Defect Detection Systems for Fused Deposition Modelling (FDM) Printer

Midterm 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 print 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. The objectives of this project are to minimize the amount of wasted filament from failed prints, 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 midterm report explores a variety design options using vision sensors, thermal sensors and laser line sensors. Out of these 3 methods, vision sensors preformed the best in terms of their low cost and high resolution. Defect detection can be achieved using a shape error method where the image of the printed part is compared to the image from the 3D model of the part where both images are edited to be the same size and orientation. If the difference between these 2 images is greater than 5%, then a defect has occurred and the printing process will be stopped in order to save filament and time. An economic assessment of our proposed solution was conducted and found to be viable as the average household user will conservatively take approximately 2 years to save more money in wasted filament than the total cost of our solution. The objectives of this project are to minimize the amount of wasted filament from failed prints, 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.

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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].

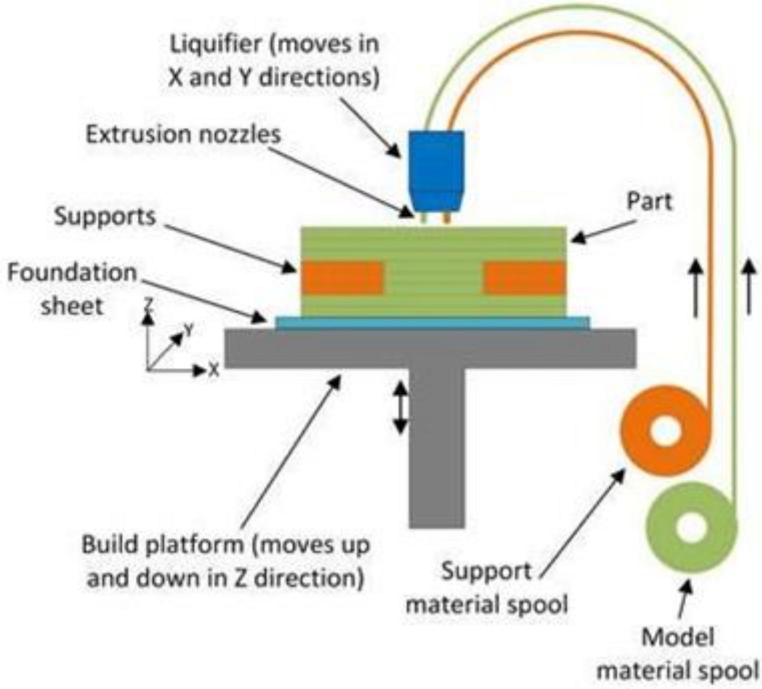
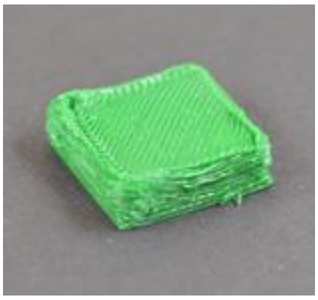


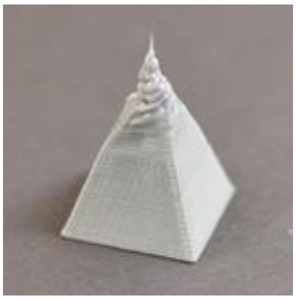
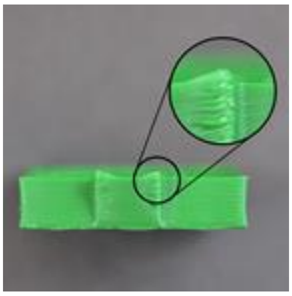
Figure 1. FDM Printing Process [3]

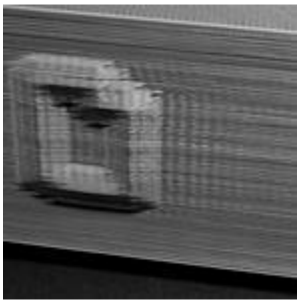
In Figure 1 above, the materials are fed from spools to the extrusion nozzles that are attached on a grid that only moves along the X and Y directions while the build platform itself is responsible for the movement in the Z direction. As a layer of the physical part, previously designed on CAD software, is completed, the table where the layer is built moves a unit down in the vertical 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]. Different materials will have different melting points and thermodynamic properties resulting in slight variations in the solidification time after extrusion.

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 [5]

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.

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 targeted customers for our design solution are the general users of budget FDM printers or FDM printer manufacturing companies such as Prusa Printers who could sell our solution as an addon to their product. As a result, the cheapest and highest accuracy solution is desirable as the users are unlikely to commit a substantial amount of money to the solution compared to the cost of the printer itself

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 in order to save money and the environment. 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, ultrasonic, and laser line profile sensors as shown in Table 2 below.

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

Sensor Type	**Description**
Proximity Sensor	The sensor emits a beam of electromagnetic radiation and senses the reflection in order to determine the object's proximity or distance from the sensor [6].

Infrared Sensor	The sensor can sense emits and detects infrared radiation to measure the heat emitted by an object and detecting motion [7].
Chemical Sensor	The sensor detects chemical concentrations in the air near the sensor.
Acoustic Sensor	The sensor uses piezoelectric materials to generate acoustic waves that propagate through or on the surface of the material and changes to the characteristics of the propagation path affect the velocity and amplitude of the wave can be detected [8].
Thermal Sensor	The sensor can detect temperature profiles.
Vision Sensor	The sensor uses images captured by a camera to determine the presence, orientation, and accuracy of parts [9].
Ultrasonic Sensor	The sensor measures distance as the sensor head emits an ultrasonic wave and then receives the wave reflected back from the target [10].
Laser Line Profile Sensor	The sensor measures elevation profiles of varying surfaces using a line laser.

Not all of these sensors above are able to effectively detect defects. Several of them will be screen out as they will not meet the hard constraints for this project, and the ones that do meet the hard constraints will be ranked based on how well they perform in order to determine an optimal solution.

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.

2.0 - 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 (pointcloud) 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. Additionally, sensors must be placed on the part as it is being printed which would not work for our design challenge.

A study conducted by Michigan Technological University, published in 2017, provided insight into some theoretical work to help define the solution for this project. The study showed a solution that involves using a vision-based error detection system. A camera is used to either take a picture or a video from 1 or multiple angles in order to compare a picture or reconstructed 3D model to the reference picture or 3D model. For the case of taking a single picture from a single angle, a shape error of greater than 5% as defined in Equation 1 below is used to determine if a defect has occurred [13]. The absolute value is taken in order to determine if a defect has occurred, considering defect can be due to an overprint or underprint in a layer.

$$Shape\ Error = \left|\frac{Area\ of\ Picture - Reference\ Area}{Reference\ Area}\right| \quad \text{(Equation 1)}$$

The area of the picture is determined from the sensor taking the picture, while the reference area is determined by the [.stl] (Standard Tessellation Language) file of the part from the same orientation that the camera has taken the picture form. The processing steps to isolate the 2 images are outlined in the flowsheet below in Figure 10.

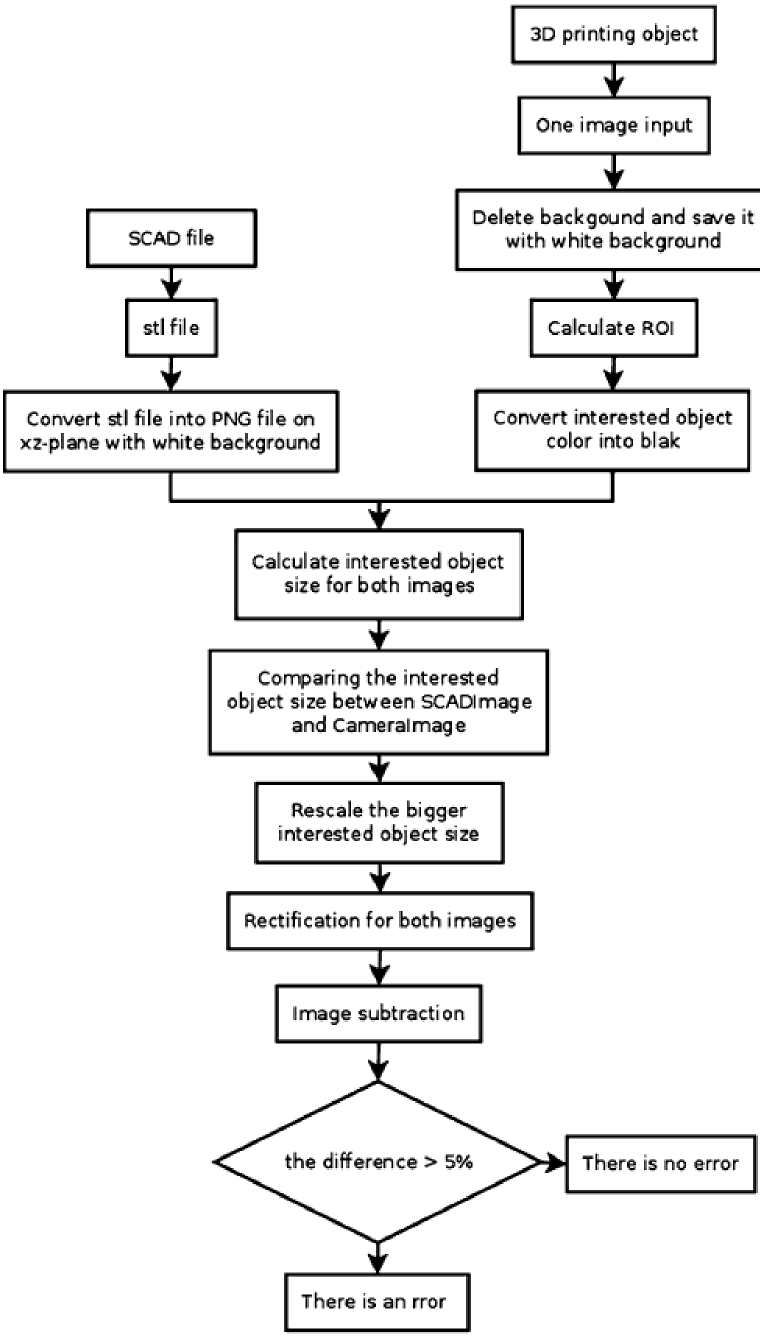


Figure 10. Flowsheet for Processing Images to Determine when a Defect has Occurred [13]

The code used to isolate the images first removes the background of both images and changes it to white. The sizes and positions of both images are then calculated and adjusted to be the same before both the image from the sensor is subtracted from the reference image. If this difference is greater than 5%, there is an error in printing the part due to a defect [13]. This method does not distinguish between different types of defects, but only compares when the print material is not in a place it should be or where there is print material where it should not be. This study compared 6 different geometries with a 100% success rate in determining if a defect has form when a defect is classified to be a shape error of greater than 5% according to Equation 1 above [13]. One of the models included a dinosaur skull where the difference between the image and reference shape can be seen in Figure 11 below. Once the sensor has detected a defect, it relays a signal to the printer to cease printing. Due to the low cost of this method and the success from various sources, it presents a viable method for defect detection. A possible solution to our project is to use this method for either a single image or multiple images taken from various orientations.

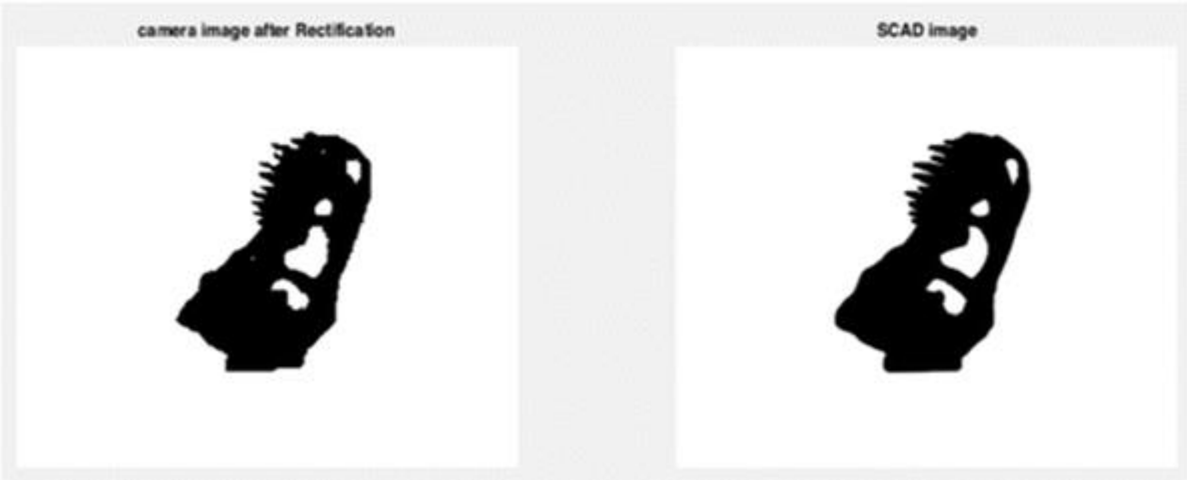


Figure 11. Comparison of the 3D Print to the Expected Model [13]

One possible solution for our project is to use this method for detecting defects when a camera is positioned to take pictures in the x-y plane (top-down view) of the 3D printed model. This would allow defects to be detected in the x-y plane compared to the study where pictures were taken in the x-z plane or y-z plane. A combination of several cameras or images taken from several perspectives would allow for more defects to be detected, and if enough pictures of various orientations of the object are taken so that the images could be combined into a 3D model, then a volume error could be considered instead of a shape error to determine defects.

Another research paper carried out by the Electrical and Mechanical Departments of KU Leuven shows and validates a methodology for using laser line profile sensors to determine defects in FDM 3D printing. In this study, the cross-sectional shape and dimensions of the extruded filament are assumed to be elliptical [14]. Moreover, the sensor should at least have a measurement accuracy of 10µm, in order to have sufficient scanning resolution, taking into account that the width of the extruded filaments measures typically between 100µm and 300µm [14]. A measuring speed of at least 50 frames per second is desirable, in order to be able to take sufficient images of the extruded filament, knowing that the print head typically moves at a speed between 10mm/s and 20mm/s [14]. As a result, a 2D laser triangulation system was selected for the measurement of the dimensions of the extruded filaments [14]. A 2MP USB microscope with an optical magnification of up to 400x was used in combination with a 650 nm laser with a divagation angle of 0.7mrad in order to implement the laser triangulation system on a low-end FDM printer for initial testing [14].

An algorithm was then developed to detect the deposited filaments and determine the dimensions of interest [14]. The laser line is detected by searching for the three maximal intensity values in the extracted image, then a parabola is fitted through these points and the maximum hereof is considered the position of the laser line [14]. Secondly, using the detected laser line, the platform is found by taking the median of the pixels, lying on both sides of the image between the edge and 1/8th of the width of the image [14]. In order to detect the extruded filament itself, an edge detection algorithm is used on both sides of the track [14]. It is supposed that a side of the extruded filament is found when the difference between the laser line and the platform exceeds a certain threshold for 3 subsequent pixels [14]. The height of the track is computed by taking the median of 3 pixels around the center of the track [14]. Using this achieved data, an ellipse is fitted through the extracted points of the laser line and the divergence of the measured points to this ellipse is calculated [14]. The detection of this laser line projected onto a deposited filament of thermoplastic material is shown in Figure 12 below.

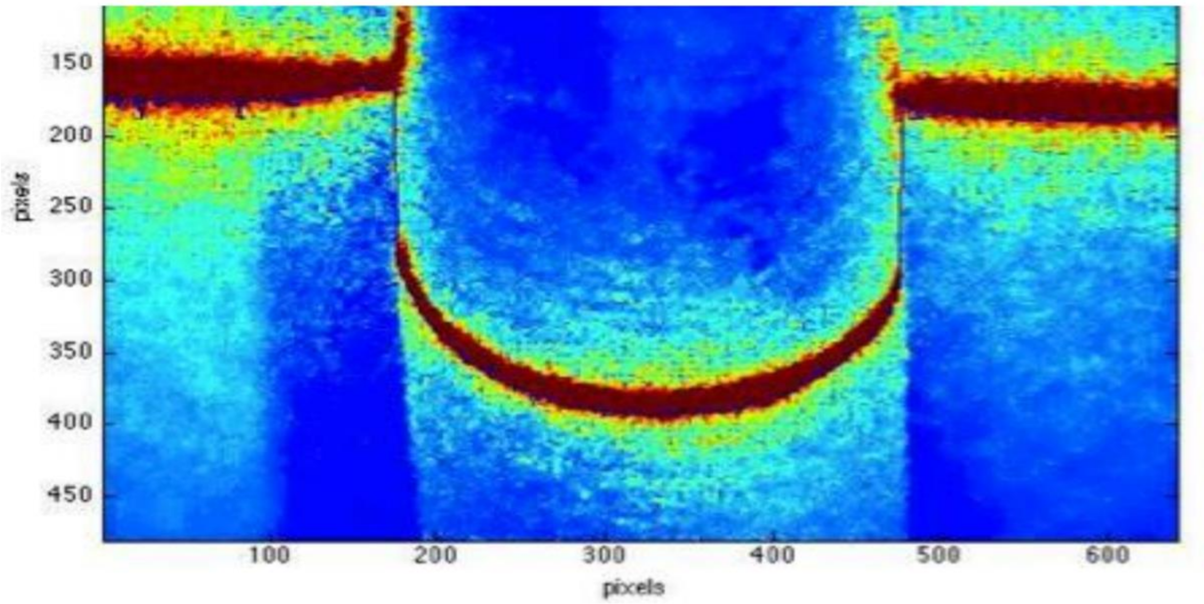


Figure 12. Detection of a Laser Line Projected onto a Deposited Filament of Thermoplastic Material [14]

This method was used to determine the elevation profiles of 5 different geometries with 1 of the geometries being a reference shape. The values determined from this triangulation method are compared to the final dimensions measured using calipers to determine the deviation which represents the error using this method. The caliper measurements are used to validate the measured dimensions, and the triangulated dimensions measured from the laser line can directly be compared to the expected dimensions of the part in order to determine an error. The results are summarized in Table 3 below.

Table 3. Comparison of the Developed System with a Conventional Measuring System [14]

	Calipers (mm)	Triangulation (mm)	Deviation (mm)
Profile 1	1.38	1.36	0.02
Profile 2	2.38	2.28	0.10
Profile 3	3.38	3.30	0.08
Profile 4	4.27	4.28	0.01
Calibration	5.00	5.00	0.00

Based on these results, it can be seen that this method is accurate up to 0.1mm and is therefore capable of detecting defects in the z-direction that is greater than 0.1mm. A possible solution for our project is to use this method to determine whether the surface of the filament is being printed on is flat. If the surface is not flat, or if there are clear differences in elevation based on the original geometry, then a defect has occurred.

3.0 - 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 the printer whenever a sensor detects a defect in the part in order to prevent wasted print material and save money. 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 4 below.

Table 4. Project Objectives, Constraints, and Free Variables

Project Objectives and Quantitative Goals	**Description**
Objectives	1. Minimize the amount of filament/material wasted 2. Maximize the number of different geometries and filament materials that our solution will work with
Hard Constraints	1. The project must cost less than $850 USD, which is the price of the Prusa i3 printer available to us 2. The project must be completed by November 25th, 2019, which is the deadline for this course 3. Resolution of the sensor should be at least 3mm as this is the largest thickness of the plastic filament that can be extruded by budget FDM printers

Soft Constraints	1. Minimum time before the next layer can be printed is 15 seconds for the Prusa i3 so the previous layer can cool 2. The height of each layer being deposited by the nozzle is less than 2mm 3. The material of the FDM printer bed 4. The nozzle type 5. The heating system used by the FDM printer 6. The printer model is Prusa i3 7. The extrusion temperature and rate 8. 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 6. Software type for post-processing of sensor data

4.0 - Design Options

In this section, various design options using the vision sensors, thermal sensors, and laser line profile sensors will be explored. The other sensors including proximity, infrared, chemical, acoustic, and ultrasonic could not meet the conditions specified by the hard constraints in Table 4 above.

4.1 Design Option using a Vision Sensor

Vision sensors measure the intensity of visual light through a lens that focuses and redirects the light to a Charged Couple Device (CCD) or Complementary Metal-Oxide Semiconductor (CMOS). Both CCD and CMOS solid-state electronic devices contain up to millions of discrete photodetector sites called pixels where the colour and brightness of each pixel is measured and stored as a number [15]. For Charged Coupled Devices, the charge needs to be transported across the chip where it can be read at one corner of the array and converted to a voltage. In a CMOS sensor, the charge from the photosensitive pixel is converted to a voltage at the pixel site and the signal is combined by row and column to multiple on-chip digital-to-analog converters. As a result, CCD sensors produce higher image quality at lower speeds while CMOS sensors produce lower image quality, but at higher speeds. The operating principles of how CCD and CMOS sensors work is shown in Figure 13 below.

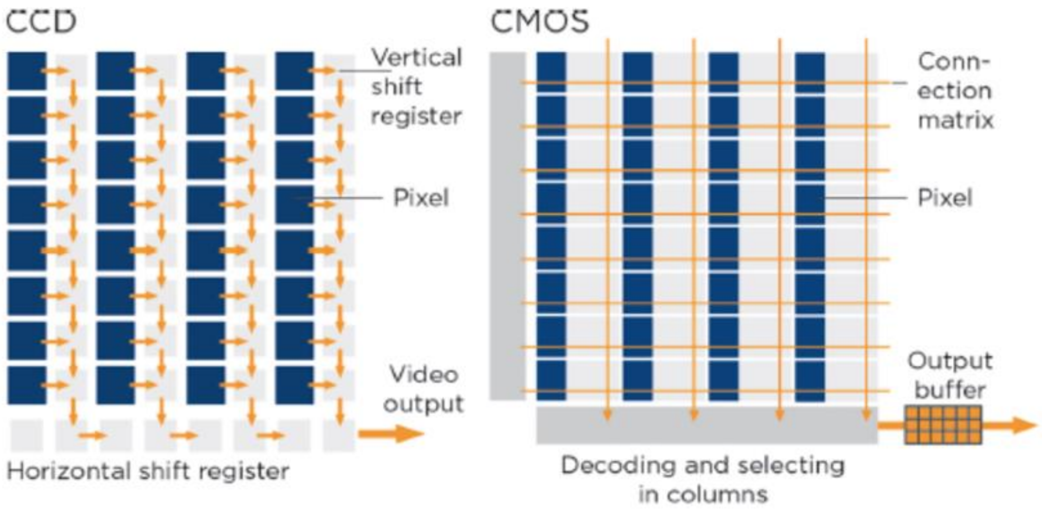


Figure 13. Operation of CCD and CMOS solid-state devices [16]

This process of measuring the intensity of visual light allows for the collection of Red, Green, and Blue data, often called RGB data across the array of pixels on the sensor. This data can then be manipulated using post-processing software such as MATLAB which stores the imported data file as a matrix. The flowchart in Figure 3 demonstrates a viable method of processing the data in order to determine if a defect has formed.

Several defects listed in Table 1 such as over extrusion, under extrusion, layer shifting, curling, and warping could be detected through the use of a vision sensor depending on the orientation of the sensor. There are multiple locations that the vision sensor can be placed in order to take pictures of the x-y plane, x-z plane, or y-z plane. Depending on the orientation of the camera, this method is limited to detecting defects that propagate in the plane that the sensor is taking a picture of. For the case of taking pictures in the x-y plane, the sensor could be mounted to the top of the FDM printer in order to obtain the top-down view required. As the printer extrudes thermoplastic material, there would be lots of vibrations due to the movement of the nozzle. As a result, the FDM printer would need to pause, and the print head would have to move to a home position away from the printed model in order to obtain a clear picture. Once the picture is taken, the nozzle can return to its previous position and the print can resume. A picture can be taken at the end of each layer or after several layers in order to monitor the progress of the print. Multiple cameras could be used to take pictures in multiple planes in order to maximize the number of defects that can be detected however, this would increase the cost of the solution. The advantages and disadvantages of this potential design option are summarized in Table 4 below when considering using an ELP 2.0 Megapixel 1080p Machine Vision Mini IP Camera as the vision sensor. This camera was chosen due to the benefits listed below with the main 2 being the high resolution for the low cost however, there is also a wide variety of other cameras that could be used.

Table 4. Advantages and Disadvantages of using a Vision Sensor [17]

Advantages	**Disadvantages**
1. High resolution (1920*1080p) 2. Low Cost (50 USD) 3. Fast data transfer speeds (32Kbps 8Mbps) 4. Good Field of View (50° x 60°)	1. Difficulty isolating the image form the background 2. Limited to defect detection in one plane when using 1 sensor 3. The vibration of an FDM printer when the sensor is mounted to it can cause motion blur 4. The printer needs to be paused in order to take a picture in the x-y plane

4.2 - Design Option using a Thermal Sensor

Another potential design option includes the use of a thermal sensor. Temperature sensors function by sensing electromagnetic waves in the 700 nm to 14,000 nm range [18]. These sensors focus the infrared energy emitted by an object onto one or more photodetectors which convert the energy absorbed into an electrical signal that is proportional to the infrared energy emitted by the object. Because the emitted infrared energy of any object is proportional to its temperature, the electrical signal can provide an accurate reading of the temperature. As a result, temperature profiles are obtained through individual temperatures measured at each pixel in the sensor.

Several defects listed in Table 1 such as overheating, curling, and warping are caused as a result of inconsistent temperatures throughout the printed part. The ability to detect any temperature variances from the expected temperatures can be used to identify when a defect could form or has already formed. If the temperature variance is within acceptable parameters, then there would be no defect forming. Additionally, the image file could also be processed using the shape error detection method illustrated in Figure 3.

The design implementation is similar to that of the vision sensor when considering mounting locations of the sensor. The thermal sensor can be placed at various locations in order to take pictures in the x-y plane, x-z plane, or y-z plane. Depending on the orientation of the thermal camera, this method is also limited to detecting defects that propagate in the plane that the sensor can measure the thermal data. The main difference is that defects could be detected before actually occurring. This means that this solution has the potential to prevent the defect from occurring or even to save more filament compared to the vision sensor by stopping the printing process sooner. The advantages and disadvantages of this potential design option are summarized in Table 5 below when considering using a Flir C2 Compact Thermal Camera.

Table 5. Advantages and Disadvantages of using a Thermal Sensor [19]

Advantages	**Disadvantages**
1. High thermal sensitivity (<0.10°C) 2. Good Accuracy (±2°C) 3. Decent angle of view (41° x 31°) 4. Lightweight (130.4g)	1. High Cost (466 USD) 2. Low Resolution (4800 pixels) 3. Minimum focus distance (15cm) 4. Large Dimensions (12.4cm x 7.9 cm x 2.5 cm) 5. Temperature Range (-10°C to 150°C) 6. Difficulty isolating the image from the background 7. Limited to defect detection in one plane when using 1 sensor 8. The vibration of an FDM printer when the sensor is mounted to it can cause motion blur 9. The printer needs to be paused to take a picture in the x-y plane

4.3 - Design Option using Laser-Based Sensors

There are 3 possible designs that were explored using laser line profile sensors which include line laser defect detection, photogrammetry, and laser shearography. These design options are illustrated in the 3 sections below.

4.3.1 – Laser Line Profile Sensor

The 2 main components required for detecting defects using a laser line profile sensor consists of a laser light source and a sensor. This method involves shining a line laser onto the surface of the printed part, having it reflect off the surface so that the reflected wave hits either a CCD or CMOS sensor as illustrated in Figures 14 and 15 below.

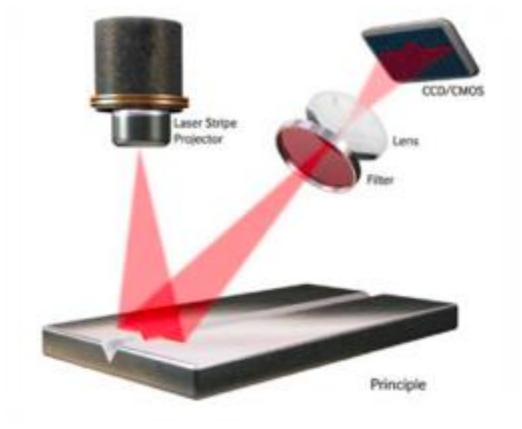
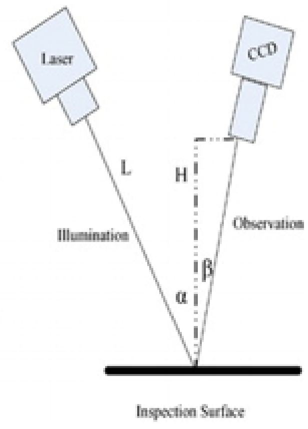
	

Figure 14. Laser Line Surface Sensor [20]	Figure 15. Schematic of Laser Line Profile Sensor [21]

The triangulation angle between the illumination and detected beams translate depth changes in the inspected surface into lateral displacements of the laser line in the recorded image according to the equation 2 below [21].

$$\delta_1 = \delta_z \frac{sin(x+\beta)}{cos(\alpha)} \qquad \text{(Equation 2)}$$

Equation 2 describes the principle of detecting depth changing by laser angle and lateral displacement, where α is the angle of incidence with respect to the normal from the surface, and δ_1 is the lateral displacement corresponding to a depth change δ_z. When $\beta=0$, the normal incidence or normal observation is obtained. This method is often used, as it results in larger lateral displacements for the same depth change, which will make it easier for the CCD or CMOS sensor to detect the difference. By applying the principle described above, and moving the laser along the surface, the surface profile of the printed layer can be obtained. This elevation can then be compared to the expected layer height and dimensions from the slic3r settings of the 3D model in order to determine if a defect has occurred.

The laser line projector and CCD or CMOS sensor could be mounted to the top of the FDM printer in order to obtain a top-down view and achieve a surface profile in the x-y plane. In order to scan the surface using the laser line sensor, this mounting setup is limited to FDM printers that can move the bed in the x-direction or y-direction in order to minimize vibrations caused by the FDM printer and to avoid having to move the sensor itself. The bed would move in the appropriate direction so that the whole surface could be scanned. In order to successfully scan the part, the printer nozzle needs to be moved to a home position away from the printed part at the end of a layer or at the end of several layers. The bed would then need to move in the appropriate direction so that the laser line scans the whole part. The bed and the nozzle would then have to be reset to their original positions so that the next layer could be printed. The advantages and disadvantages of this potential design option is summarized in Table 6 below when considering using a scanCONTROL 3000-25/BL laser line profile sensor.

Table 6. Advantages and Disadvantages of using a Laser Line Profile Sensor [22]

Advantages	**Disadvantages**
1. Good Resolution (2048 points / profile) 2. Good Measuring range in x-direction (15.0mm) 3. Good Measuring Range in z-direction (15.0mm)	1. Expensive (needs to be custom ordered) 2. Low Scanning Speed (300 Hz) 3. Relatively complex data processing compared to vision sensors 4. Vibration of FDM printer when sensor is mounted can cause significant errors 5. Printer needs to be paused for a long time to scan the x-y plane

4.3.2 – 3D Scanning

Another potential design option includes the use of 3D scanning the surface of the printed part in order to recreate the 3D geometry. This method uses the same principle as the laser line profile sensors, except the laser line scans the entire part in order to recreate the model geometry. This method involves having the laser line sensor scan the x-z plane and y-z plane to reconstruct the sides of the part. By increasing and decreasing the height as well as the angle of the laser scanner, the surface in the x-y plane can also be scanned. Once all the faces are scanned using the laser line sensor, the part can be reconstructed as a 3D model. In order to scan the entire surface area of the part, the FDM printer itself can be rotated, or the laser sensor can rotate around the FDM printer. In both cases, a lot of additional support structures would be needed in order to properly mount and scan the surfaces of the printed part. In order for the part to be scanned, the same procedure of pausing the printing process after a layer or a certain number of layers must be applied.

To determine if a defect has occurred, the reconstructed 3D model of the part can be compared to the original 3D model of the part that is being printed. In order to compare the 2 different 3D models, they first need to be scaled to the same size and orientated in the same direction. The 3D models can then be overlapped and the difference between the 2 models can be analyzed to determine if a sufficiently large defect has occurred in order to stop the printing process. The advantages and disadvantages of this potential design option are summarized in Table 7 below when considering using a scanCONTROL 3000-25/BL laser line profile sensor.

Table 7. Advantages and Disadvantages of 3D Scanning [22]

Advantages	Disadvantages
1. Good Resolution (2048 points / profile) 2. Good Measuring range in x-direction (15.0mm) 3. Good Measuring Range in z-direction (15.0mm)	1. Expensive (needs to be custom ordered) 2. Low Scanning Speed (300 Hz) 3. Relatively complex data processing compared to vision sensors 4. Rotation of the FDM printer or Scanner can be very challenging 5. Printer needs to be paused for a long time to scan the entire surface profile of the part

4.3.3 – Laser Shearography

Laser shearography involves optically illuminating an object's surface with laser light so that a speckle pattern can be visualized. This laser light is scattered by a negative lens to construct the laser speckle pattern. The scattered light hits the object's surface and then reflects back to a beam splitter which splits the laser light into 2 rays. The first ray is sent to a reference mirror to be bounced back and collected by an imaging lens of a CCD or CMOS sensor. The second ray is sent toward a shearing mirror, where the light is sheared before returning to the CCD or CMOS sensor. The CCD or CMOS sensor images the first derivative of the out-of-plane deformation of the test part surface in response to a change in load [23]. This process is illustrated in figure 16 below.

As the CCD camera obtains the images, a software called Istra 4D can be used to analyze the displacement gradient data obtained [24]. If there are no defects present on the surface, the displacement gradient will equal 0 [25]. If defects are present, the slope will fluctuate as shown in Figure 17 shown below [25].

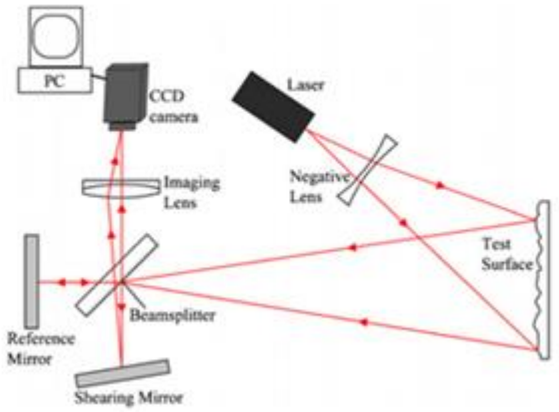


Figure 16. Schematic diagram of Shearography [26]

Figure 17. Displacement Gradient data at each point of the speckle pattern [26]

This laser shearography setup can either be mounted to the top of the FDM printer or supported by its own stand in order to apply the speckle pattern in the x-y plane. In order for the speckle pattern to be applied, the printer nozzle needs to be moved out of the way into a home position after completing a layer or several layers. The speckle pattern can be applied to the top surface and a mechanical load can be applied to the sides of the printed part. Once the sensor has measured the displacement gradient, the printer nozzle can return to its original position and resume printing. The advantages and disadvantages of this potential design option are summarized in Table 8 below when considering using a Q-800 Laser Shearography Inspection System by Dantech Dynamics.

Table 8. Advantages and Disadvantages of Laser Shearography [27]

Advantages	**Disadvantages**
1. Good Resolution (1392 x 1040p)	1. Very Expensive (needs to be custom ordered) 2. Slow inspection speed (30mm x 30mm / 20s) 3. Large sensor dimensions (70mm x 70mm x 160mm) 4. Heavy (1.2kg) 5. Relatively complex data processing 6. Printer needs to be paused for a long time to scan the entire surface profile of the part 7. Can be difficult to mount on FDM printer with such large dimensions 8. Requires mechanical deformation of the part while printing 9. Requires training courses on how to use the sensor

4.4 - Recommendations

The selection process to determine the optimal solution will compare various design options with respect to multiple criteria of different levels of importance such as the cost of the sensor and the resolution of the sensor. The design options will then be ranked relative to a fixed reference, which are constraints for each criterion specified in Table 4, and the design that performed the best will be selected. A Weighted Decision Matrix (WDM) was used to compare the various design options as shown in Figure 18 below. A high weighting was used for both cost and resolution of the sensor as these are the 2 main constraints that the design options will be compared against based on the expected users of this solution mentioned in the design options section of this report. In addition to the constraints, many of the design options involve different levels of complexity which will also be included in our decision.

		Design Options									
		Vision Sensor		Thermal Sensor		Laser Line Profile Sensor		3D Scanning		Laser Shearography	
Constraints	Weighting (%)	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Cost (USD)	45%	10	4.5	-5	-2.25	-6	-2.7	-10	-4.5	-10	-4.5
Resolution (mm)	25%	8	2	0	0	10	2.5	10	2.5	10	2.5
Sensor Scanning Time (s)	10%	10	1	10	1	0	0	-5	-0.5	-10	-1
Simplicity of Design	10%	10	1	10	1	0	0	-10	-1	-10	-1
Number of detectable defects	10%	7	0.7	10	1	10	1	10	1	10	1
	Total Score		9.2		0.75		0.8		-2.5		-3

Figure 18. WDM Comparing Design Options

A rating ranging from -10 to 10 was used to assign the performance of each design option with 10 being an excellent rating, -10 being the worst rating, and 0 being an average rating. This rating range was chosen in order to encompass a wide variety of different performances by each design option. The score is determined by multiplying this rating by the relative weighting of each constraint. As a result of this, the minimum and maximum overall scores are -10 and 10 respectively when each individual score is added together. The constraint for sensor scanning time was included in the WDM since defects could occur the longer the printing process is paused due to the cooling of the printed part. The cooling of the printed part is dependent on the conditions of the room such as ambient temperature and airflow in the room. The simplicity of the design was also included to differentiate between how easily the solution could be implemented to the 3D printer. The simpler the design, the less effort and knowledge required by the end consumer in order to properly install our solution which would make simpler solutions more desirable.

Based on the WDM, vision sensors performed the best with a score of 9.2 by a considerable margin as the second and third best solutions are laser line profile sensors and thermal sensors with scores of 0.8 and 0.75 respectively. As a result, a defect detection method using vision sensors will be developed to demonstrate a proof of concept method of augmenting an FDM 3D printer so that it can automatically stop the printer whenever a sensor detects a defect in the part in order to prevent wasted print material and save money. The research study conducted by Michigan Technological University can provide a viable method of detecting defects from vision sensors using a shape error detection method as specified in the technical review section.

5.0 - Economic Assessment of Design

In order for the design of a vision sensor defect detection system to be viable in terms of cost, an economical assessment must be conducted. This assessment will consider the average cost of filament wasted by the average household user of budget FMD printers.

The 3D printing market is expected by some experts to exceed $21 billion in worldwide revenue in 2020 with one of the major contributing factors being the consumable filament used in FDM printing [28]. The market for filament materials used in 3D printing reached $310 million in 2014 and is estimated to grow to $1.4 billion by 2019 with 60% of the market being consumed by businesses, and the other 40% being consumed by individual customers [28]. Worldwide prices for plastic filament range between $19 and $175 per kilogram depending on material, diameter (mm), colour or other specific characteristics [28]. In cases when there are high shipping costs, a kilogram of filament can be as much as $40 or $50 [28]. The most common and cheapest print material for budget FDM printers is Polylactic Acid (PLA) [29]. Additional information about the benefits of PLA can be found in Appendix A at the end of this report. A 1kg spool of PLA can have costs ranging from $20 USD to $60 USD depending on the quality of the thermoplastic material, with an average cost of $25 USD [29]. Currently, a hollow-shell part just 5cm x 5cm x 2.5cm with a similar mass to that of a mobile phone case, can take several hours to print [30].

For the average household user of budget FDM printers, errors in the printer settings can lead to defect formation causing a significant amount of wasted print material and time. Due to the long printing times, the printing process is often unmonitored and can result in a significant amount of wasted material if defects occur. As a result, a conservative estimate of approximately 10% of the material is assumed to be wasted by our end users. With the cost of a potential vision sensor being around $50 for the ELP 2.0 Megapixel 1080p Machine Vision Mini IP Camera, and an additional $10 for the support structure and additional cables required to successfully operate this camera, the total cost of our solution will be around $60. Based on the amount of wasted material, this corresponds to a loss of $2.50 for the average 1kg spool of PLA. It would then take 24 1kg spools of PLA to equal the cost of our solution. If the end user consumers 1 spool per month of print material, it will only take 2 years until our proposed solution is saving more money in terms of wasted print material than the actual cost of purchasing the solution.

As the estimated market value for filament material is $1.4 billion, and having 40% of this market being consumed by common household users, the total value of the market being consumed by common household users is $560 million. If our solution is scaled up to reach only 10% of this market, this would result in saving $5.6 million in wasted print material which corresponds to 224000 kilograms of filament saved when assuming the average cost of filament is $25. As a result, not only does this solution significantly reduce the environmental impacts of wasted plastic material but can also save a significant amount of money for the potential end user.

6.0 - Updated 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 7 below. Additionally, a Gantt Chart is provided in Appendix B to help visualize the project schedule.

Table 7. 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 6^{th} 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 4. Design Brainstorming	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 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. Set up a Failure Design Library	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. Creation of a Failure Design Library consisting of multiple 3D printed designs with critical defects to determine if our system can detect them.
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	Redo the tasks in Week 8 and continue the research on the viability of the working principle. Testing should also be validated or improved. Create more failed prints with different geometries and determine if our solution can detect them.

	5. Rapid Prototyping	
Week 10 (November 3 - 9)	1. Continued Illustration of Working Principle (Quantitative) 2. Continue Calculations 3. Rapid Prototyping 4. Explore the use of a combination of sensors	Finalize and validate and calculations and designs. Continue to improve upon the design and advance the design process. Experiment with using different angles to determine the best orientation of sensor setup. Explore using multiple sensors in order to improve the solution.
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 3. Prepare for Final Presentation	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. Practice the Final Presentation so that we can receive feedback during the Formal Meeting and improve upon it for the Final Presentation.
Week 13 (November 24 - 30)	1. Final Report Submission 2. Final Presentation	Submission of Final Report and delivery of Final Presentation. Fix

		any problems before the final submission.

7.0 - 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 8 below. The likeliness of each risk occurring decreases from the top of table to the bottom.

Table 8. 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 for design are 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 or program limitations for image analysis.	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.

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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												