The University of British Columbia
Department of Materials Engineering
MTRL 466: Engineering Project I

Defect Detection in Fused Deposition Modelling (FDM)

Final Report

(Group 2)

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Table 1: Abbreviations used throughout the report

AM	Additive Manufacturing
FDM	Fused Deposition Modelling
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactic Acid
PETG	Polyethylene Terephthalate Glycol-modified
AE	Acoustic Emissions
DAQ	Data Acquisition
LCA	Life Cycle Assessment
CES	Cambridge Engineering Selector
CO_2	Carbon Dioxide
GHG	Greenhouse Gas

Executive Summary

Fused Deposition Modeling (FDM) is the most widely used 3D printing technology, representing the largest installed base of 3D printers globally. While FDM printing enables rapid prototyping and has revolutionized manufacturing, it has a great deal of material waste associated with the process and no cost-effective solutions on the market. The Georgia Institute of Technology reports that 35% of the plastic used in an open 3D printing studio is wasted [1] mostly due to failed prints. With the market growing for this additive manufacturing (AM) technology, there is a clear market need for an in-situ defect detection system.

The objective of this project is to create a proof of concept that will minimize material waste by sensing and stopping a print when a defect is spotted. A defect is “an imperfection or abnormality that impairs quality, function, or utility [2]” and occurs when a print run is unsuccessful. This refers to either print failure which can be defined as issues that arise while the print is still on the print bed and lead to print rejection, or part failure which refers to a “successful” print which then fails during its intended operation.

Literature review is done to understand the scope of the project and determine the limitations set out by the project constraints. From the research, possible design options are considered and using the initial constraints as criteria, the most promising solution is determined. With laser line projection being chosen as the defect detection method, 3 groups are formed to tackle the solution: hardware team, software team, and life cycle assessment. Under these umbrellas a detailed design and implementation plan is constructed. Key components under consideration include experimental setup, image processing steps, error propagation and socio-economic analysis.

Analyzing the associated energy consumption (electricity use) related to material waste proves to be where the majority of environmental aspects associated with FDM lay. Therefore, the initial objective of reducing material waste is modified to minimizing energy consumption, as this will inherently reduce the environmental impact. Finally, a sensitivity analysis proves that if a defect detection system costing $300-$400 CAD is implemented, the system would pay itself off in one year if 80% of defects were detected, in two years if 40% of defects were detected, or alternatively three years if approximately 25% of defects were detected.

Problem Definition

There are different processes that can be used to 3D print an object, such as material extrusion, vat polymerization, and powder bed fusion. During this term our team worked only with the material extrusion process, or fused deposition modelling (FDM), using PLA (Polylactic Acid) filaments. Before defining the problem tackled by this project, it is important to understand the basics of how an FDM printer works.

The user has to create a 3D version of the object they want to print using a CAD program. The printer cannot interpret CAD files, so the file has to go through a slicer before being sent to the printer. Slicer is a program that divides the CAD model in horizontal “slices” that the printer can interpret and print. Each “slice” corresponds to a layer in the printed object. Now that the printer can interpret the file, it can start extruding material. The user has to make sure there is a spool of filament loaded into the printer before starting the process. When the print starts, the nozzle is heated up, softening the filament. The print bed moves in the x-y coordinates (horizontally) and nozzle moves in the z direction (vertically), depositing layers of filament. After being deposited, the filament cools down and solidifies in the shape determined by the CAD file [3]. Figure 1 shows a schematic of an FDM 3D printer and the axis on which the nozzle and print bed (called “build platform” in Figure 1) move.

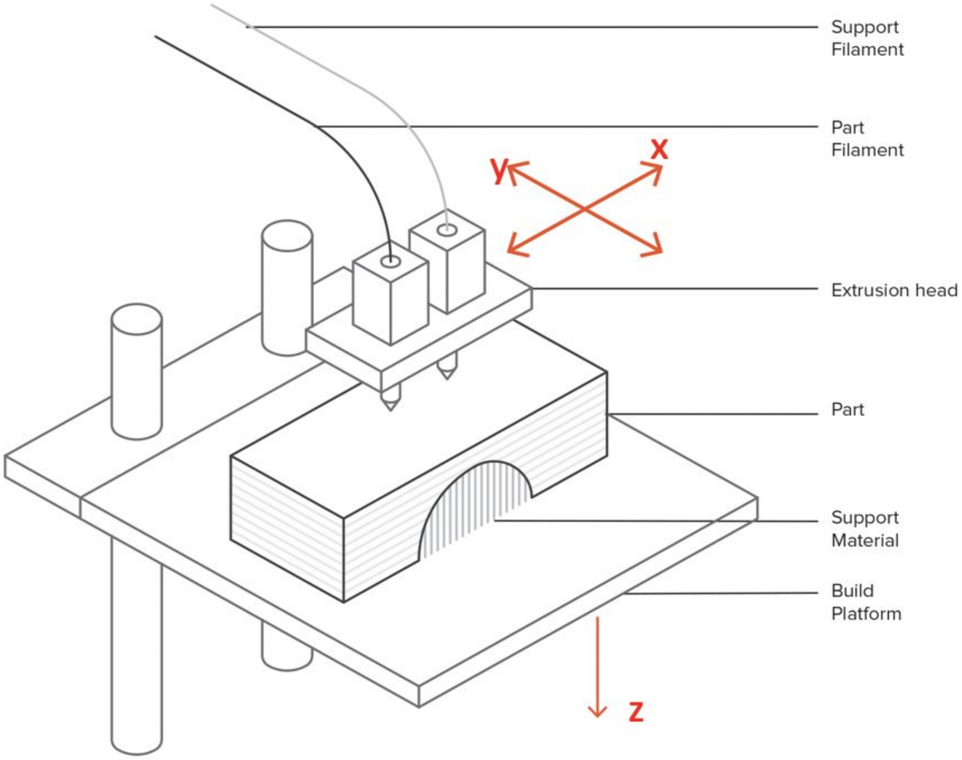


Figure 1: Schematic of a typical FDM printer [4]

Additive manufacturing processes, such as FDM printing, require less raw material than subtractive manufacturing processes, because it only uses the amount of material required for the final product [5]. One of the main problems with FDM printers is that most printers accessible to the general public doesn't have a system to detect when a defect has happened, so if a defect occurs, it will keep printing and wasting material until the user stops the machine. Defects happen when the user selects non-optimal printer settings, such as temperature and speed of nozzle. The concept of defects is very broad, so the definition of "defects" used in this report will be further outlined in the technical review section.

A study conducted by the Georgia Institute of Technology showed that around 35% of the plastic used in an open 3D printing studio was wasted [1]. The open studio had 25 printers operating at all times and was mainly used by engineering students at a large university. For the study, two collecting bins were labeled and placed in the studio for users to sort the kind of material they were disposing of: failed 3D prints or support material. In order to calculate the fraction of material wasted, the inventory of the filament was recorded periodically. The duration of the study was ten weeks, and the material used to print was ABS (Acrylonitrile Butadiene Styrene) filaments. The conclusion of the study was that 35% of the total amount of ABS used during the study was wasted, either because the print failed or because the material was just used as a support for the print and had to be removed upon completion of print. The study also revealed that 55% of the 35% of material wasted was due to failed prints. To put in perspective, 106 kg of ABS filament were used during the study, which means that more than 20 kg of plastic were wasted because of defective prints [1].

Even though the study was conducted during only ten weeks and in one location, it illustrates the need for reduction of material waste in 3D printing. Depending on the dimensions of the object to be printed, the printing process might take more than 10 hours. For that reason, most people observe the beginning of the print to make sure the object is attached to the print bed and the material is extruding and then leave the printer running by itself, coming back every few hours to check if everything is still running smoothly. If a defect occurs while the printer is unattended, it will propagate and all the material used will go to waste.

The objective of this project is to create a proof of concept that will minimize material waste by sensing defects and stopping the printer when a defect is detected. The requirements for the solution are that it has to be non-contact, so it won't interfere with print quality, has to cost less than the printer itself (less than $400) since it is an add-on to the printer, and has to be able to sense defects and stop a print that may lead to the entire object going to waste. The solution is intended to be sold to manufacturers of FDM printers, so that the cost for the final consumer can be lowered. This implies that the solution must be compatible with multiple FDM printers and printing materials. For this project the group was limited to using a Prusa i3 printer with PLA filaments, but our intention is that the solution will be compatible with a multitude of materials.

Technical Review

During the FDM printing of a part, a defect or "an imperfection or abnormality that impairs quality, function, or utility [2]" may occur. These defects can be negligible or could lead to two distinct categories of failure: print failure and part failure. Print failure refers to issues that arise while the print is still on the print bed which lead to print rejection. Part failure refers to a "successful" print which then fails during its intended operation. To detect print failure, a printer can be calibrated by printing certain test objects to determine what the baseline capabilities are. While there are many different objects that can be printed, they contain similar features that are designed in such a way to ensure that if the part fails, it will fail in a repeatable manner. For example, overhangs are printed to determine at what angle a part will fail depending on printer parameters such as: temperature, and speed (among others). For the purposes of this project, we will focus on defects that lead to print failure or defects arising during the printing process.

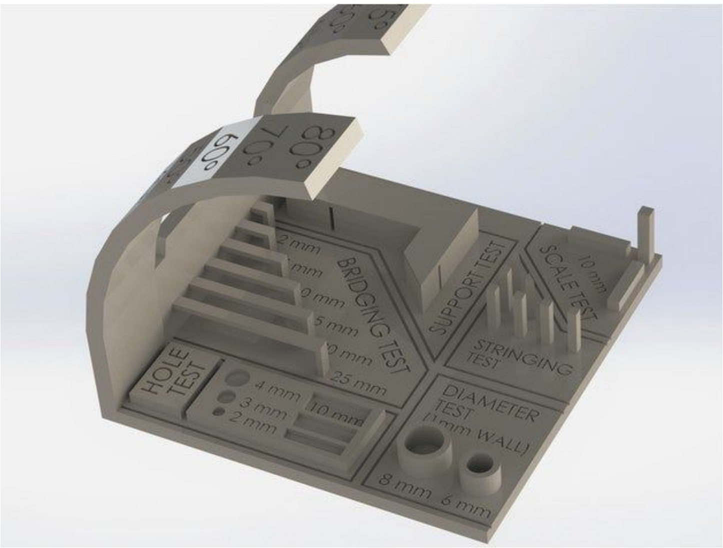


Figure 2: 3D Printer Test including Overhang, Bridging , Scale, Diameter, and Hole tests [6]

Baumann et al identified five main categories of defects which are as follows: detachment, deformed objects, missing material flows, surface errors and deviation from the model [7]. The approximate size range, negative effects and the frequency of various defects within each category will be further discussed.

Detachment describes a lack of object adhesion to the print bed which causes the object to detach from the bed. [7]. This defect may cause a slight bending in the object, or, it may cause the object to fall over or become displaced on the bed. In the event of the latter, if the object is no longer in the correct location, the nozzle will continue to print where the object should have been (i.e: the nozzle will continue to print directly onto the print bed instead of the layer it should have been creating). This causes an immediate failure and rejection of the part as the filament is extruded onto the bed in a disorganized manner having no particular shape. Detachment may occur due to uneven cooling during the print, an uncalibrated distance between the nozzle and the print bed and vibrations from external sources shaking the object off the print bed [7]. Warping due to uneven cooling is the most common of these defects, however an uncalibrated distance from the print bed and external vibrations while less common may lead to ultimate failure of the part [7].

A deformed object results from a collapse in structure [7]. Bridges or overhangs which can be described as “sections of [an] object where parts of the lower layer are intentionally missing [7]”, and are supported by only one or two points are prone to this type of failure. The nozzle missing the print bed is also an error that may lead to a deformed object [8]. These defects may be as small as the layer thickness, ~150-350 microns (for Prusa) or extremely large [7]. The collapse of a bridge is common, especially with complex designs, whereas the nozzle missing the print bed is uncommon and usually due to human error [8].

Missing material flows describes any defect that is caused by issues with the filament feeding through the nozzle [7],[8]. This can occur if the filament spool runs out, the nozzle begins printing too close to the print bed, the nozzle is blocked, the filament snaps, or the filament tangles [8],[9]. For the Prusa, there is a viewing window on the extruder head which will stop the extruder from moving if no filament is detected, ie: if the spool runs out or the filament snaps. However for errors such as the nozzle beginning to print too close to the bed or if the nozzle becomes blocked, no filament will be extruded however the extruder will continue to move as if it was laying filament down. If the nozzle becomes unblocked, all of the blocked material will be extruded quickly causing additional defects.

Surface errors include any small defects on the surface of the print. These are some of the hardest to detect as they are generally smaller than the thickness of a layer ~150-350 microns [8]. Surface errors can occur due to misprints in first layer, gaps between the infill and the wall, cracks between layers and stringing of the filament between two vertical objects positioned close together [8]. Cracks between layers are the most common and serious defect of all the surface errors.

Deviation from the model includes defects such as a print with a bowed bottom (elephant's foot), a leaning object, waves in the print, bumps from over extrusion and holes in the top layer [8]. The most common of these defects are elephant's foot, leaning objects and holes in the top layer [8]. Elephants foot is especially common with large objects and a print bed that is too hot. Elephant's foot as well as holes in the top layer can be small enough to be negligible or up to as large as the layer thickness ~150-350 microns. Leaning objects on the other hand can be of any size.

With the system outlined in this report several different types of errors can be detected on the condition that they are at least as large as the layer thickness (of the printed filament) ~150-350 microns and/or they propagate. Based off of those conditions, detachment, a total collapse in structure, missing material flows, surface errors, and cracks between layers are defects that can be detected. However for isolated surface errors and cracks between layers, as well as deviation from the model, detection will not be possible using the current system.

To detect these defects, a variety of techniques will be explored in the Design Options section. These include: thermal, infrared, sonar, acoustic, optical, laser line projection, and laser speckle projection detection methods.

Project Objectives and Quantitative Goals

As described in the project definition, 35% of materials are wasted during FDM printing and 55% of that is due to printing failures [1]. FDM failures cause time delays and generates an excess of wasted material as different types of defects are formed, ultimately increasing capital costs. Therefore, the objective for this term is to develop a proof of concept that will minimize material waste. This is done through sensing defects during an FDM print and stopping the printer when the height measured differs from the height in the CAD file in more than a threshold number that will be set by the user and it has to be at least equal to the thickness of a layer (150 microns-350 microns).

There are constraints that were followed more strictly from the problem definition. The method chosen should be a non-contact process, meaning that if a defect is being produced during a print run, the sensor should be able to detect it and stop the process automatically without user interference. Another constraint is the cost of the sensor solution; it should be no more than an FDM printer ($400 CAD). Most importantly, it must be able to sense failures that may lead to the complete failure of the print and stop the printer immediately. Furthermore, the solution should be versatile in that it is compatible with various types of FDM printers and materials. The type of sensory method is the free variable, as it is being manipulated such that the project objective and each constraint are met, and the goal of this project is to create a proof of concept for detecting defects.

Design Options

To detect the errors outlined above, six different sensing methods were considered as possible solutions. These included thermal, sonar, acoustic, speckle laser projection and line laser projection. These methods were researched and reviewed. The least plausible were thermal, sonar and acoustic sensing. Laser speckle projection, optical sensors and laser line projection were explored in more detail as they were more promising.

Thermal sensors came up as a possible solution because the PRUSA i3 model extrudes heated PLA filament at roughly 220°C [10], and the final part is built on a heated bed held at 60°C [10]. Defects that protrude from the print will cool faster than the rest of the object, as they have increased surface area for convective cooling. A thermocouple cannot be used as it is a contact solution, and the goal of this project is to find a non-contact solution. A pyrometer is a non-contact thermal sensor, however the smallest point that can be measured is 0.7mm [11]. This would severely limit the possible defects the solution could detect. Infrared cameras, such as the Microsoft Azure Kinect [12] "offer a high-speed, non-contact form of temperature measurement, and provide the data accuracy necessary to correlate process parameters and in-process temperature data with measures of finished part quality [13]". However, this technology does not provide a direct correlation to part quality. Certain inferences must be made to relate temperature at certain points during the print to finished print quality. Due to the indirect nature of this technology it will not be further considered for this purposes of this project.

Sonar stands for "Sound Navigation Ranging [14]". "For sonar equipment to function, three key elements are necessary: [a] source, [a] medium, and a receiver [15]". This system works when the sound source travels through the medium to the receiver which then "transform[s] the sound waves into an electrical signal in order to determine the distance from the sensor to the surface [15]. However, this technology can be unpredictable as depending on the shape of the object sound waves may be deflected causing the sensor to not pick up crucial data. Furthermore, sonar only detects an average height of a surface and cannot detect small height variations. For the purposes of this project, this setup will be too costly and therefore will not be further considered.

Acoustic emission (AE) is a technology that was tested by Wu et al to detect errors in the first layer of the FDM printing of ABS. AE has the "advantages of information richness, non-intrusive installation, and high throughput for real-time monitoring [16]". There are three main parts required for an AE system: "[an] AE senor, [a] preamplifier, and [a] DAQ (data acquisition) system [16]". For this particular experiment, acoustic measurements were recorded in two printer situations: "normal printing and printing failure with material peeling, buckling, and scratching [16]". This study concluded that an increased number of AE signals was indirectly related to an increased number of defects. For the purposes of this project, this setup will be too costly and therefore will not be further considered [17].

The three most promising options are discussed in more detail below.

Laser Speckle Projection

One common use of speckle metrology or laser speckle metrology is in the metrological measurement of metals [18]. When a coherent laser beam is shown on an optically rough surface, the reflected wavelets from each point on the surface come together to form a complicated pattern. The formation process is analogous to ripple patterns on the surface of a pond that has been disturbed by raindrops or some other object [18]. To apply this technique, a laser beam is used to illuminate the surface of interest and depending on the information sought, a section of the volumetric speckle pattern is selected and photographed. When the surface is deformed, the speckle pattern moves accordingly. The displaced speckles are photographed again and then superimposed on the first image to obtain a specklegram [18]. To delineate the speckle displacement, a narrow laser beam is sent at the points of interest and their corresponding far field diffraction spectrum received on a screen.

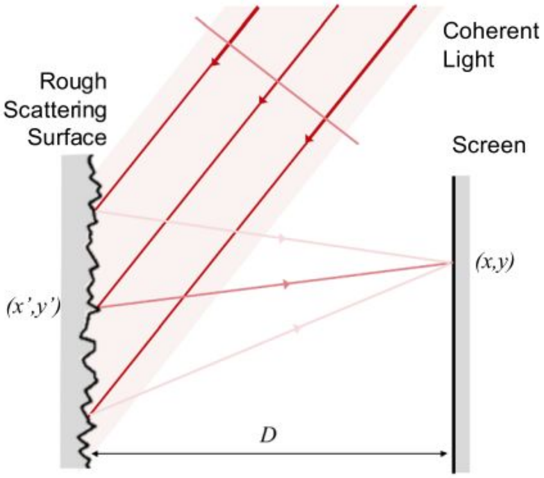


Figure 3: Simple schematic showing scattering of a coherent light on a rough surface

Figure 3 above shows a simple diagram of how the laser speckle principle operates. The collimated beam and wide spot size is essential for fully developed speckles [26]. This method will work for this project by comparing the specklegram generated from each layer with what is expected and analyzing for any deviations.

Laser speckle projection is capable of providing a three dimensional image of the surface being inspected. This allows for high accuracy detection in deviation in that changes in any orientation can be adequately captured. This accuracy however requires that a lot of data be processed at each layer which will require a faster processor most likely at a higher cost.

Optical Sensors

Optical sensor technology makes use of one or more cameras alongside a computer based image processing system. These sensors are useful as they have the capacity to detect detachment, missing material flow, as well as deformed objects as they pick up on horizontal movements of the part as well as uneven vertical growth. Due to the prevalence of cameras, optical sensors have been successfully used in a variety of different setups to detect errors in FDM printing.

Optical sensors have a setup that is generally composed of one of more cameras. The rest of the setup has varied greatly in previous work. Outlined in the paper entitled *Vision Based Error Detection for 3D Printing Process* the setup consisted of multiple cameras working alongside an "auxiliary thresholding algorithm [7]". This algorithm has the capacity to receive the footage from the optical cameras and "segment the digital image into binary images with a clear distinction between the object and the background [7]." To identify whether the print was successful or not, the differential images (in this case the difference between three images) were generated. For this method during "an error free print the object does not change its horizontal location but will only grow vertically [7]." Another method outlined by Nuchitprasitchai et al, involves the use of a single or double camera set up. Analysis occurs via taking a 2D image of the printing 3D object. The image of the printing part is then compared to a 2D shape model. Some rectification occurs (on the computer) and then image comparison (of what is printing to the model) takes place. This occurs via subtracting the actual image from the model image, "If the difference of subtraction is greater than 5%, there is an error; otherwise, there is no error flagged [19]".

One of the major benefits of using optical sensor technology is that it has successfully been used before in very similar applications to this current project- experiment could be modeled after a number of previous works. However, on top of good cameras being quite expensive (out of our price range) one of the downsides of using this technology is that the field of view is limited to a single side of the print. This can make defects hard to distinguish and identify if they are not present on the side being examined. Also if the FOV is from the top looking down onto the part, depth and contrast can make errors hard to detect. Nuchitprasitchai et al mentioned that "this system would be improved if it was applied to all sides of the printing object. For future research, this error detection system [should] be implemented and extended from the basic approach into 360° around FFF-based 3D printing [19]". Additional improvements were mentioned by the authors Baumann et al where they suggested that the algorithm be further developed for "resilience against lighting changes, [and] marker mis-detection [7]".

Laser Line Projection

Laser line scanning technology is an accurate, contactless and fast method currently employed in the inspection of the localization of surface abnormalities on large surface areas [20]. This technology is widely used in the manufacturing industry because of the low weight and compact size of the scanners, allowing easy integration with robot systems [20]. Figure 4 below shows a schematic of how the laser line projection works showing a change in height. Besides purchasing an off the shelf scanner, this method provides the option to create a tailored solution with a camera and a line laser.

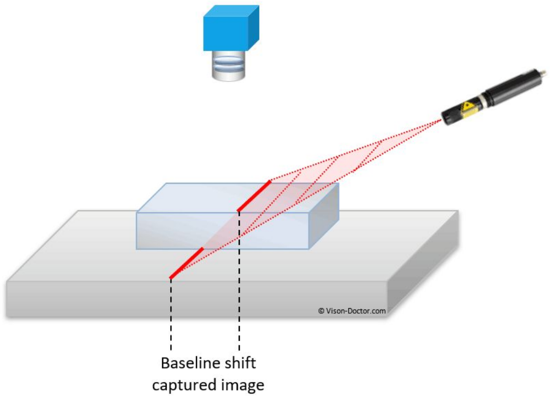


Figure 4: Schematic of the baseline shift of a laser line for height detection [21]

Laser line scanning technology works on basic geometric optical principles to accurately detect surface abnormalities (defects). Simply put, a laser line is projected onto the surface being inspected and the reflected light is picked up by the camera for analysis. This method works by determining deviations in the z-direction on each layer. From the original CAD model, the average position of the laser line can be determined as a function of height (layer number). This position is then compared to the real time position of the laser to determine if there is an undesired shift. The change in the z-direction on the print surface translates to the change in y on the 2D image received by the camera. For this method, defect detection is classified in two ways. Points of interest; those points that deviate from the from the average by more than 0.15mm - 0.35mm and if the reflected line is not in the same position as calculated from the CAD model. The values selected for the deviation is based on the thickness of each print layer.

Due to the promising nature of this method, we decided to develop it further. Detailed explanation of how it works and our implementation is described in the next section. The laser line method is advantageous in terms of speed. The cost of custom equipment is also affordable and can be justified considering the cost of the printer (a $50 red laser was used for testing). It is a fast, non-contact method capable of achieving high resolutions. The simple commercial scanner shown above has 1280 points in the line profile [19]. As this method is based solely on geometric optical principles [22], it is relatively easier to understand and apply as compared to the laser speckle, which will significantly help when troubleshooting.

There are also some disadvantages to this system which can lead to inaccuracy and uncertainty. Similar to the optical technology introduced above, surface reflectivity issues are prominent in laser line projection. Shadowing might also occur when a part of the object or printer lies in the path of the projected laser line to the camera [20].

From reviewing the advantages and challenges of the top 3 design options, it was decided that laser line projection would be the most promising solution. Rationalizing the decision for the chosen design option came from constraints (budget, method, whether it will sense defect), other considerations include time and resource restrictions. While all 3 options were non-contact, the laser line projection would be the most cost-effective as compared to laser speckle projection and optical sensor. It was noted above that laser speckle projection would not be as cost-effective as line projection. This was due to the fact that it would require an additional computer due to the amount of data. Optical cameras are quite expensive, the FOV is limited, and contrast between the printing part and the background is difficult to achieve. This made it clear that optical sensors were not a promising solution for our team.

Detailed Design and Implementation

Our implementation of the laser line projection method can be split into hardware and software components. The hardware portion of this design is concerned with equipment setup and the physics behind the measurement calculations. The software portion deals with image processing. The goal of this term's project was creating a proof of concept, therefore it was more hardware focused. Optimization of the process will be done next semester which will be heavily software based.

Analysis and Experimentation Techniques

Physics and Experimental Setup

To detect defects, our solution requires adequate understanding of Euclid's Law of Reflection. This simply states that light travels in straight lines and reflects from a surface at the same angle at which it hit it [23]; angle of reflection equals angle of incidence. Figure 5 below shows a simple schematic illustrating the process, where θ_I and θ_R are the angle of incidence and angle of reflection respectively.

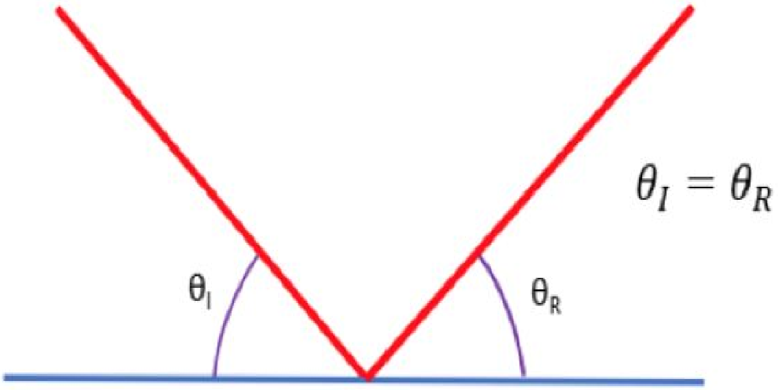


Figure 5: Schematic of Euclid's Law of Reflection

We then applied the aforementioned law of reflection to find changes in height. Figure 6 describes how a laser could be used to determine a height deviation on a surface. This figure describes how geometry can be used to relate a change in height, y, with the corresponding change in distance, x. This relationship is shown in the equation below.

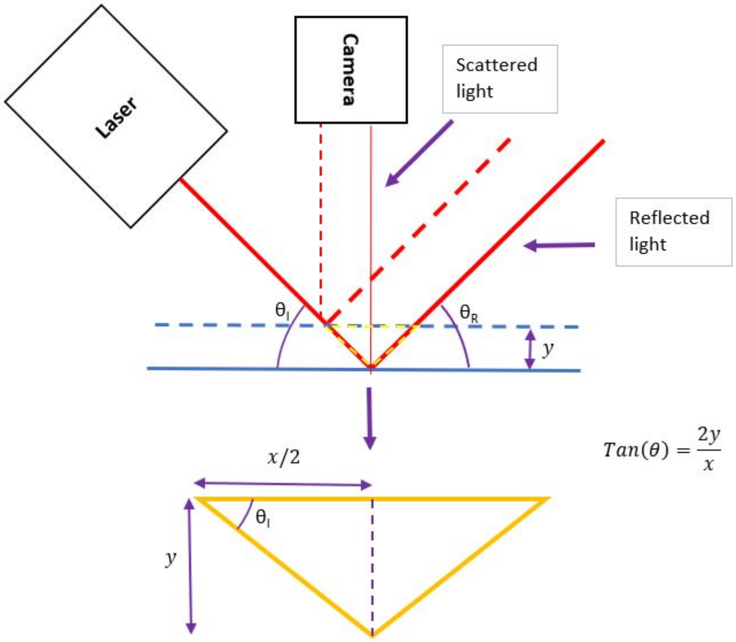


Figure 6: Applying the law of reflection to find changes in height

$$y = \frac{x}{2} * tan(\theta)$$

To implement our solution, the angle of incidence and the distance of the camera and laser from the surface need to be optimized. The variables are optimized to maximize the change in height, and therefore defect size, the setup can detect. In our system the camera is measuring “x”, so maximizing “x” for a given “y” will allow for the detection of smaller defects. According to the equation shown above, the angle of incidence must be minimized to maximize “x”.

The distance of the laser to the surface should be minimized, as this will yield the highest intensity of laser line. A higher intensity will make it easier for the software to separate the laser and ambient light. There is a limit to how close the laser can be to the surface, however, as it can not get in the way of the printer. Our solution will have the laser as close to the object as reasonable.

Finally, the distance of the camera to the surface should also be minimized. It is only possible to detect a height change equal to or greater than the side length of a pixel. The closer a camera is to a surface, the less area each pixel is responsible for representing. Figure 7 below, shows that the length of a pixel is proportional to the distance of the camera to the surface. Similarly to the laser, the camera will be as close as reasonably possible. Not only must the camera stay out of the printer’s way, but the camera’s field of view must remain large enough to see the desired area.

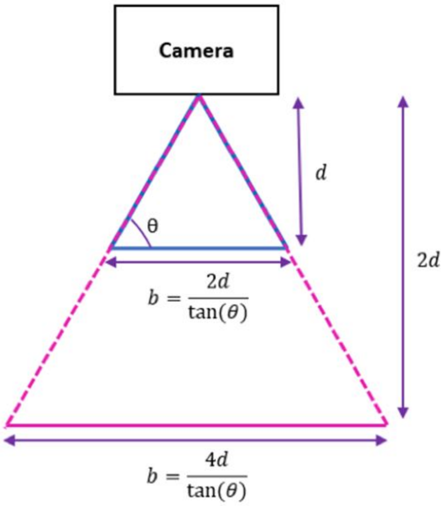


Figure 7: Schematic of relationship between field of view of camera and its distance from the surface

Image Processing

While the experimental setup was configured by the hardware team, the software team was assigned the task of determining how to process the image.

The first step for the software team was to conduct research on edge detection in images, as we would need to determine the difference between the edges of the laser line over the image to know the size of the defect.

To analyze an image, it was necessary to understand the components that make up an image, specifically the fact that a picture is a matrix of numbers. Colour images are represented as three matrices. Each matrix will have a certain amount of red, green, and blue that make up the image. The elements of the 3 matrices are the numbers ranging from 0 to 255.The number specifies the intensity of each pixel [24]**.** Pixels are the basic building blocks of a digital image and are created using geometric coordinates [25]**.**

After preliminary research into the edge detection, an idea was discussed to determine the location of a laser line edge of a simple black to white contrast as shown in Figure 10.

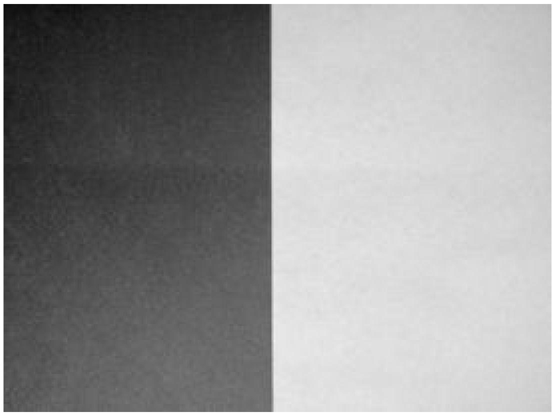


Figure 10: Image used to determine the edge between black and white [26]

Plotting pixel value vs. distance x would generally start with some noise at a low intensity, and then gradually go up over a small number of pixels to a maximum intensity with again some noise. This idea is sketched in Figure 11 below. While this shows a transition between white and black, a clear edge location value cannot be concluded. Therefore, by shifting the data from the image over by one pixel and taking the difference between the two, this would give a line in the x-direction (vertical direction) that can be used as reference for the edge.

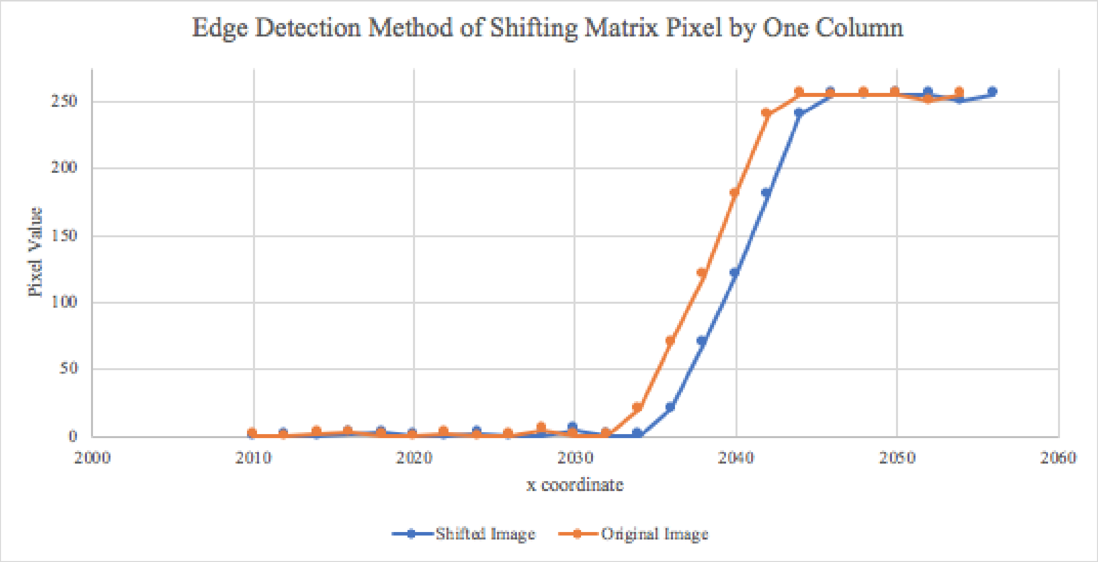


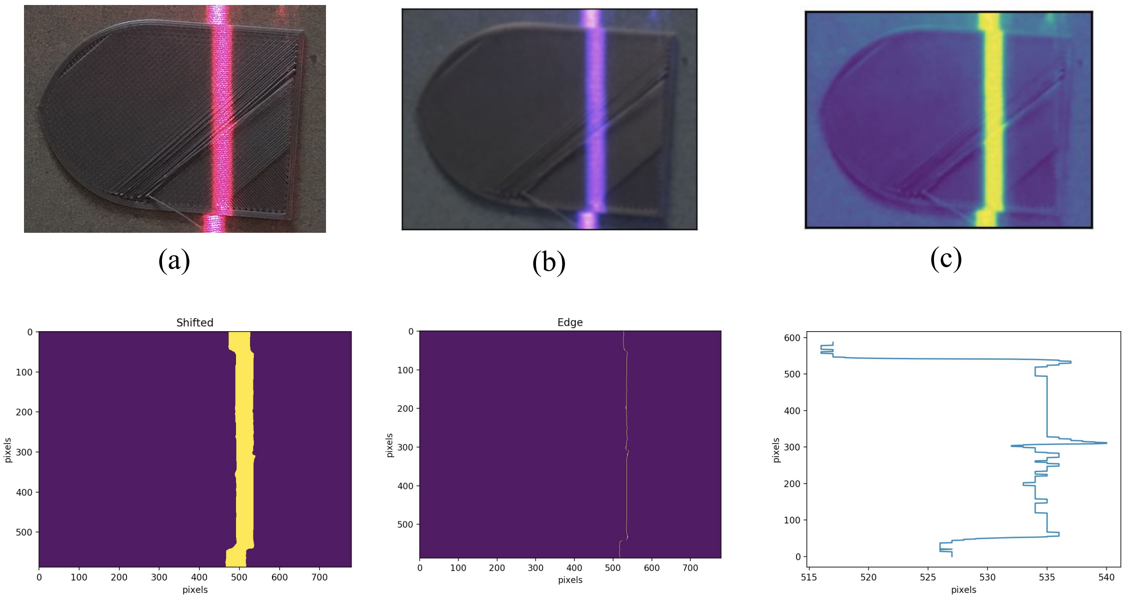
Figure 11: Example of shifting the matrix data one pixel to the right on a graph of pixel value vs. x coordinate

This method for a simple image would be the way we go about our image processing for the laser line.

Using Python, the following steps were carried out in the code:

After the image was cropped, to reduce the noise of the external background, and imported on to the computer, the first step in the code was to open the image. Lines of code were written to output the size of the image in pixels for the x and y coordinates, so that we could relate pixels with field of view. The next step involved blurring the image. Due to the fact that the laser line used this semester was not uniform in intensity, the image was blurred as a method to make it more uniform. Splitting the image into their distinct red, green, and blue matrices would help us isolate for the red laser line as the coloured image would be transformed into a grayscale image. Intensity of each pixel was represented by a single value when this step was performed. Next, a threshold value for intensity was selected. This was done to separate the line from the background. For this term, we manually selected the threshold values. The value for the threshold was set to 200. A new matrix is created to represent the Shifted Image by shifting all the pixels in the original image to the left by one column. Matrix subtraction between the Original Image and Shifted Image was calculated and plotted. This results in a single vertical line that represented the edge of the laser with x-axis and y-axis units of pixels. Due to the limited resolution of the edge plot, a new plot with scale changes made to the x-axis to better identify the stable jumps in the laser line. Using this new plot, the values between the segmented edges were manually calculated in units of pixels. Following, relating pixels to meters was calculated.

The process for edge detection described above was conducted on multiple objects in order to provide quantitative evidence that our proof of concept was a valid investment to continue on in the next term. One of the objects tested was a 3D printed shield printed by the team. The results for the printed shield from the procedure above is shown in Figure 12 below.



(a) (b) (c)

(d) (e) (f)

Figure 12: Image processing steps for 3D printed shield, (a) Original Image, (b) Blurred Image, (c)Red band Image, (d) Shifted Edge Image, (e) Difference between Shifted and Original Edge Plots, (f) Zoomed Edge Plot

Evaluation of Detailed Design

To evaluate our solution, we measured the thickness of a standard test piece; a 0.5mm blade from a feeler gauge. A feeler gauge is a gauge consisting of numerous thin blades, each with a calibrated thickness. We also tested it on a defected piece that was manually stopped after a few layers of print. This was done to evaluate how our system performed on 3D printed objects.

Equipment Setup

The hardware component of our setup involved two retort stands, a red line laser and an iphone 6. See Figure 8.

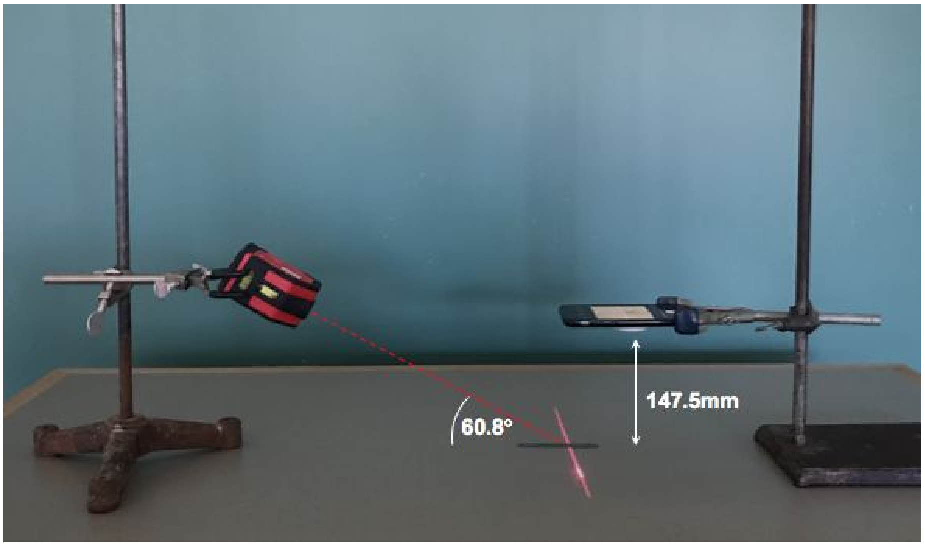


Figure 8: Experimental setup to calculate the height of a 0.5mm feeler gauge

To measure the angle of the laser, we used digital calipers to measure the difference between two positions of the laser on the retort stand (dy) and the corresponding difference in the location of the projected laser line (dx). Figure 9 below shows how these values were used to calculate the angle of incidence. The distance from the camera to the print surface was also measured with digital calipers.

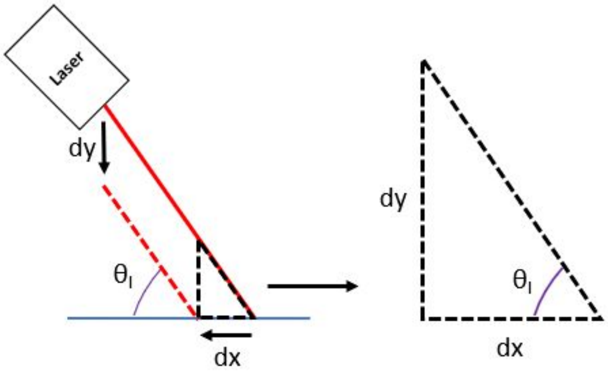


Figure 9: Calculation of incident angle from distance measurements

Calculations and Error Propagation

After image processing as described in the preceding section, we calculated that the thickness of the feeler gauge caused a seven pixel shift and knowing the pixel length to be ~ 41µm, we can calculate the value for x/2 according to the equation:

$$Shift\ size\ (x/2) = no.\ of\ pixels * pixel\ length$$
$$x/2 = 7 * 41.00529101\mu m = 287.037\mu m$$

The thickness of the feeler gauge is then calculated as:

$$y = (x/2) * tan(\theta)$$
$$y = (287.037\mu m) * tan(60.8) = 514\mu m$$

We recognise that there is some uncertainty in the numbers we calculated and these were mainly due to systematic errors. The two main systematic errors we identified from our process are:

1. Errors due to measurements taken with the digital caliper
2. Errors in estimating the number of pixels

The combined uncertainty due to systematic errors, assuming uniform distribution can therefore be calculated as shown in the figure below. The digital calipers were used for four different measurements so the uncertainty in all of those measurements were included.

$$U_C = \frac{10\mu m}{2\sqrt{3}} = \mathbf{2.886\mu m}$$

$$U_P = \frac{41.00529101\mu m}{2\sqrt{3}} = \mathbf{11.837\mu m}$$

$$U_S = (4 * U_C) + U_P$$

$$\boldsymbol{U_S} = (4 * 2.886) + 11.837 = \mathbf{23\mu m}$$

Figure 13: Uncertainty calculation for 0.5mm feeler gauge experiment

It is worth noting that the uncertainty due to the pixel length is dependent on the distance from the camera to the print surface; reducing as the distance to the camera reduces. As a result, this value will change when an optimized position is decided on for the camera location.

Our solution was also tested on a print that was manually stopped after a few layers of print, pictured in Figure 12 above. We calculated the size of defects on the last layer of the print to be 587µm. Since this is larger than the thickness of a layer, we can conclude that our solution would have detected the defect and ultimately stopped the printer.

Life Cycle Assessment

Arguably, Climate Change has become one of the most pressing global issues humanity faces today. As a product of urgency, the concept of having sustainable designs in practice is emphasized greatly in the marketplace. Industrial manufacturing systems, that is the process of transforming raw material into usable products, are responsible for a large portion of global greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2) into the atmosphere as well material waste [27]. The process of how an item is produced, or the materials chosen can have a severe impact on how environmentally sustainable it may be in the long term, and as a result, affects if the process or material is implemented [28].

To measure these impacts, a life cycle assessment (LCA) can be performed using various programs. Each stage of a products life in terms of energy use, water use, production of harmful by-products and impacts on land are measured [29]. A single life cycle is broken down into separate stages of a products life, this is schematically shown in Figure 13. Specifically, from its raw material acquisition, to manufacturing the product, to transporting the final product, to use of the product and finally, disposal or recycling of the product [29].

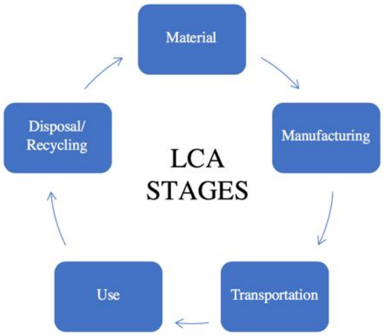


Figure 14: Life Cycle Stages of a Product/Technology [27]

In FDM, an average of 35% of material waste (by weight) is produced when printing [1]. 55% of that is directly from defects that lead to printing failures, generating unusable or rejected parts [1]. The remaining 45% of material waste comes from using support material during printing, however this will not be discussed as the focus of this report is on reducing material waste that stems from printing failures only [1].

The goal of this section is to determine how significant the problem of wasted material parts are for the environment, and where that impact derives from. An LCA will be performed to examine the types of environmental contributors associated with 3D printing to determine whether or not having a defect detection system is worth it. If defects are detected and the print stops immediately, avoiding printing the entire object, then filament material can be conserved as well as energy (electricity) to operate the machine. Analyzing the effects that these two factors have on the environment and eventually on the economics side, can help in confirming whether or not there is a need for a defect detection system, and whether or not this idea should be invested in further.

Material Filament

As part of the overall LCA of an FDM printer, the materials used to print can also have a significant impact on the environment from producing the raw filament itself. To determine how much of an impact, an LCA of the top three printing filament materials were analyzed. The three materials include, polylactic acid (PLA), which is a biodegradable polymer made from corn starch [30], acrylonitrile butadiene styrene (ABS), and a copolymer called polyethylene terephthalate glycol-modified (PETG) [31]. They are all types of thermoplastic polymers, meaning that they liquify in response to heat, and will solidify when cooled [30].

To determine if material choice has a significant role in the sustainability of FDM printing, Cambridge Engineering Selector (CES) Software was employed using the Level 3 database. For an accurate comparison of the environmental impact that each material has from production, a 1m^3 cube was used for measurement. The average densities of each material were obtained from the CES database and the mass of each cube was calculated and input into CES to obtain the corresponding LCAs of each material. The material properties are shown in Table 2 below.

Table 2: Material properties of ABS, PLA and PETG required to complete the LCA

	ABS	**PLA**	**PETG**
Density (kg/m^3)	1.02e3 – 1.08e3	1.28e3 – 1.42e3	1.26e3 - 1.28e3
Volume (m^3)	1	1	1
Mass (kg)	1.05e3	1.35e3	1.27e3

Despite the fact that PLA is a biodegradable polymer, which means that it has the ability to naturally decompose, this can only be done in specialized facilities which aren't available in all regions [32]. Additionally, only 9% of all plastics are actually recycled globally [33]. Therefore, it was assumed that all three materials (ABS, PLA and PETG) were thrown out and sent to landfill after its use, with no possible end of life potential. Each object was assumed to have a life span of 2 years before natural wear and tear occurred, as well as were polymer extruded as the manufacturing method. Additionally, it can be assumed that each part has the same transportation method which in turn doesn't contribute to any significant differences between the 3 materials in this category, allowing for emphasis to be placed on how each material is produced.

The LCA performed on the three materials looked at two important parameters, the first is the CO_2 footprint which is the amount of CO_2 (in kg) emitted into the atmosphere upon creating 1 unit of the product [29]. The second parameter is the embodied energy which is the fossil-fuel energy (in MJ) consumed in making one unit of product. Intrinsic energy, which is energy stored in the material that may be recovered or stored into other forms, is also included [29]. The results from each material are shown in figure 14**.**

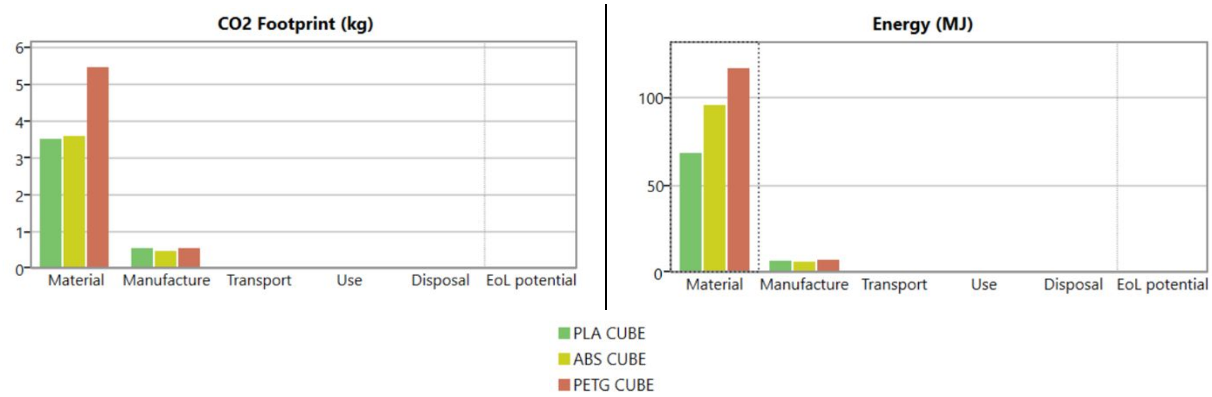


Figure 15: (a) The CO_2 footprint (kg) and (b) Embodied energy (MJ) for each material.

When looking at how FDM affects the environment based on materials alone, it is clear that PLA has the least environmental impact regarding both its CO_2 footprint and the energy involved to produce the raw material. ABS is the second least contributing, followed by PETG. The material properties of each polymer can help to explain these results.

As PLA is a type of bioplastic derived from agricultural sources such as corn starch, instead of fossil fuels, the embodied energy is significantly less than both ABS and PETG [32]. PLA also has the lowest melting point of 160°C [34], compared to the other two materials, meaning that during processing, it takes less heat, or energy rather, to extrude the material into its desired shape [32]. As PETG and ABS have melting points of 250°C and 200°C, respectively, more energy is necessary to melt and shape the material [35] [36]. This causes both the CO_2 footprint and the embodied energy of the material to increase considerably.

Energy Consumption

Although material waste and in turn, material choice can contribute to how sustainable FDM printing is, there is evidence that depicts energy consumption as the largest contributor. Energy consumption simply considers the electricity use as a resource which is essential to operate and run an FDM printer and can therefore be classified as the manufacturing-related energy [30].

A 6-month long case study done in Compiegne, France printed a plastic orthotic insole using FDM techniques to determine which part of 3D printing has the largest environmental impact [37]. As discussed, the two major impactors surround the material polymeric filaments used to print and the energy consumption required to operate the printer. The results from the case study were compared to orthotic insoles that were made by traditional handmade manufacturing practices [37]. An LCA approach was taken, to analyze the effects that producing and distributing 3D printed objects have in 4 distinct damage categories (human health impact, ecosystem quality, climate change and resources), however for the relevance of this report, only the resources category was analyzed.

The results are shown schematically in figure 15**.** Within the resource category, the production phase of the process was the largest contributor, of 70%, where 95.9% was directly from electricity consumption

[37]. This holds significant value, as it confirms that acquiring the raw materials, distributing the product, product usage and it's end of life phase are negligible compared to actually operating the machine to print the orthotic insoles.

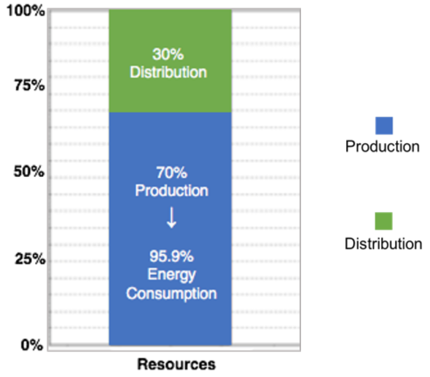


Figure 16:. Life Cycle Assessment of the resources required to produce and distribute a 3D printed insole.

The study finished with a sensitivity analysis which analysed what the outcome would be if the printing time was reduced by 2 hours. It was found that 30% of resources would be cut, confirming that printing time can have a significant impact on the environment [37].

In a separate study comparing the LCA's of 3D printing versus injection moulding, inkjet printing and CNC (computer numerical control) milling, Jeremy Faludi, a professor at UC Berkeley and TU Delft, also showed that electricity is the largest resource used in FDM printing, rather than material waste [38]. As electricity use is a function of time, it is important to reduce the amount of time spent running the machine which will inherently reduce environmental impacts.

Energy and Cost Analysis

Energy Consumption

The case study presented that 13.9 kWh (2309 W running for 6 hours per print) was required to 3D print one single insole [37]. In Canada, specifically in British Columbia, this translates to $1.58 CAD in electricity alone, to print one insole.

Evidently, 35% of material produced from 3D printing is wasted. 55% of that is directly because of defects that lead to printing failures [1]. This means that if 100 kg of insoles were 3D printed, then 35 kg would be wasted. Of those 35kg, 19.25kg would be from printing failures alone. As the goal of this project is to create a system that will eliminate 19.25 kg of material from being sent to landfill, a sensitivity analysis was performed to see what the savings in energy are for producing material filament versus the energy needed to print one insole.

If 100 kg of insoles are produced and one insole (size 10) weighs 0.08788 kg (3.1 ounces) [39], then a total of 1138 single insoles are made. Due to printing failures only, 219 insoles would be sent to landfill. This is tabulated in Table 3, below.

Table 3: Summary of how many PLA printed insoles are sent to landfill based on printing failures

Amount of Material	Weight (kg)	Amount of Insoles
100% Material Used to Print	100 kg	1138 insoles
35% Total Material Waste (by weight)	35 kg	398 insoles
55% of Material Waste from Print Failures Alone	19.25 kg	219 insoles

Finally, if the study concluded that it requires 13.856 kWh, and takes 6 hours to print one insole. Therefore, to print 219 failed insoles, then 1314 hours (55 days) and 3034 kWh are needed. Using the BC Hydro Smart Energy calculator, it costs $346.02 CAD to print 219 failed insoles, and a total of 19.25 kg of materials are sent to landfill [40].

Material Filament

A similar analysis can be conducted based on the embodied energy needed to produce PLA filament material. From the LCA shown in Figure 14 (b), 64.0 MJ or 17.8 kWh of energy is needed to produce 1m^3 (or about 1000 kg) of PLA filament. Therefore, to produce only 1 kg of filament, it requires 0.0169 kWh. If one 3D printed insole (size 10) weighs approximately 0.0878 kg (3.1 ounces) [39], then only 0.00149 kWh are needed to produce the PLA needed for one insole. Using the same BC Hydro calculator, this cost is only $13.14.

A comparison summary of the loss in energy and capital for both producing the amount of PLA required for insole, and the energy consumption to print one insole are shown in Table 4.

Table 4: Energy and Cost losses comparing material filament and energy consumption

If 219 insoles are sent to landfill:	
Material Filament	Energy Consumption
0.3285 kWh in losses	3034 kWh in losses
$13.14 CAD in losses	$346.02 CAD in losses

Therefore, it is clear that the environmental impacts associated with printing 3D parts lay within the energy consumption to operate an FDM printer, rather than the embodied energy of the material itself, as 99.99% more energy is required.

Sensitivity Analysis

Finally, a sensitivity was conducted which shows what the savings in energy and cost would be per year, as well as how many kilograms of PLA would be prevented from ending up in landfills, if different percentages of defects were discovered. If one machine operates 24.7, then exactly 1460 insoles can be printed in one year, where 281 would be sent to landfill due to printing failures. The breakdown of savings is tabulated in Table 5**.** From a cost perspective, if a defect detection system of around $300 is implemented, then the system would pay itself off if more than 80% of the defects were detected in the first year. Further calculations were done which are tabulated in Appendix C, which show that if 40% of defects were discovered, then the system would pay itself off in 2 years. And lastly, if around 25% of defects were detected, the system would pay itself off in approximately 3 years.

Table 5: Sensitivity Analysis on the effects of detecting defects during printing in one year

% of Defects Detected	Energy Saved (kWh)	Savings ($ CAD)	Savings in landfill (kg)	Savings in Insoles
20%	778.7	$88.81	4.94	56
40%	1557.4	$177.62	9.88	112
60%	2336.1	$266.44	14.82	169
80%	3114.8	$355.25	19.76	225
100%	3893.5	$444.06	24.7	281

LCA Conclusion

The International Journal of Mechanical and Mechatronics Engineering released a paper confirming that production, specifically energy consumption, was in fact the largest contributor to the environment compared to every other category including, material acquisition, transportation/distribution, product use, disposal and end of use potential [30].

Through an LCA analysis of both the PLA material filament and energy needed to 3D print one insole, it was found that environmental impacts are strongly connected to the electricity used during printing. 99.99% more energy is needed to print a part, then to produce the material for the part, translating in higher costs in electricity. Finally, this discovery changed the project objective to reducing energy consumption instead of material waste, as this is where the significance of both energy and capital stand. Therefore, investment for more efficient printing technologies or technologies that will stop the machine from running, ideally turning it off, when a print goes awry, is recommended.

Recommendations

This semester as outlined in the Detailed Design and Implementation section, a proof of concept and LCA were generated for a line laser defect detection system. As this project is eight months, the focus next semester will be refining and building the software as well as the optimization of the setup.

For the proof of concept, on the hardware side of things a line laser was fixed to a retort stand at a calculated angle. A levelled phone camera was fixed onto another retort stand and situated so that it was directly above the object being measured. Images taken were then processed using an edge detection technique in python coupled with manual thresholding and blurring of the image. For the laser currently in use, the image must be blurred to properly detect the edges. With this technique a feeler gage of 500 micron size was measured to be 513 microns plus or minus 23 microns which is an error of 2.6% (Refer to the Detailed Design and Implementation for the Calculations).

For the preliminary set up next semester, the following steps are recommended (See Appendix A preliminary algorithm flow chart).

1. Placing the camera on top of the laser so they are at the same position in regards to the object being measured. This will be done to ensure that the images being taken are unobstructed by the printer nozzle. The geometry of having both the laser and the camera on the same side of the set up will have to be analysed to determine how to get accurate measurements.
2. Attach the camera and laser setup to printer. Current plan is to 3D print arms that will stick off of the printer nozzle x-stepper on both sides of the print bed (see Appendix B for Prusa Components). The camera/ laser will be secured in between the two extensions to account for the fact that the part will be growing in the z-direction (from the bed vertically) and to ensure that the camera and laser are always at the correct height above the object.
3. Use an arduino and a pulley system to get the camera and laser to move across the wire.
4. Move or scan the laser along the print every layer, taking pictures along the length of the printing part. This will ensure that the entire layer is scanned for defects, not just one line on the surface. Multiple tests will be performed to determine how long the data will take to process and how many images should be captured for optimal performance. The number of layers which will be scanned as well as the number of images taken will be modified to ensure optimal processing time and results.
5. Design an algorithm to capture image, send it to the edge detection software, process it, and send a positive or negative signal to the print head to continue or stop extruding.

As our project is 8 months long, our groups recommendation is to move forward with a line laser defect detection system into next semester. With the work outlined in this report as well as the completion of the steps outlined in the Recommendations section, the line laser defect detection system and software can be set up for optimal defect detection and minimal (if any) false positives.

Project Work Summary

For the initial stages of this project, each individual did a literature review on the defect detection in FDM printing to determine what work had previously been done. From there, collaborative efforts were put into writing each of the three different reports- each person took on a different portion of the writing each time.

For the work distribution, we split up the group into three teams - hardware, software, and Life Cycle Assessment (LCA). The hardware team, dealt with the physics and physical setup of our laser and camera model as well as the printing of test parts. The software team focused on the edge detection code (this semester). The life cycle team conducted an LCA validating the pursual of this project. Hardware team was composed of: Catherine, Clement and Sofia; software team was Isabella and Jenna; Aleisha took charge of the LCA. The tasks assigned to each individual in the team can be found in the table of tasks in Appendix D.

While each team worked separately to complete their allocated research and tasks, collaboration amongst all teams was necessary when looking at the big picture of the project. As the focus for this term was creating a proof-of-concept, defining a set scope for the project was a key challenge amongst all groups. From meetings with our sponsor, it was decided that rather than over promising the solution, we would focus on detecting defects larger than a layer size that propagate to fall within range of the laser line. Furthermore, we focussed on simple objects with solid infill. These decisions were made as a team.

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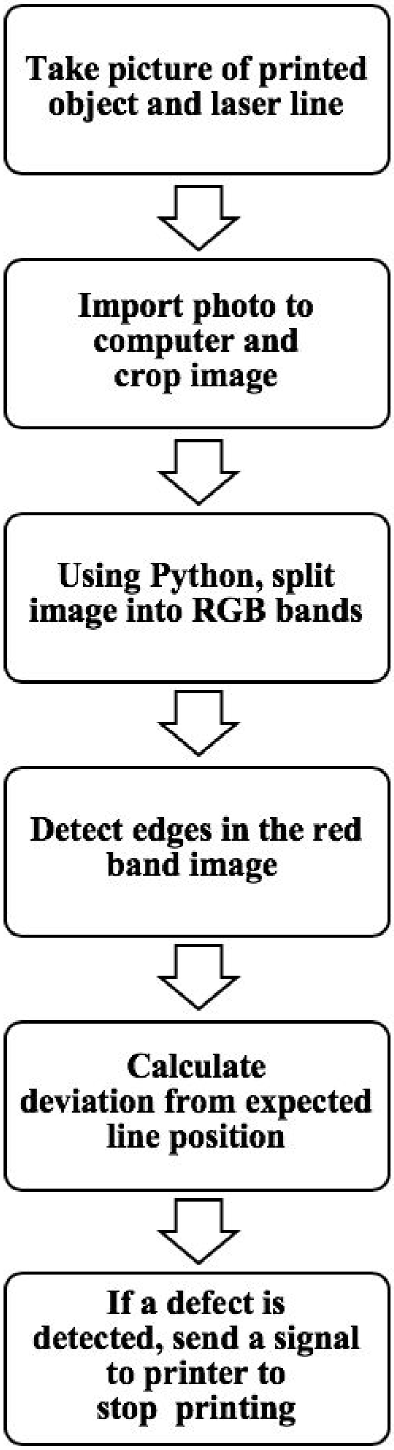
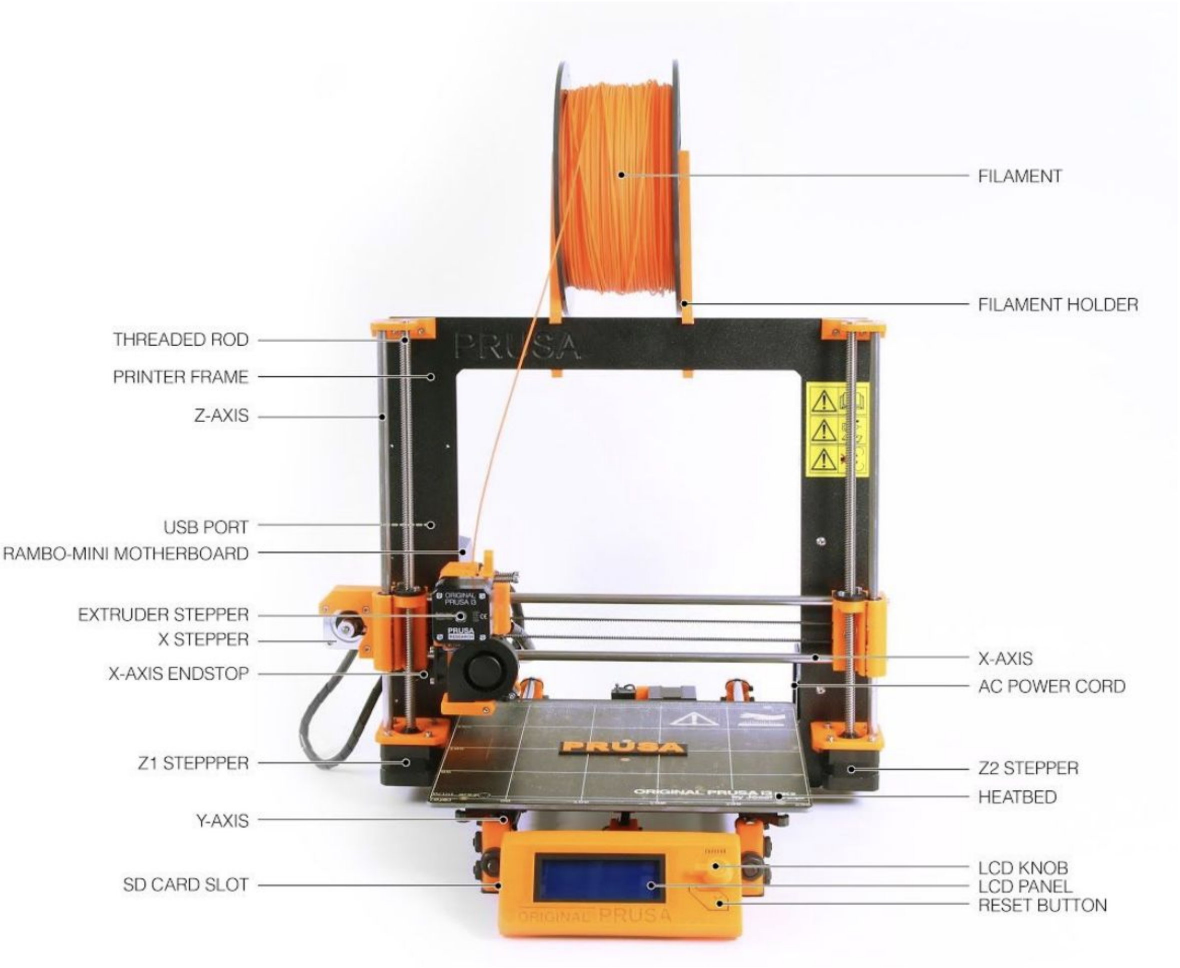
Appendices

Appendix A: Software Flowchart



Appendix B: Prusa i3 Components [10]



Appendix C: Results from the sensitivity analysis conducted on the energy and cost effects of detecting defects, assuming printing with one FDM printing non-stop.

Table 6: Sensitivity Analysis on the effects of detecting defects during printing in one year

% of Defects Detected	Energy Saved (kWh)	Savings ($ CAD)	Savings in landfill (kg)	Savings in Insoles
20%	778.7	$88.81	4.94	56
40%	1557.4	$177.62	9.88	112
60%	2336.1	$266.44	14.82	169
80%	3114.8	$355.25	19.76	225
100%	3893.5	$444.06	24.7	281

Table 7: Sensitivity Analysis on the effects of detecting defects during printing in two years

% of Defects Detected	Energy Saved (kWh)	Savings ($ CAD)	Savings in Landfill (kg)	Savings in Insoles
20%	1557.4	$177.62	9.88	112.4
40%	3114.8	$355.25	19.76	224.8
60%	4672.2	$532.87	29.64	337.2
80%	6229.6	$710.50	39.52	449.6
100%	7787	$888.12	49.4	562

Table 8: Sensitivity Analysis on the effects of detecting defects during printing in three years

% of Defects Detected	Energy Saved (kWh)	Savings ($ CAD)	Savings in landfill (kg)	Savings in Insoles
20%	2336.1	$266.44	14.82	168.6
40%	4672.2	$532.87	29.64	337.2
60%	7008.3	$799.31	44.46	505.8
80%	9344.4	$1,065.74	59.28	674.4
100%	11680.5	$1,332.18	74.1	843

Appendix D: Gantt Chart

Table 9: Table of Tasks

Task	Week	Completed by	Comments
Initial literature review complete	1	All	Milestone
Problem definition	1	Isabela, Clement & Catherine	
Research already existing solutions	1	Jenna, Aleisha & Sofia	
List of all possible solutions	2	All	Milestone
Research all possible defects	2	Sofia & Catherine	
Research all possible sensing methods	2	Clement, Aleisha & Jenna	
Begin writing proposal report	2	All	Divided among members
Preliminary proposal report written	3	All	Milestone
Finalized proposal report finished and research continued	4	All	Milestone
Finish final copy of proposal report	4	All	Divided among members
Familiarize with physical FDM printer (if available)	4	All	Group activity
Research defect size ranges	4	Catherine, Sofia & Isabela	
Research sensors (prices/precision/existence)	4	Clement, Aleisha & Jenna	
Top three solutions chosen with week 4's research	5	All	Milestone
Combine week 4 research into tables for solution comparison	5	All	Used to determine top three
In depth comparison of functionality of top solutions	5	Sofia, Catherine & Isabela	
In depth comparison of economics of top solutions	5	Clement, Aleisha & Jenna	
Most promising solution chosen	5	All	
Preliminary presentation and midterm report completed	6	All	Milestone
Prepare presentation	6	All	Divided among members
Write report	6	All	Divided among members
Practice presentation	6	Catherine & Jenna	Two presenters
Complete midterm report and research	7	All	Milestone

how the system will be used			
Complete midterm report	7	All	Each member had a different section
Reaseach line laser systems on the market	7	Catherine & Jenna	
Make sample objects; some with defects	7	Clement & Sofia	
Test line laser plus a phone camera on the printed objects; what do images look like?	7	Aleisha & Isabela	
Finalize method of using our system	8	All	Milestone
Print objects and try to catch defects on camera	8	Clement & Sofia	
Precision needed	8	Clement & Catherine	Done by analyzing objects we printed
Determine where line laser should be shining on the object being printed	8	Sofia & Isabela	Done by analyzing objects we printed
Determine the language for our code and how to interface with the CAD model	8	Jenna & Aleisha	This is to prove we can write the needed code
Complete a flow chart for the algorithm	8	Catherine & Isabela	
Determine where the system will be placed	9	All	Milestone
Mathematically determine how the angle of incident effects the system	9	Catherine & Clement	
Compare theoretical values to example images from last week	9	Jenna & Sofia	
Determine how change in height of the object effects the measurements	9	Aleisha & Isabela	
Combine information to determine where the system will be placed	9	All	
Complete proof of concept	10	All	Milestone
Update the algorithm flow chart	10	Catherine & Isabela	May change due to system placement
Film the reflection of the line laser during a print with a defect	10	Cement & Sofia	This should be done in a dark room
Use the video to validate that algorithm will work	10	Jenna & Aleisha	
Prepare final presentation and report	11	All	Milestone
Write report	11	All	Work will be split later
Prepare presentation	11	All	Each member will work on their section

Present and turn in final project	12		Milestone
Edit report	12	Catherine & Jenna	Members that are not presenting
Practice presentation	12	Aleisha, Clement, Sofia & Isabela	Presenters