Defect Detection Method for an FDM Printer

Proposal Report

MTRL 466

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Group: 1
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Executive Summary

The goal of this capstone project is to demonstrate a proof of concept method for augmenting a fused deposition model (FDM) 3D printer with the ability to sense defect formation and stop the printer from wasting more material on a failed print. The initial problem is that a large number of 3D prints end in failures from budget FDM printers due to printing defects such as over and under extrusion of filament material from the nozzle, stringing and oozing, overheating, layer shifting, layer separation, warping and many more. This project proposal will explore a variety of sensors that can be used to detect defects and then will focus specifically on vision bases sensing as the proposed sensor detection method. Defect detection can be achieved by translating video frames from a camera into an HSV file using an image conversion software to isolate the 3D model so that it can be compared to the original CAD image and overlapped to check for errors. The objectives of this project are to maximize the number of defects detected by the sensor while also minimizing the cost of the solution. Additionally, the number of different geometries and filaments that allow defects to be detected will also be maximized. This can be achieved by adhering to a weekly project schedule, performing a risk assessment, identifying the budget and safety concerns regarding the solution, and having an effective communication plan throughout the project.

Table of Contents

1.0 - Problem Definition

Fused deposition Modeling (FDM) is one of the most common 3D printing techniques for rapid prototyping. FDM printers use a thermoplastic filament, which is heated to its melting point and then extruded, layer by layer, to create a three-dimensional object as seen in Figure 1 below [1]. These printers can use two types of materials, the modeling material which is used to construct the part and the support material which is used as scaffolding to support new layers on the print. The most common printing material for FDM is acrylonitrile butadiene styrene (ABS), a common thermoplastic that is used to make many consumer products, from LEGO bricks to whitewater canoes [1]. For a comprehensive list of FDM materials and their highlights, see Appendix A [2].

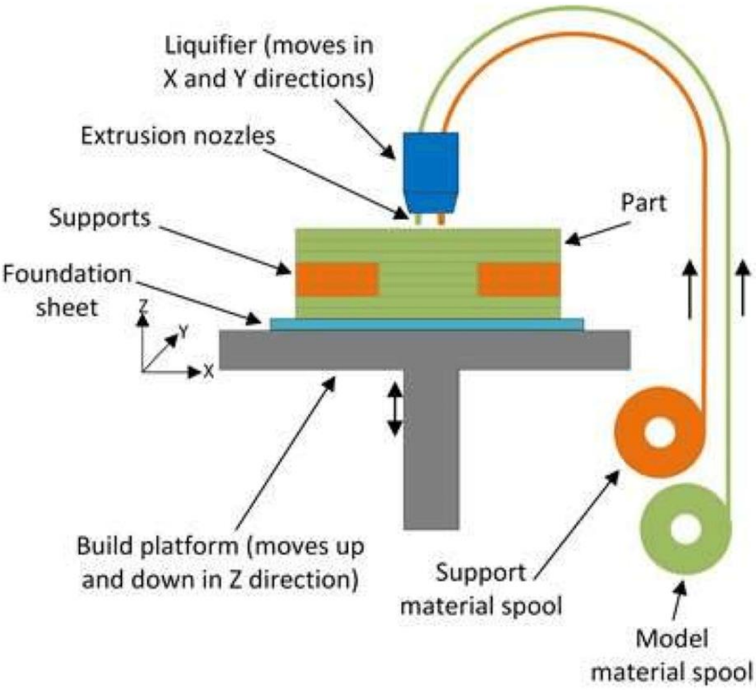
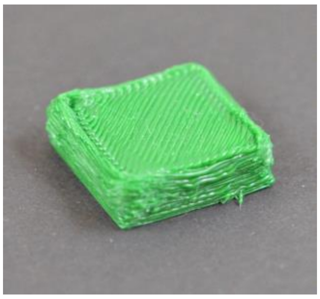
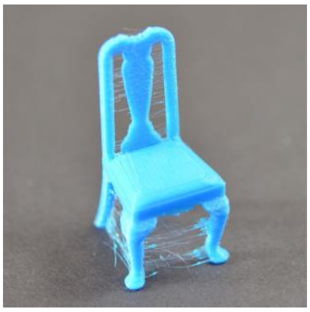
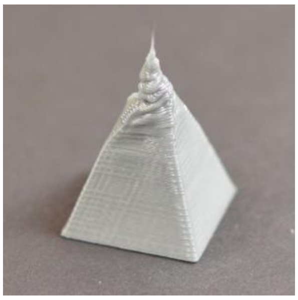


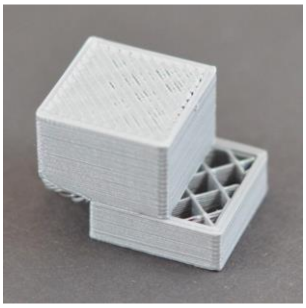
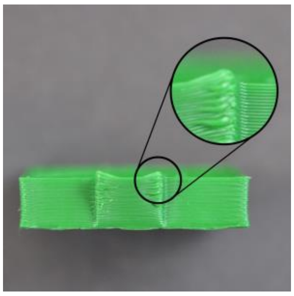
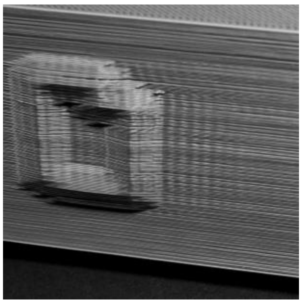
Figure 1. FDM Printing Process [3]

In Figure 1 above, the materials are fed from spools to the extrusion nozzles that are attached on a grid that only moves along the X and Y directions while the build platform itself is responsible for the movement in the Z direction. As a layer of the physical part, previously designed on CAD software, is completed, the table where the layer is built moves a unit down in the Z direction to allow for the next layer to be printed. The nozzle then repeats the process of printing another layer of the physical part above the layer that has been created earlier. The build material layer is heated to above its melting point for solidification in 0.1 seconds after extrusion, allowing it to combine with the previous layer through adhesion [4].

As a part is being printed, several types of defects can form even with proper printing settings. With the printing process taking a significant time to complete, the FDM printing process would not be cost-effective to be manually monitored. Therefore, defects often go undetected for long periods of time which results in wasted print material and time. The common types of printing defects are listed in Table 1 below.

Table 1. Defect Type and Description for FDM Printers

Diagram	Defect Type	Description
 Figure 2. Over Extrusion [5]	Over Extrusion	The nozzle extrudes too much print material causing the outer dimensions of the part to be altered.
 Figure 3. Under Extrusion [5]	Under Extrusion	The nozzle does not extrude enough print material causing gaps between adjacent extrusions of each layer.
 Figure 4. Stringing and Oozing [5]	Stringing and Oozing	Stringing (otherwise known as oozing whiskers, or “hairy” prints) occurs when small strings of plastic are left behind on a 3D printed model [5]. This is common when the extruder is moving to new locations.
 Figure 5. Overheating [5]	Overheating	Caused when there is not a balance in extruding temperature and cooling so that the part can maintain the specified dimensions.

 Figure 6. Layer Shifting [5]	Layer Shifting	It can be caused if the printer is bumped or moved, resulting in the tool head moving to a new location.
 Figure 7. Layer Separation and Splitting [5]	Layer Separation and Splitting	If the layers do not bond well enough together, layer separation and splitting can occur.
 Figure 8. Curling and Warping [5]	Curling and Warping	This is usually caused by overheating issues. If the plastic does not cool quickly enough, the part can change shape over time. Warping can also be caused by the plastic shrinking as it cools.
 Figure 9. Vibrations and Ringing [5]	Vibrations and Ringing	Ringing is a wavy pattern that may appear on the surface of the print due to vibrations or wobbling [5].

Most defects occur since FDM printers are usually not equipped with any defect detection or correction systems. For the purpose of this project, the printer that will be focused upon is a Prusa I3 as it is the one available to us through our project sponsors. This printer does not have any intervention system to detect defects occurring. The overall goal is to demonstrate a proof of concept method for augmenting an FDM 3D printer with the ability to sense defect formation and stopping the printer from wasting more material on a failed print. The requirement for this project is that the cost of the solution (external system) must be less than the 3D printer itself as well as being financially justifiable in terms of the cost savings from the potential wasted material. The solution must also be able to effectively detect defects and prevent wasting print material using a certain type of sensor or combination of sensors. A variety of sensors can be used to detect defects including proximity, infrared, chemical, acoustic, thermal, vision, and ultrasonic sensors as shown in Table 2 below.

Table 2. Sensor Type and Description for Detecting Defects on FDM Printers

Sensor Type	**Description**
Proximity Sensor	In order to sense objects, the proximity sensor radiates or emits a beam of electromagnetic radiation, usually in the form of infrared light, and senses the reflection in order to determine the object's proximity or distance from the sensor [6].
Infrared Sensor	An infrared sensor can sense certain characteristics of its surroundings by emitting or detecting infrared radiation as well as being able to measure the heat emitted by an object and detecting motion [7]. Infrared sensors can be rather expensive and may not be an appropriate solution for this project.
Chemical Sensor	A chemical sensor detects chemical concentrations in the air near the sensor and would be challenging to detect defects occurring during the print.
Acoustic Sensor	Acoustic sensors use piezoelectric materials to generate and detect acoustic waves. As the acoustic wave propagates through or on the surface of the material, any changes to the characteristics of the propagation path affect the velocity and/or amplitude of the wave [8].
Thermal Sensor	Thermal sensors can detect temperature. These sensors can be expensive and the data obtained may not be able to effectively detect defects.
Vision Sensor	Vision sensors use images captured by a camera to determine the presence, orientation, and accuracy of parts [9].
Ultrasonic Sensor	Ultrasonic sensors measure distance as the sensor head emits an ultrasonic wave and then receives the wave reflected back from the target [10].

The most viable sensors for this project would be either a vision sensor or ultrasonic sensor as they have the best chance of detecting defects from the data they collect. Of these, a vision sensor will be the method of detection that will be focused upon as it is the preferred method of accurate defect detection throughout our research.

The key issues to address include creating a financially viable solution, collecting useful data from the sensor and being able to detect defects during the printing process. This would involve creating a budget for all parts required to detect and stop the 3D printer, mount the sensor in a way in which it can obtain accurate data and creating a code to filter through the data in search of defects so that it can notify to the printer to stop printing. The project sponsors have provided sufficient knowledge about 3D printers so that our design team can create an optimal solution with their interests in mind.

1.1 - Technical Review

Some of the existing solutions to enhance the ability of budget FDM printers to detect defects require human interaction in order to stop the printer once a defect has occurred. An example of this is using Octoprint software on a Raspberry Pi. The Raspberry Pi (a small computer) would be connected to the FDM printer and a vision sensor using a USB cable while the Octoprint software would allow for the ability to control the vision sensor and monitor the visual data of the 3D printer remotely. This would require a person to constantly check the data from the visual sensor throughout the print in order to detect defects. This solution is not viable as it requires human interaction in order to stop the print instead of having it done automatically.

Similarly to this, another solution uses machine vision to compare the dimensions of the part to the model. This method involves 3D scanning to capture a coordinate of 3D points (point-cloud) on the product surface which can then be used as a geometric representation of the printed part [11]. This solution is not viable as it requires the use of a 3D scanner which exceeds the budget for this project.

A third solution involves the implementation of a robust and real-time ultrasonic motion-capture system with the addition of optical and magnetic sensing [12]. To design and implement the system, a distance-estimation method called the Extended Phase Accordance Method (EPAM), which can measure the distance to a moving object with a standard deviation of less than 1 mm, was devised [12]. The current version of the system conducts motion capture using 5 markers attached to a user and can work at around 10 frames per second (fps), with an error of less than 55 mm and a standard deviation of 42 mm [12]. This solution is not viable as it requires a lot of data collection and identification resulting in a design process that can exceed our project deadline.

Some theoretical work to help define the solution for this project is to use vision-based error detection by using a camera that will take a video of the part at a specified frame rate at single or multiple angles as it is being printed. The video frames will then be converted into an HSV file using an image conversion software to isolate the 3D model as seen below in Figure 10. It can then be compared to the original CAD image and overlapped to check for errors [13]. Once the sensor has detected a defect, it relays a signal to the printer to cease printing. The error margins in the study taken into account were 5% and the proposed method showed a 100% detection rate for failure [13]. Due to the low cost of this method and the success from various sources, it presents a viable method for defect detection.

Figure 10. Comparison of the 3D print to the expected model [14]

2.0 - Project Objectives and Quantitative Goals

The need statement for this project is to demonstrate a proof of concept method of augmenting an FDM 3D printer so that it can automatically stop whenever a sensor detects a defect in the part. This can be done by physically attaching a sensor to the FDM printer and writing code to filter through the data from the sensor to determine when a defect is forming. The quantitative goals for this project are to adjust the free variables while adhering to the constraints in order to achieve the project objectives as defined in Table 3 below.

Table 3. Project Objectives, Constraints, and Free Variables

Project Objectives and Quantitative Goals	**Description**
Objectives	1. Maximize the number of defects detected by the sensor 2. Maximize the number of different geometries and filaments that allow defects to be detected 3. Minimize the cost of the solution
Constraints	1. The project must cost less than $850 USD, which is the price of the printer 2. The project must be completed by November 25th, 2019 3. The thickness of each layer being deposited by the nozzle 4. The material of the FDM printer bed 5. The nozzle type 6. The heating system used by the FDM printer 7. The printer model is Prusa i3 8. The extrusion temperature and rate 9. FDM printer and slicer settings

Free Variables	1. Types of defects detected 2. Type of sensor used 3. The location of the sensor 4. The geometry and material of the solution 5. The lighting, temperature, noise levels and airflow in the room

3.0 - Initial Project Schedule

In this section, the weekly accomplishments that our group aims to achieve in order to meet the entire project goals are given in Table 4 below. Additionally, a Gantt Chart is provided in Appendix B to help visualize the initial project schedule.

Table 4. Weekly Schedule of Goals

Week	Goals	Description
Week 1 (September 4 – 7)	1. Choose Capstone Project and Begin Research	Group meeting with our sponsor occurred on September 6th where we formed our group and started research.
Week 2 (September 8 - 14)	2. Task Identification and Planning 3. Problem Identification	Giving clear and defined design objectives, constraints and free variables as well as finding out the greatest risks of the overall project. A general budget usage plan will also be created. Possible safety hazards will be identified and the rough draft for the Proposal Report will be created.
Week 3 (September 15 - 21)	1. Design Objective 2. Identify Design risks 3. Budget Scoping 4. Identify Safety Hazards 5. Project Proposal Writing	Giving clear and defined design objectives, constraints and free variables as well as finding out the greatest risks of the overall project. A general budget usage plan will also be created. Possible safety hazards will be identified and the rough draft for the Proposal Report will be created.
Week 4 (September 22 - 28)	1. Finalize Proposal Report 2. Review Project Proposal Feedback 3. Technical Research for Solutions	Finalize the Proposal Report and edit for spelling, grammar, and content. Review Proposal Report once feedback has been given in order to optimize the Midterm Report and Presentation. Further research should be conducted to determine how to

	4. Design Brainstorming	effectively implement a defect detection sensor.
Week 5 (September 29 - October 5)	1. Continued Design Brainstorming 2. Continued Design Options Narrowing	Continue to advance the design process and assess the best options for effective defect detection based on the objectives, constraints, and free variables.
Week 6 (October 6 - 12)	1. Select Final Design 2. Project Risk Assessment Update 3. Discuss Economic / Socio-Economic & LCA 4. Project Presentation 5. Report Preparation	A consensus should be reached regarding the final design. New information about the risk assessment should be shared and a discussion about the association of our design with Socio-Economic & LCA should be held. Finally, the Midterm Presentation should begin to be prepared for and the Midterm Report should be drafted.
Week 7 (October 13 - 19)	1. Midterm Report & Presentation Accomplishments	The Midterm Presentation will occur during the week and the Midterm Report will be submitted.
Week 8 (October 20 - 26)	1. Discuss Midterm Review Feedback 2. Iterate Final Design 3. Improve Economic / Socio-Economic & LCA 4. Illustrate Working Principle (Quantitative) 5. Calculations 6. Rapid Prototyping	Review feedback for Midterm Report and the Midterm Presentation. Improving upon the aspects of Socio-Economic & LCA while also quantitatively demonstrate the working mechanism of the design. Finally, test data should be identified, and the viability of the design should be discussed.
Week 9 (October 27 - November 2)	1. Continued Iteration of Final Design 2. Continued Improvement of Economic / Socio-Economic & LCA 3. Continued Illustration of Working Principle (Quantitative) 4. Continued Calculations 5. Rapid Prototyping	Redo the tasks in Week 8 and continue the research on the viability of the working principle. Testing should also be validated or improved.
Week 10 (November 3 - 9)	1. Continued Illustrate Working Principle (Quantitative)	Finalize and validate and calculations and designs. Continue to improve upon the design and advance the design process.

	2. Continued Calculations 3. Rapid Prototyping	
Week 11 (November 10 - 16)	1. Final Report Preparation	Assign specific tasks to group members in order to split the remaining workload of the Final Report
Week 12 (November 17 - 23)	1. Final Report Preparation 2. Create Final Report Rough Draft	Continually improving upon and working on the final report. Prepare a draft of the Final Report so that it can be discussed in the weekly formal meetings.
Week 13 (November 24 - 30)	1. Final Report Submission 2. Final Presentation	Submission of Final Report and delivery of Final Presentation.

4.0 - Risk Assessment

The greatest risks associated with the project's overall success, the consequences of these risks, and possible solutions to these risks are shown in Table 5 below. The likeliness of each risk occurring decreases from the top of Table 5 to the bottom.

Table 5. Project Risks and their Associated Consequences and Solutions

Risk	**Consequences**	**Solution**
Not enough time to complete the project.	The project objectives will not be met resulting in an incomplete solution and a poor mark in this course.	Monitor the project progression and increase the time spent on the project if the project is falling behind schedule.
Discovering that the proposed solution exceeds the budget.	The project does not adhere to all the objectives and constraints resulting in an inappropriate solution and a poor mark in this course.	Create and update a budget plan for the project which monitors prices of possible parts needed. Identify any potential equipment or software needed for the proposed solution as the project progresses.
Parts ordered are delayed or not delivered on their expected delivery date.	This can delay the project progression resulting in missed deadlines or missing components in the required deliverables.	Allow for unexpected delays to occur, keep track of the delivery status, update delivery info and have a backup plan prepared during the weekly meetings.

Insufficient knowledge required to complete the project	An inappropriate solution is created or the inability to provide a proof of concept method to detect defects results in an incomplete solution and a poor mark in this course.	Have a plan on how to achieve the final solution in addition to researching existing methods, asking for guidance from sponsors, and asking questions to clarify understanding.

5.0 - Technical Resources

The technical resources required for this project can be divided into 3 main categories as shown in Table 6 below.

Table 6. Technical Resources Required

Categories	**Technical Resources**
Physical Hardware	1. Vision Sensor (Camera) 2. Arduino Board or Raspberry Pi 3. Wiring and miscellaneous electronics 4. FDM printer and filament
Software	1. Python or Java code compiler 2. OpenCV or similar slicer program 3. SolidWorks CAD program
Technical Knowledge	1. Sponsor or teaching assistant (TA) with Python programming skills 2. Sponsor or TA with experience working with image processing

5.1 - Budget

The budget for the entire project is must be less than $850 USD as this is the current value of the Prusa I3 printer available for this project. To minimize the cost of the solution, most of these materials are to be sourced from within the Materials Engineering Department with a few exceptions. In addition to this, the software needed for the project is available under student licenses for free.

Upon brief cost calculations for the sensors, Arduino, and other expenses, the estimated value of the solution is around $200 to $300 USD, a fraction of the cost of the printer. When considering that a 1kg spool of Polylactic acid (PLA) costs around $25 USD, and assuming about 25% of each spool goes to waste in failed prints caused by defects, it would only take 32 to 48 spools to recover the value of the solution. Assuming that a spool is consumed at a rate of one per month, then it would only take 3 to 4 years to recover that value. The expected lead time for any items purchased is around 3 to 4 weeks to allow for shipment and delays.

5.2 - Safety

The project will require the members of the team to be trained to use the Prusa I3 FDM printer. The main safety hazards all relate to the FDM printer itself and consist of the hot nozzle that melts the plastic during printing (210 - 250 °C), the hot printing bed (80 - 110 °C), and the moving gears and motors for the extruder [15]. The safety risks posed by these hazards can include severe burns and pinch points that may catch clothing or skin. With proper training on how to use the FDM printer, any potential injuries can be minimized or avoided.

6.0 - Communication Plan

Each team member is part of the facebook messenger group chat called MTRL 466 Group for this course. This is where private meetings are arranged, questions are asked, the conversation about the project is held and where files are shared in order to maintain good communication throughout the project. Each group member will also fill out the Weekly Tracking Guide which records the work each member did that week, problems that arose, time spent working on the project and goals for next week. The group will meet at least once per week to discuss any action items that need to be completed or discuss questions posed by the sponsor or group members. Additionally, the group will also meet 30 minutes before the weekly formal meetings in order to be prepared. The team will communicate with the project sponsor through email, the UBC Wiki page and weekly formal meetings with the entire team on Wednesdays or Fridays. Emails will be sent to the sponsor with the rest of the group members cc'd while any relevant files will be posted on the UBC Wiki page for everyone to access. For each meeting, the leader will create the agenda while the secretary will take notes and produce meeting minutes for circulation after the meeting to confirm any specific details about the meeting outcomes.

References

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Appendicies

Appendix A.

Material	Highlights
Antero™ 800NA (polyetherketoneketone)	• High heat and chemical resistance • Low outgassing and high dimensional stability • Excellent strength, toughness and wear-resistant properties
ULTEM™ 1010 resin (polyetherimide)	• Food safety and bio-compatibility certification • Highest heat resistance, chemical resistance and tensile strength • Outstanding strength and thermal stability
ULTEM™ 9085 resin (polyetherimide)	• FST (flame, smoke, toxicity)-certified thermoplastic • High heat and chemical resistance; highest flexural strength • Ideal for commercial transportation applications such as airplanes, buses, trains and boats
PPSF (polyphenylsulfone)	• Mechanically superior material, greatest strength • Ideal for applications in caustic and high heat environments
ST-130™ (Sacrificial Tooling)	• Designed specifically for hollow composite parts • Fast, hands-free dissolution time • High heat and autoclave pressure resistance
FDM Nylon 6™ (polyamide 6)	• Combines strength and toughness superior to other thermoplastics • Produces durable parts with a clean finish and high break resistance
FDM Nylon 12™ (polyamide 12)	• The toughest nylon in additive manufacturing • Excellent for repetitive snap fits, press fit inserts and fatigue-resistance applications • Simple, clean process – free of powders
FDM Nylon 12CF™ (polyamide 12CF)	• Carbon-filled thermoplastic with excellent structural characteristics • Highest flexural strength • Highest stiffness-to-weight ratio
PC (polycarbonate)	• Most widely used industrial thermoplastic with superior mechanical properties and heat resistance • Accurate, durable and stable for strong parts, patterns for metal bending and composite work • Great for demanding prototyping needs, tooling and fixtures
PC-ISO™ (polycarbonate - ISO 10993 USP Class VI biocompatible)	• Biocompatible (ISO 10993 USP Class VI)[1] material • Sterilizable using gamma radiation or ethylene oxide (EtO) sterilization methods • Best fit for applications requiring higher strength and sterilization
PC-ABS (polycarbonate - acrylonitrile butadiene styrene)	• Superior mechanical properties and heat resistance of PC • Excellent feature definition and surface appeal of ABS • Hands-free support removal with soluble support
ASA (acrylonitrile styrene acrylate)	• Build UV-stable parts with the best aesthetics of any FDM material • Ideal for production parts for outdoor infrastructure and commercial use, outdoor functional prototyping and automotive parts and accessory prototypes
ABS-ESD7™ (acrylonitrile butadiene styrene - static dissipative)	• Static-dissipative with target surface resistance of 10^7 ohms (typical range 10^9 – 10^6 ohms)[2] • Makes great assembly tools for electronic and static-sensitive products • Widely used for functional prototypes of cases, enclosures and packaging
ABS-M30i™ (acrylonitrile butadiene styrene - ISO 10993 USP Class VI biocompatible)	• Biocompatible (ISO 10993 USP Class VI)1 material • Sterilizable using gamma radiation or ethylene oxide (EtO) sterilization methods • Best fit for applications requiring good strength and sterilization
ABS-M30™ (acrylonitrile butadiene styrene)	• Versatile material: good for form, fit and functional applications • Familiar production material for accurate prototyping
PLA (Polylactic acid)	• Fast printing • Good tensile strength • Economical and user-friendly • Ideal for concept models
FDM™ TPU 92A (thermoplastic polyurethane)	• Elastomer material with Shore A value of 92 • Extremely flexible, durable and resilient • Compatible with soluble support • Accelerates elastomer prototyping without the need for molds

[1] It is the responsibility of the finished device manufacturer to determine the suitability of all the component parts and materials used in their finished products.

[2] Actual surface resistance may range from 109 to 106 ohms, depending upon geometry, build style and finishing techniques.

Appendix B.

	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13
Tasks	Sept 8 - 14	Sept 15 - 21	Sept 22 - 28	Sept 29- Oct 5	Oct 6 - 12	Oct 13 - 19	Oct 20- 26	Oct 27 - Nov 2	Nov 3 - 9	Nov 10 - 16	Nov 17 - 23	Nov 24 - 30
Tasks Identification and Planning												
Problem Identification												
Design Objectives												
Identify Project Risks												
Budget Scoping												
Identify Safety Hazards												
Proposal Due												
Review Project Proposal Feedback												
Technical Research for Solutions												
Design Brainstorming (3/4 Designs)												
Design Options (Narrow to 2?)												
Select Final Design												
Project Risk Assement Update												
Discuss Economic / Socio-Economic & LCA												
Project Presentation & Report Preparation												
Midterm Report Due												
Midterm Presentation												
Review Midterm Report Feedback												
Iterate Final Design												
Improve Economic / Socio-Economic & LCA												
Illustrate Working Principle (Quantitative)												
Calculations												
Rapid Prototyping												
Final Report Prepartion												
Final Report Due												
Final Presentation												