>
<td>110.33</td>
<td>156.48</td>
<td>209.69</td>
<td>256.25</td>
</tr>
</tbody>
</table>
Table 3.2: Mass flow rate vs pressure input for hair gel (mg/s)

<table>
<thead>
<tr>
<th>Nozzle Diameter (mm)</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.417</td>
<td>15.01</td>
<td>25.82</td>
<td>70.36</td>
<td>130.99</td>
<td>190.49</td>
<td>275.09</td>
<td>341.07</td>
</tr>
</tbody>
</table>

It is observed that there was no extrusion from 0.417 mm diameter nozzle at low pressures and very low extrusion at high pressures. So the data for that particular nozzle was not considered in the analysis. A plot for mass flow rate vs applied pressure for different nozzle diameters is presented in figure 3.9. Also, a plot for hair gel data is presented in figure 3.10. It is observed that the mass flow rate is almost linearly proportional to the applied pressure for toothpaste for different nozzle diameters. Similar trend is observed in hair gel for a nozzle diameter of 0.417 mm and hence more nozzles were not used. This result clearly justifies that equation 3.16 holds true.

Figure 3.9: Mass flow rate vs nozzle diameter for toothpaste
It is observed from these experiments that there was no extrusion through 0.417 mm nozzle and very low extrusion through 0.468 mm nozzle. The reason for this low extrusion is the moderate viscosity of the toothpaste. It is very hard to push the viscous material through nozzle and also, it was observed that the material after coming out of the nozzle try to spread. If the material is hard to push through the nozzle then a lower viscosity fluid is recommended, if the material spreads freely after coming out of the nozzle then higher viscosity fluid is recommended. The reason being, materials with low viscosity do not retain their shape after extrusion and as such moderate to high viscosity is required to extrude stable filaments. But high viscosity may limit the flow through fine extrusion nozzles which was observed in the experiment conducted. To address this issue, a material with higher viscosity and shear thinning behavior is preferred [50]. When no pressure is applied to the syringe, the apparent viscosity of the fluid is high, equals to the nominal viscosity but with the pressure application, the apparent viscosity of the fluid drops, enabling fluid flow through fine nozzles. After exiting the nozzle, the pressure drops to zero, the viscosity again increases to nominal value and the material retain its shape.

Figure 3.10: Mass flow rate vs nozzle diameter for hair Gel
3.6 3D Printed Strand Width for Varying Process Parameters

Based on the discussion in section 3.5, it is concluded that the extrusion velocity or material flow rate is dependent on various factors including pressure applied, apparent viscosity of the material, radius and length of the nozzle. But for a particular material and application, the same nozzle is used, hence the length and radius of the nozzle are not considered as process parameters. Also, apparent viscosity is a function of shear rate which is further a function of applied pressure. This implies that extrusion velocity or the material flow rate is a function of applied pressure as described in the following equations from 3.21 to 3.23:

\[
\bar{V}_E = \left( \frac{R^2 \Delta P}{8 \eta_{app} L} \right) \Rightarrow \bar{V}_E = f (\Delta P, \eta_{app}) \quad (3.20)
\]

\[
\eta_{app} = f (\dot{\gamma}) & \dot{\gamma} = f (\Delta P) \Rightarrow \eta_{app} = f (\Delta P) \quad (3.21)
\]

\[
\Rightarrow \bar{V}_E = f (\Delta P) \quad (3.22)
\]

\[
Q = Area \ of \ nozzle \times \bar{V}_E \Rightarrow Q = f (\Delta P) \quad (3.23)
\]

However, the relationship between material flow rate and applied pressure cannot be defined since the fluid apparent viscosity changes with the application of pressure to the material. To explain this further, an experiment was conducted with NEA123T by Norland Products, a polyurethane based resin containing nano-particles. It has high nominal viscosity of 300,000-400,000 cps and exhibits shear thinning behavior at high pressures. “It has UV photo-initiators with maximum absorption at 365 nm and a heat-initiator active in the 60 to 80 °C range. It is a single component adhesive that cures tack free in seconds to a tough, resilient polymer when exposed to ultraviolet light.” [51] The strands printed with this material were characterized
based on different process parameters, namely print speed and extrusion pressure. The purpose of this experiment was to experimentally justify how the process parameters contribute to the strand width. The nozzle used for this experiment had a diameter of 0.51 mm and nozzle to bed distance was kept at 90-95% of nozzle diameter. The resulting strand width was measured using microscope, Nikon Eclipse LV150 which has a resolution of 0.01 mm, sample measurement image is presented in figure 3.11.

Two replicates with two runs per replicate were conducted and three strand width measurements per strand were taken at the extremes and middle of the strand. For constant process parameters, maximum variation of 5% was observed at different locations within same strand and 10% variation for different strands. Mean strand width (mm) for varying print speeds and applied pressures is tabulated in table 3.3, where X represents the formation of inconsistent strands or unsuccessful printing.
Table 3.3: Diameter of printed strand (mm)

<table>
<thead>
<tr>
<th>Pressure (PSI)</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>0.88</td>
<td>0.67</td>
<td>0.42</td>
<td>0.31</td>
<td>0.22</td>
<td>X</td>
</tr>
<tr>
<td>70</td>
<td>0.52</td>
<td>0.39</td>
<td>0.23</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>50</td>
<td>0.42</td>
<td>0.24</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

3.7 Using ANN to Predict Strand Width

An Artificial Neural Network (ANN) was proposed to characterize this process with two input parameters and one output parameter. Inputs to this ANN were applied pressure and print speed, and the output was strand width. The activation function was hyperbolic tangent and the network was trained on 10 data sets obtained in table 3.3. The ANN is graphically described in figure 3.12.

![ANN Model to Predict Strand Diameter](image)

Figure 3.12: ANN model for predicting strand width

The ANN models were developed in LabVIEW using Analytics and Machine Learning (AML) Toolkit [52]. This toolkit includes supervised and unsupervised
machine learning algorithms, however, ANN is categorized as a supervised learning approach. ANN can define a complex, non-linear form of hypotheses with parameters $W$ and $b$ that can be fitted into provided data, where $W$ is the weight of each node and $b$ is the bias \[53\]. The neuron is a computational unit that takes inputs, $x_i$, and outputs $f(z)$ where

$$z = W^T x = \sum_{i=1}^{n} W_i x_i + b_i$$

(3.24)

and $f$ is the activation function which is hyperbolic tangent. This activation function predicts the output ($y$) and the predicted output $\hat{y}$ is given equation \[3.25\]

$$\hat{y} = f(z) = \tanh(z)$$

(3.25)

For a fixed training set $\{(x^{(1)}, y^{(1)}), \ldots, (x^{(m)}, y^{(m)})\}$ of $m$ training sets where $x^{(i)}$ and $y^{(i)}$ are inputs and outputs of $i^{th}$ training set respectively, the cost function is given by equation \[3.26\]

$$J(W, b) = \left[ \frac{1}{m} \sum_{i=1}^{m} \frac{1}{2} \| \hat{y}^{(i)} - y^{(i)} \|^2 \right]$$

(3.26)

The AML toolkit randomly selects the weights, $W$, and bias, $b$, values during the first iteration of optimization. Afterwards, for each successive iteration, the optimization algorithm updates the values of $W$ and $b$, in order to minimize a cost function. It is important to note that the user provides the number of neurons in the hidden layer and stopping criteria for optimization. If the stopping criteria (Mean Squared Error (MSE) and maximum number of iterations) are violated, then the program stops the optimization process.
The next step is to identify the number of hidden neurons and maximum number of iterations which will be used to stop the execution of ANN. For this purpose, MSE was calculated for different number of hidden neurons and different iterations. Figure 3.13 presents the performance of ANN for varying iterations over different number of hidden neurons.

Figure 3.13: MSE as a function of maximum number of iterations for different neurons

From this graph, it is observed that MSE saturates to a value of 0.015 after 1500 iterations for 5 hidden neurons. However, for number of hidden neurons other than 5, MSE takes either more iterations to converge to this value or converges at a higher value. Hence, from this data, it was advisable to use 1500 iterations. But the behavior of different number of hidden neurons at 1500 iterations was unknown. So MSE was calculated for different number of hidden neurons at 1500 iterations which is presented in figure 3.14.
From the performance of ANN at fifteen hundred iterations for different number of hidden neurons it can be implied that MSE is least for 5 hidden neurons and increasing the number of hidden neurons increases MSE. Hence, a combination of hidden number of neurons and maximum number of iterations were chosen as five and fifteen hundred respectively, which yields the desirable MSE.

The LabVIEW VI developed for this purpose is trained on the data set obtained from printing strands with different applied pressures and print speeds tabulated in table 3.3. The VI developed is presented in figures 3.15.
The ANN model presented in figure 3.15 is trained, with inputs of print speed and extrusion pressure, and output of printed strand width. When this model is trained, it creates and saves a model file with the extension of .json.

Another VI, presented in figure 3.16 uses the saved .json file to deploy the model and predict the strand width. For any given print speed and desired strand
width, this ANN can predict the extrusion pressure. This prediction was used for the characterization and discussed in section 4.1.

3.8 Using ANN to Predict Pressure in Real-Time

After developing the ANN model discussed in section 3.7, another ANN model was proposed to predict the extrusion pressure based on input parameters, print speed and desired strand width. Using the same methodology discussed in section 3.7, the number of hidden neurons and maximum number of iterations were found to be 3 and 1500 respectively. For this combination, the execution time to deploy the model on Host (PC) was found to be within the range of 30 to 40 ms with mean squared error of 0.070.

This ANN VI was integrated with FPGA VI to execute in real-time. For any given print speed and desired diameter of the strand (which is equal to diameter of nozzle used), this ANN predicts the extrusion pressure. Based on this prediction, a voltage signal is sent to the pressure control valve to get the desired pressure. In this process, the intervention is not needed. Another FPGA VI was developed with some modifications to the previous FPGA VI presented in figure 3.5. This VI calculates the extrusion feed or print speed and then passes it to the Host (PC) through FPGA interface where it saves the data to shared library node. This shared library node then pass this value to the ANN. This ANN predicts the extrusion pressure which is then stored to another shared library node. This shared library node passes the data to FPGA using FPGA interface. Using extrusion pressure prediction, FPGA VI calculates the voltage to be sent to the pressure control valve. To stop the execution, the period between two pulses is measured and if it was more than 20 ms, the execution is aborted as presented graphically in figure 3.17. The VI are presented in figure 3.18 and 3.19. ANN VI are presented in figures 3.15 and 3.16.
Figure 3.17: Execution, frequency calculations and condition to stop

Figure 3.18: FPGA VI communicating with ANN on Host (PC) in real-time
Based on the value written to the analog channel, the desired pressure is obtained for the pressure control valve which is used for the functioning of the PEM. The overall process flow diagram, beginning from the digital signal acquisition from Rumba board to control of PEM is presented in figure 3.20.
Figure 3.20: Overall process flow
CHAPTER 4

Results and Discussion

In this chapter, ANN model was used to characterize 3D printed strand width of NEA123T. Furthermore, another ANN model which predicts the extrusion pressure was integrated to the PEM in real-time. Using this ANN based PEM, multi-layer NEA123T scaffolds were successfully 3D printed.

4.1 ANN based Characterization

Referring to the experiments described in section 3.6, strand width was predicted for different controlled process parameters using ANN model developed in section 3.7. To determine the accuracy of ANN, first the prediction was made on the parameters used in the training process of ANN. From the results of strand width prediction, it was observed that the maximum error was restricted to 0.03 mm as presented in figure 4.1.

![Figure 4.1: ANN prediction over training dataset](image)

Figure 4.1: ANN prediction over training dataset
To determine the performance of ANN, strands were 3D printed over random process parameters, not used in the training process and a prediction was made with ANN. This prediction was then compared to the experimentally measured value and the error ranged from 0.01 mm to 0.03 mm. As presented in 4.2, it can be observed that ANN prediction over random dataset was also close to the actual experimental value. These results gave confidence to use this ANN model for the characterization.

![Figure 4.2: ANN prediction over random dataset](image)

Figure 4.2: ANN prediction over random dataset

Using the same methodology, the strand width was predicted for different process parameters. Distinct trends were observed due to non-linear relationship between material flow rate and apparent viscosity. These plots are presented in figures 4.3 and 4.4.
Figure 4.3: Predicted strand width for varying print speeds and different constant pressures

Figure 4.4: Predicted strand width for varying extrusion pressures and different constant print speeds
From these plots, it is observed that if one of the process parameters is known within the range of ANN training dataset then other process parameter can be predicted using ANN. Ideally, for printing a strand of width same as nozzle diameter, the print speed should be equal to the material extrusion velocity, $\bar{V}_{E}$[49]. This implies that for a fixed print speed there exists a unique pressure to be applied to the syringe. If the applied pressure is less than the desired pressure, then there will be less material flow rate resulting in strand width less than the diameter of nozzle, if the extrusion pressure is too low then the strand will be formed with gaps which means unsuccessful prints. On the other hand, if the applied pressure is more than the desired pressure, then it will result in high material flow rate and the printed strands width will be more than the diameter of the nozzle.

In a very similar manner, for a given pressure, there exist an unique print speed. If the print speed is less than the desired print speed then the width of printed strands will be more than the diameter of the nozzle. If the print speed is more than the desired print speed then resulting strand width will be less than the nozzle diameter or there will be unsuccessful printing.

This explanation can be supported by the images of 3D printed strands. Figure 4.5 presents the printed strand of width more than the nozzle diameter. From the cross-sectional view of strand, it is observed that the printed strand is almost rectangular. The process parameters used for printing were 95 PSI and 100 mm/min, however, from the characteristic plot it is observed that for printing a strand of width 0.5 mm at 95 PSI, the print speed should be 280 mm/min. But the slow speed of platform resulted in more material deposition and hence the printed strand is thicker than nozzle diameter and rectangular in cross-section. Similarly, figure 4.6 presents the printed strand of diameter less than the nozzle diameter.
The process parameters used for printing were 70 PSI and 200 mm/min, however, from the characteristic plot it is observed that for printing a strand of width 0.5 mm at 70 PSI, the print speed should be 125 mm/min. But the faster speed of the platform resulted in lee material deposition and hence the printed strand is thinner than nozzle diameter.
Figure 4.7 presents the formation of inconsistent strand due to extremely low deposition of the material. The process parameters used for this print were 95 PSI and 600 mm/min.

![Unsuccessful print](image)

Figure 4.7: Unsuccessful print

4.2 Printing Scaffolds using Real-Time ANN based PEM

Since with the developed methodology and Real-Time ANN based PEM strands were successfully printed, this module was then used to print multi-layer scaffolds using NEA123T to demonstrate that it can be used on fabricate complex geometries.

To illustrate the working of Real-Time ANN based PEM, the process for printing just one line is explained and the same concept is extended over the entire geometry. Considering the print head is at location, X=0, Y=0 and E=0, and a G-code command for first line is: G1 X10 E10 F100

The position movement in X and E directions are equal so the print speed will be replicated to the extrusion feed. Based on the commanded G-code, the extruder step pin generates a PWM Frequency of 0.5 KHz, this PWM signal is then read by the FPGA Target which first calculates the PWM frequency and then using this frequency it determines a print speed of 100 mm/min. After the print speed is determined, this print speed is passed to Host (PC) and saved to a shared library node, this shared library node is then used by ANN VI which predict the extrusion pressure
of 65 PSI. The input parameters for the ANN are print speed 100 mm/min (calculated by FPGA) and desired strand width of 0.51 mm (equal to the nozzle diameter). This predicted extrusion pressure is then saved to another shared library node and passed to FPGA Target. FPGA Target receives the value and converts this value into a number between 0 and +2047 as per calibration of pressure control valve. This calculated number, 1488 represents 6.67 Volts, which is then written to the analog channel if pulses are being received from extruder pin. This voltage is then sent to the pressure control valve which outputs 65 PSI to the syringe from which dispensing occurs.

First, a two layer scaffold with 20% infill was printed and it was observed that due to lack of available support structure, material was sticking to the nozzle instead of the base, which in turn distorted the perimeter of the scaffolds. Afterwards, another scaffold with 40% infill was printed where it was observed that more material was sticking to the base but some was still sticking to the nozzle due to poor bonding between layers. To increase the support structure further, 80% infill was chosen and single layer scaffold was printed which resulted in better print quality. To address the issue of poor bonding between layers, each layer was printed and post-cured after being printed by using the UV LED. Then, a second layer was printed on the post-cured layer, following this approach, three layer scaffold was successfully printed. All the printed scaffolds are presented in figure 4.8.
Figure 4.8: Printed Scaffolds
CHAPTER 5

Conclusions and Future Research Recommendation

This research is focused on the development and integration of a PEM, capable of dispensing multi-materials as per commanded G-code from an existing multi-modality 3D printer. The general viscous extrusion approach using stepper motor based module was discussed. Delayed extrusion and oozing were issues faced with stepper motor extrusion. Due to this, post processing of G-codes was required in order to extrude extra material before printing and using continuous flow to print. However, this does not provide good control over the flow of material during printing. Also, when transitioning to next layer, oozing or uncontrolled was experienced. To address these issues, PEM was proposed. The hardware setup for PEM and photo-polymerization module was prototyped and integrated into the multi-modality additive manufacturing platform. While using PEM, it was observed that low viscosity fluids do not retain their shape after being extruded through the nozzle and it is hard to push moderate to high viscosity materials through a fine geometry extrusion nozzles. To extrude stable filaments through PEM, shear thinning fluids were proposed which exhibit high nominal viscosity and with the applied pressure their apparent viscosity decreases, enabling improved fluid flow. A poly-urethane based resin, NEA123T, was chosen for this study and a methodology was developed to characterize the strand width with varying controllable process parameters of PEM using ANN model. The ANN performance was verified over the dataset used in training process and random dataset where a maximum error, MSE, of 0.03 mm was observed from the prediction.
Using this ANN model, strand width was predicted, and plotted for various of process parameters. Different trends were observed

Another ANN model was proposed to predict extrusion pressure based on selected input parameters, print speed and desired strand width. This ANN model was successfully integrated with the FPGA Target, Host(PC) and existing multi-modality 3D printer.

An ANN based real-time PEM was successfully developed which addressed delayed extrusion and oozing. Using the developed module, NEA123T scaffolds were successfully 3D printed and polymerized. While printing multi-layer scaffold, poor bonding strength was observed between layers because of partial curing. A three layer scaffold was successfully 3D printed by post curing each layer after being printed.

Some recommendations for future research are also described. The ANN used for this study was trained with 10 datasets. However, it is recommended that ANN should be trained on a larger dataset obtained using Design of Experiments (DOE) approach. For a particular material, more input parameters such as Nozzle to Bed Distance (NBD), UV intensity, and nozzle diameter can be included in the ANN model for better performance. Multiple materials can be dispensed and 3D printed using this setup and an ANN can be trained over multiple materials using the same methodology. A vision system for real-time feedback could be incorporated so that the open-loop system can be converted into a closed loop system. If there is an error between prediction and actual value, the control system can take necessary corrective actions to dynamically change controller process parameters.

Also, Nordson pressure sensor syringes can be integrated into the system. These syringes have embedded sensor which can measure the pressure at the nozzle entrance and can provide that information as feedback to the control system. A controller can be developed to accept this information and perform a corrective action.
Appendix
A Portion of G-code for 80% Infill Printed Scaffold:

G21; set units to milimeters
G28 ; home all axes
G90 ; use absolute coordinates
T2;
M82 ; use absolute distances for extrusion
G92 Z0
G92 E0
G1 Z0.450 F600.000
G1 X30.578 Y20.578 F600.000
G1 X39.422 Y20.578 E8.86414 F100.000
G1 X39.422 Y29.422 E17.72829
G1 X30.578 Y29.422 E26.59243
G1 X30.578 Y29.422 E35.38140
G1 X30.578 Y20.653 E44.95408
G1 X30.225 Y20.225
G1 X39.775 Y20.225 E44.95408
G1 X39.775 Y29.775 E54.52676
G1 X30.225 Y29.775 E64.09944
G1 X30.225 Y20.300 E73.59695
G1 X30.658 Y20.475
G1 X39.212 Y21.185
Bibliography


[36] P. Ravi, “Towards the fabrication of bioresorbable constructs with customized...


[50] C. Zhu and J. E. Smay, “Catenary shape evolution of spanning structures in
direct-write assembly of colloidal gels,” *Journal of Materials Processing Tech-

