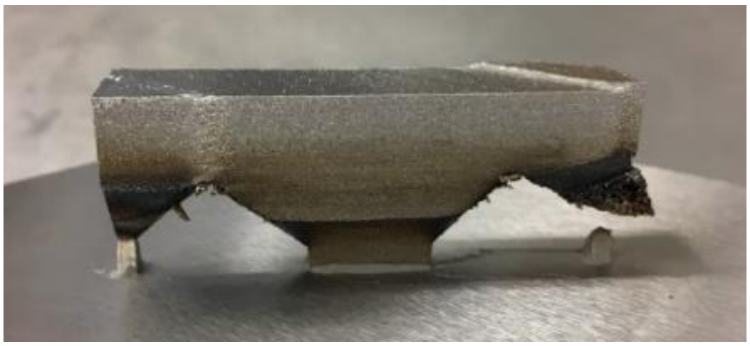
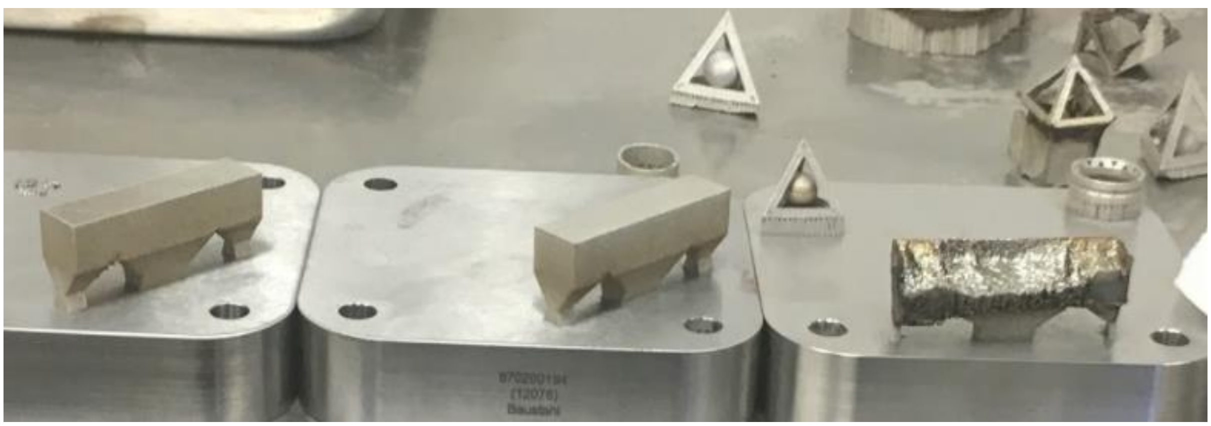
Final Design Review Report

Additive Manufacturing Part Failure Detection

Sponsor: Lawrence Livermore National Laboratory

June 2017





Prepared by:

Angel Coria - coria@calpoly.edu

Jake Whipple - jwhipple@calpoly.edu

Shaunessy Grant - skgrant@calpoly.edu

Table of Contents

1.0 Introduction

The following report is the Critical Design Review Report for the Additive Manufacturing Part Failure Detection project sponsored by Lawrence Livermore National Laboratory. Currently, the Lawrence Livermore National Laboratory uses additive manufacturing techniques, more specifically powder bed fusion, in order to manufacture metal parts that cannot be manufactured using normal metal manufacturing techniques. The objective of this project is to create a part failure detection sensor system that will allow Lawrence Livermore National Laboratory to detect cracking during the building process. Due to the time intensive nature of the SLM process, a part that may take 14 days to create could have a defect within the first hour of manufacturing, but the operator would have no idea that there was a fault in the manufacturing until culmination of the process. The proposed system will allow the operator to know when in the process the part became defective, and therefore save resources and machine time. There is currently no solution to this issue, so any progress made by the Cal Poly team will greatly enhance the understanding of the failure modes that occur. In addition to preventing wastage of time and resources, by determining when in the process the failures occur, the engineers and technicians working with this technology will be able to better understand what features of the design are contributing to failure. Since there is currently no diagnostic data available for this process, the engineers working with parts that fail are required to reverse-engineer the causes of any failures, and modify the design based on their analysis. With the results from this project, it will be clear when during the build a failure occurred, therefore easy to tell what the cause of failure was.

Metal Additive Manufacturing is a cutting-edge technology new to the engineering field, and as such, there is limited information available, and very few publications on issues similar to our project. The basis of this process is that a part is created by fusing metal powder with a laser, one layer at a time starting from the bottom of the part. The user inputs the desired part STL file from which the part will be based. The STL files take the original designed part files and breaks them into sections for manufacturing. The machine then designs a path for the laser to follow to form the layers that will be fused together to form the part. The first layer is created by depositing a very thin coat of powder, typically between twenty and seventy-five microns thick, onto a thick base plate, and using a blade to ensure that the coat is level[1]. Then the laser fuses the fresh powder to the base plate in the pattern that has been determined by the machine. These lasers heat the powder up to the material melting point, which varies depending on the material, but theoretically melt pool can reach temperatures of 5000°K[3]. Once the layer has been fused, the base plate is dropped down to allow the next coat of powder to be laid. The base plate is continuously lowered into a vertical build chamber to allow for each layer to be deposited and

fused in the same physical location. Often, the first few layers of the part are designed to be an external support that can easily be cut from the base plate without damaging the part[4]. Each subsequent layer is created in a similar fashion; a coat of powder is deposited on top of the previous layer, fused to the previous layer, and another film of metal powder is deposited. Once the part is complete, it must be cut off from the base plate, as the first layer was welded to the base plate. Multiple build cycles can be done on the same build plate; as each build cycle is completed, the part is cut off and the build plate can be reused[2]. The build chamber is an Argon environment, to prevent any metal powder particles from straying off the build plate and creating unwanted geometry. The build plate and build chamber are sealed off from the technology below, to protect the internal components from the Argon and metal powder.

Cracks and other part failures can occur during the build from the intense temperature gradients that occur from the internal welds of each layer. As the laser leaves each spot, the heat dissipates into the surrounding powder, or into the previously solidified layers of the part. This can lead to heat building up in the part, and creating thermal stresses in the part in addition to the thermal stresses from the welding process. The material that Cal Poly will be using on the SLM (Selective Laser Melting) powder bed fusion machine that was donated by Lawrence Livermore National Laboratory is stainless steel, which is fairly resistant to cracking. However, many other materials are used in this process across many industries, and each of these different materials have individual material properties. For example, Titanium (used frequently by Lawrence Livermore National Laboratory) is much more prone to cracking, which leads to difficulties in creating parts with complex geometries. This project will help operators identify cracks and which features or processes are causing these cracks.

The student team working on this project is composed of three engineers from the California Polytechnic State University in San Luis Obispo. Shaunessy Grant is a 4th year mechanical engineering student, Jake Whipple is a 4th year computer engineering student, and Angel Coria is a 5th year mechanical engineering student. This team will work in conjunction with the Mechanical Engineering Department and the Industrial and Manufacturing Engineering Department at Cal Poly, SLO, to develop and prototype a system that can detect a failure in the SLM process. This project will utilize the SLM 125 HL machine that was donated to California Polytechnic State University by Lawrence Livermore National Laboratory. The machine is being set up, with fully operational capabilities expected by Winter Quarter 2017. Since Lawrence Livermore National Laboratory use their SLM machines around the clock, time off for design, prototyping, and testing will be very expensive. Utilization of the SLM machine donated to Cal Poly during the entire designing and prototyping process will allow the team to interact with the machine without disrupting Lawrence Livermore National Laboratory's manufacturing schedule.

2.0 Background

As mentioned above, there is no current technology that allows the operators to determine part failure prior to part completion. One major reason that there is no real-time diagnostic data is that as the part is lowered into the build chamber, the walls of the chamber block all visibility of the growing part. This greatly hinders the options for sensors, and presents challenges for how to access the part as it is being made. Additionally, the build chamber is sealed off from all of the equipment below the build plate, which makes it very difficult to access the part from underneath. The build chamber is also in an Argon environment, so anything above the seal of the build plate would need to be compatible with Argon gas. Another difficulty will be selecting a sensor that can withstand the temperature of the machine. The lasers operate at several thousand degrees Celsius, and the build plate can reach two hundred degrees Celsius. The sensor chosen will need to be able to produce accurate data while operating at these temperatures. The high temperatures and large temperature changes can induce high stresses resulting in cracks. These cracks can occur at any point in the process, for example, a crack at the bottom of the part can occur towards the end of the build-time due to stress compilations throughout the creation of the part. The cracks are a result of the cyclic loading that the part is undergoing with every layer added or fatigue cracks. These cracks may propagate throughout the part, making it difficult to analyze the root cause once the part is complete.[2] Cracks can also cause parts to shift so that the initial layers are in different locations with respect to subsequent layers, changing the geometry of the part.

To determine when in a build parts are cracking, it was clear that some sort of diagnostic tool would be required. Cameras, thermal sensors, CAD comparison, acoustic sensors, accelerometers, displacement sensors, infrared detection, x-ray detection, strain gauges, load cells, and image processing were all considered as potential candidates for the final sensor system. However, thermal sensors, accelerometers, and acoustic sensors were deemed the most applicable to this project due to the fact that there would be no need for any analysis prior to the build. Since each part is unique, it would be very difficult to calculate the stresses and strains, displacement, predict images, and analyze CAD parameters for each layer of each new part. It would also be difficult to get infrared or x-ray readings through the metal powder and walls of the build chamber. Cameras would require constant attention from the machine operators, which is not feasible during a 14 day build. Thermal sensors, accelerometers, and acoustic sensors were researched in greater detail after initial analysis and discussion with the Lawrence Livermore National Laboratory Metals Additive Manufacturing team.

2.1 Thermal

Thermal sensors measure the temperature of an object or environment to determine energy characteristics of whatever is being measured. Higher temperature correlates to more energy in the body of inspection. In this project, thermal sensors could be used to monitor the melt pool where the metal powder is being fused together, to make sure that there are no discrepancies or spikes in temperature indicating that the laser is not following the desired path. This would help if a failure had occurred and shifted the part so that the laser was operating in an area that had already been sintered.

The most common form of thermal monitoring for applications similar to this project is pyrometry, which is a non-contact method using the thermal radiation emitted from the body of interest to determine the temperature of said body. This is done by comparing the intensity of the radiation of the body of interest to the radiation from a "black body," or a body that emits no radiation and absorbs everything.[6] This provides a baseline to use as a reference for any part being analyzed. One of the two methods of obtaining these pyrometry measurements is through photodiodes, commonly referred to as photoelectric pyrometers. These sensors capture radiation and transmit an electric signal that is proportional to the intensity of the thermal radiation observed by the sensor. Almost all of the research that has been conducted with this technique uses Germanium photodiodes with a wavelength of 400 - 1700 nm[5] to analyze the melt pool and monitor the success of the build through the thermal responses. However, these sensors have an active capture of about 10 mm^2, which would require an array of sensors in order to be able to capture the entire build area. Such an array would be invasive to the build chamber and does not meet the requirements set out by LLNL.

Figure 1: Germanium Photodiode

The other method of pyrometric data analysis relies on digital cameras and image processing. This process uses an array of pixels which convert light into electrical signals that are proportional to temperature.[5] There are two methods of this digital imaging as well. One is that all of the data from the pixels is gathered and processed by a single processing unit. The other method uses a different processing unit for each pixel individually. There are pros and cons to each; a single processing unit simplifies the data gathering process, but produces results that may

not be as reliable. Multiple processing units reduce the time that it takes to process the images, but is much more complex and reduces the area over which the imaging may take place. One disadvantage to the digital image analysis method is that it would require constant high-resolution images, which take up a lot of storage and can be difficult to extract specific data from. Overall, the thermal research promoted using pyrometry over digital imaging.

Thermocouples are another method of thermal monitoring that would allow for the detection of defects. This is a contact-based measurement, and therefore less desirable for our project because of the constantly changing surfaces. Thermocouples are a set of two dissimilar wires, connected at one end and free at the other. The disconnected ends are placed on two different surfaces, and can measure the voltage change due to the temperature difference between the two surfaces. This voltage difference affects the current flow through the circuit, and can be measured and translated back into temperature readings.[5] As mentioned before, this option requires direct contact to the parts being measured, and could be difficult to integrate onto a part that is constantly changing.

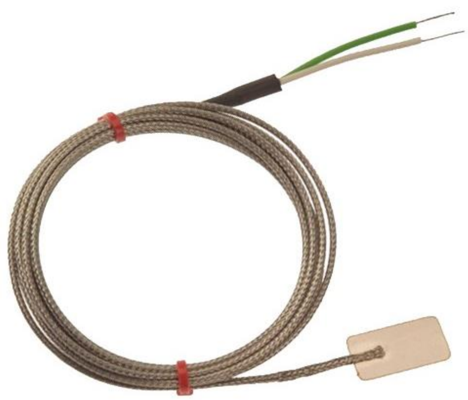


Figure 2: Example of a thermocouple

Low intensity lasers have also been used for failure detection by measuring the location of an object in respect to where the 3D CAD model expects it to be. This is enabled by a transmitter that sends the laser in the direction of the part, and a receiver that can determine the length of time for the laser to be reflected back. The time is then translated into distance, and used to locate or dimension the point of interest.[5] This could be of use to the project in ensuring that the part is being formed to the specifications of the part drawing. It could be possible to input the approximate time that the laser should take to return from any given point at any time during the process, and if it differs from the signal received, create a warning that the part was not being built to specifications. One of the issues with this method is that it would be very difficult to arrange lasers to cover the entire build plate, and monitor the entire build surface for

discrepancies. Since the part is being built below the surface of the powder, this would require some sort of internal inspection, and way of detecting the contours of the part beneath the powder. This would also require a lot of prior analysis in determining exactly where each layer of the build is expected to be at any time of the build.

2.2 Acoustic Sensors

Besides thermal based systems, audio detection systems have also been a point of interest for researchers. One of the audio detection systems looked into is ultrasonic. Ultrasonic detection relies on the use of waves that tend to exceed frequencies greater than 20 KHz and can exist up to frequencies of 25 MHz[7]. Using ultrasonic would require the use of a transducer, which converts energy from one form to another.[8] Ultrasonic waves have the capability of detecting surface or internal flaws without affecting the integrity of the material. Ultrasonic testing works by first having a pulser/receiver generate high voltage electrical pulses. The electrical pulses reach the transducer which turns the pulses into high frequency ultrasonic energy. The sound is in the form of waves and when there is a discontinuity in the wave path some of the energy will be reflected to the transducer. The transducer will convert the wave energy into an image of the echo.[9] The echo can show the size and location of cracks but requires constant observation to understand the readings.[10] Constant observation is not feasible for a build with time lengths greater than a few hours, but this could be overcome with an automated system of the feedback signals showing when a crack was beginning to propagate. Aside from errors in the feedback signal, another issue is that the ultrasonic vibrations being sent into the part cause vibrations which could affect the layer of powder that was laid down and cause unwanted stress propagation.

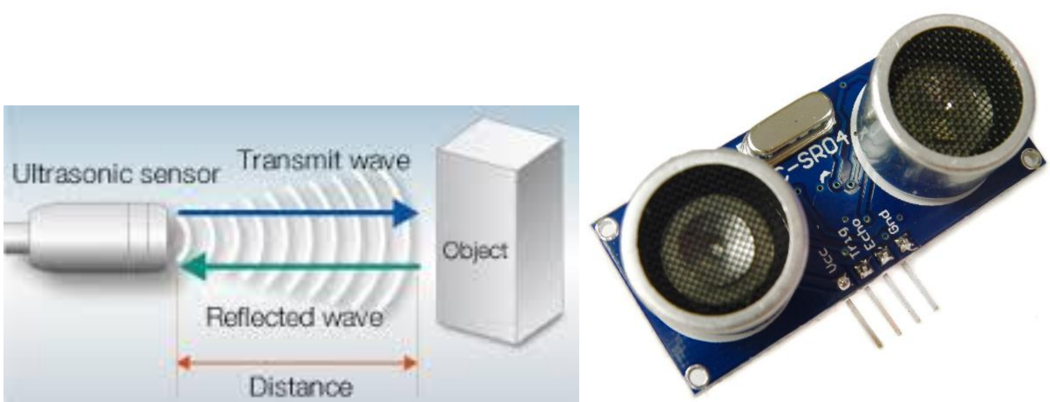


Figure 3: Demonstration of ultrasonic detection and example ultrasonic sensor

Another form of audio detection that is of interest is acoustic emissions (AE). Acoustic emissions occur when there is a sudden redistribution of stress in a material which results in the creation of an elastic wave. The waves are then picked up by sensors. The sensor waits for a signal that signifies redistribution of stress, because this indicates crack inception or growth. Acoustic emission signals are easiest to detect when material is loaded near the yield stress or if the material is undergoing plastic deformation. The signal generated through AE is dependent on the size of the crack. If two cracks originate at the same point the larger crack will produce a larger signal. In order for AE to work best, noise sources, such as frictional losses and impact sources must be reduced or eliminated with methods such as noise blocking or electronic filtering.[11] Acoustic emission seems as the superior of the two audio detection methods because with the right noise cancelling technology cracks would be able to detect cracks without the need of constant observation, and the hardware would be much more simple.

2.3 Acceleration

Another minimally intrusive method would be the integration of a vibration monitoring system into the baseplate itself. This method is of particular interest to our team for there has not been much research put into this diagnostic tool. However, this system would have to be able to withstand a large amount of heat for the baseplate can reach 200°C hen manufacturing certain parts.[2] Due to the rapid heating and cooling that occurs in the SLM process, the residual stresses that build up on the part being manufactured are massive. This creates cracks and other deformities that could potentially be felt by a system that is attached to baseplate. The primary cause of these residual stresses that lead to cracking and deformities is a temperature gradient mechanism that is a result of large thermal gradients that occur around the laser spot.[12]

Figure 4: Example of a vibration sensor

Since the material strength is reduced due to the temperature rise, coupled with elastic compression induced by the underlying material, when the material cools the top layer will be plastically compressed. This will cause shrinking and bending to the top most layer exposing the part to the risk of being defect. Another mechanism that causes susceptibility to defects is thermal contraction. Like the temperature gradient mechanism, the deformation is caused by the underlying material creates tensile stress in the top layer and compressive stress below. These stresses can exceed 750 MPa in a single direction,[13] only building as the density of the part increases. Through visiting the additive manufacturing lab at Lawrence Livermore National Laboratory and discussing the issue with the experts and technicians there, we learned that the residual stress that is found inside of these parts means that cracks occur rapidly rather than progressively. As seen in the picture below, striations (horizontal lines denoting a change in the process or geometry) occur at various layers throughout the build. These striations are not considered failures, but show that a failure could be imminent, as the stresses have already caused small deviations in the geometry. For example, the build seen below did not fully fail until the build was nearly complete, but striations are visible in layers about halfway through the part. A system that could measure the amplitude of any vibration that occurs on the build plate would be able to sense a change in vibration magnitude and alert the operator that a change in the build has occurred.

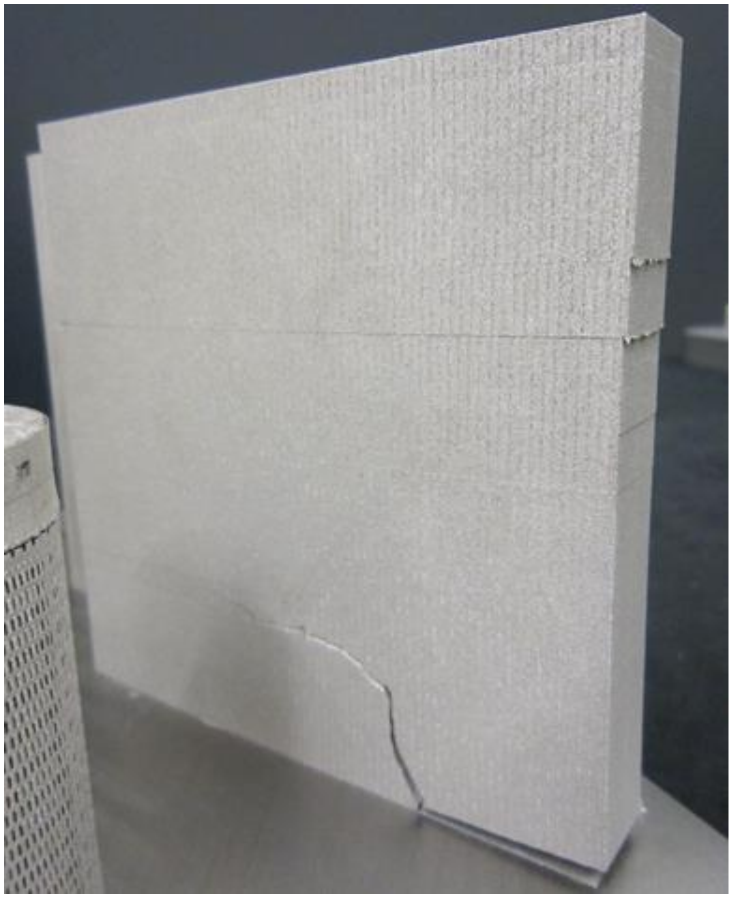


Figure 5:Example of a completed build that failed containing striations

3.0 Objectives

The objective of this project is to design and prototype a sensor system to investigate the feasibility of using commercially available sensors to detect when failure occurs in the powder bed fusion process. First and foremost, the sensor must be safe to use in all regards, from the safety of the operators to the safety of the machine and parts being built. Secondly, the customer has very high security precautions that we must be compliant with. The system must not to use any wireless or Bluetooth connections, as this is a government lab. Both of these conditions must be met with no exceptions. The detection system is also to be non-intrusive to the machine, and not disrupt any part of the manufacturing process. This constraint is particularly important with the Cal Poly SLM machine. As this is a brand-new machine, valued at over $500,000, and that will be used for multiple different unforeseen applications in the future at the university, the

machine should not be altered irreversibly in any way that could hinder future usage. Through testing and research a sensor will be selected to employ in the design. There are no current solutions for this problem, so extensive research, testing, and evaluation will be done to determine how to provide Lawrence Livermore National Laboratory with a system that can be easily repeated for future uses as well. The design will be based off of SLM 125 machine that Lawrence Livermore National Laboratory donated to Cal Poly. With access to this machine, a system will be designed that could easily be replicated for use at Lawrence Livermore National Laboratory.

Through initial analysis and understanding of the task, a number of requirements were identified that will ensure a successful project. The Quality Function Deployment method was utilized to narrow down and identify the different sensors that will be evaluated (Appendix A). This method focuses on the customer requirements, internal evaluation of what is possible, what can be done within the given time constraints, and what the team skill levels can achieve. Then the customer requirements will be combined with the individual goals of the team, giving them an order of importance. Existing designs and solutions were evaluated against our requirements, and analyzed against our potential solution. This process helped solidify the specifications and goals of this project, and clarify the relationships between internal goals and external requirements. However, the bulk of the problem analysis and definition came from discussions with the sponsor. The project scope was clarified to ensure that all desired outputs were being covered. The personal goals of the team were also taken into account based on past experience and desired experience and outcome of this project. These personal goals were measured against the goals and desires of the customer, and adjusted accordingly.

Below is the Engineering Specifications Table (Table 1), outlining the specifications and requirements. In the Tolerance column, the baseline goals are shown for each requirement, and the allowance of deviation from each of these goals. The Risk column states whether the specification is expected to be a high (H), medium (M), or low (L) risk to achieve. The Compliance column shows how the requirements will be verified, through analysis (A), inspection (I), testing (T), or similarity to existing designs (S).

Spec.	Description	Requirement	Tolerance	Risk	Compliance
1	Non-Intrusive	Build Space	Max	H	A, T, I
2	Maintenance	<30 minutes	Min	L	T, I
3	Install	Less than 2 hours	Min	M	T, I
4	Ease of Operation	Does not disrupt process	5 minutes	M	T, I
5	Safety	No harm to operators	0	L	A
6	Power	Industrial Power Supply	Min	M	S
7	Temperature	Can withstand 400°C	Min	H	S

Table 1: Engineering Specifications Table for Metal Additive Manufacturing Part Failure Detection System

Above all, the product must be safe for the technicians to use. It must be able to withstand the high temperatures that occur during the additive manufacturing process. Due to the laser welding, the temperature of the build plate upon which the part is grown may reach 400°C. It must be compatible with the other aspects of the powder bed fusion environment, such as vacuum sealed chambers. It must be able to integrate with the SLM machine with the possibility of withstanding many builds. Often, multiple parts are built on the same build plate, and the system needs to be able to detect part failures across any parts in the build. Another requirement is that the sensor system must be low maintenance and easy to install. Any additional operations that are required for the detection system cannot modify the methods that the operators are currently using to produce parts, and cannot want to modify any part of the machine process making the part. Machine downtime during the sensor system installation process must be minimized. These machines are constantly producing parts for multiple customers, and we do not want to create any sort of set-back for Lawrence Livermore National Laboratory. It should be

mobile and easy to transport between machines, if necessary. There are four similar machines at the Lawrence Livermore National Laboratory, and ideally this system will be compatible with all of the machines. The lab owns three Concept Laser machines, and one SLM 280 machine[2]. The SLM machine is the same manufacturer and make as the one at Cal Poly, it just has a larger build space, about 280x280x365 mm^3 compared to Cal Poly's 125x125x125 mm^3.[1] The laser machines follow the same patterns, building the part up from the bottom one powder layer at a time. It will be easy to replicate, and generic enough that it can be used with any Powder Bed Fusion machine.

Due to the availability and condition of the SLM 125 machine at Cal Poly, the sensor system must not be intrusive to the machine in any way. The instructors using the machine at Cal Poly have requested that nothing be done to modify the machine. This will greatly limit the sensor types allowed, and how the system will be able to be installed. Most testing will be done on the Cal Poly machine, but due to constraints from the university, the design limitations for testing purposes on campus are harsher than those from the sponsor. The system designed will fall within the Cal Poly requirements, and if the team feels that there is an alternative, superior solution that does not fall within the Cal Poly requirements, a system that may fit the needs of Lawrence Livermore National Laboratory will be detailed and recommended.

In addition to designing a sensor system that can detect when cracks occur, a secondary objective is to go beyond the minimum requirements of the sponsor, and provide the machine operators with an alert system that will allow them to stop the process when a failure is first detected. Currently, because there is no detection system for this process, many materials and resources are wasted due to early part failure. Since Lawrence Livermore National Laboratory is working with new materials and custom-made parts, these resources can be very rare and expensive. Some of the parts being made can cost thousands of dollars, and this would save the costs of full production for a part that is faulty. By notifying the operators when a failure has occurred, an option will be given to discard the build and save valuable time and other resources that would have gone into completion of a faulty part.

** Updates to Section 3 - Objectives

1) The sensor selection process will be heavily dependant on research, but ultimately, Lawrence Livermore would like the sensors installed on the Cal Poly SLM machine to be the exact models of the sensors that they are purchasing for their own machines.
2) Objectives Updated: Requirements as Defined by Sponsor (11/3/2016)
    a) Diagnostic System shall be able to detect when a part cracks during a build (identify the point in the build when the crack propagates)

b) Develop a simple notification system to alert the operators of a failed build
c) For example, when a certain threshold is reached, a light could turn on
d) Design should be inexpensive, conclusive and simple
e) Minimize waste of test material required
f) It should be safe for human operators
g) It shall be integrated into the SLM Machine without negatively affecting the build process or damaging the machine

4.0 Design Development

4.1 - Initial Design - 1st Iteration

This project has two main components to it that will be designed for. The first is which type of sensor to use to detect any failures that may occur during the builds. This is the primary issue, and majority of this project. Prior to any testing, there is no information that would help determine which sensor type would be the most appropriate. The second issue is the location of any sensors implemented. The location of the sensor depends on the type of sensor chosen. For example, a thermal sensor should be mounted near the laser for a Lagrangian reference frame of the melt pool. Acoustic and vibrational sensor should be mounted touching or embedded in the base plate, to monitor the development of the part. Project design sessions began with determining which sensors would be the most applicable, then analyzing the different potential locations. Multiple “ideation” sessions were held, where various sensor configurations brainstormed and discussed. Because this project is based upon configuring different off-the-shelf products, the majority of the brainstorming would come from researching each individual sensor type and learning how to integrate them into the overall system.

Initial research on sensor types was difficult due to the fact that there is no data on previous trials or initial design concepts to build upon. Since this project is unique and has not been attempted before, it was difficult determining what type of measurable output would be able to be sensed by a sensor. Also, because this technology is so new at Cal Poly, a lot of the initial decisions were made based on the sponsor’s understanding of the machine workings. Based on the recommendations of the sponsor and the sponsor’s understanding of the SLM machine workings, the thermal sensor, acoustic sensor, and vibration sensor categories were researched in detail. Research helped determine which general sensor areas had been used

successfully in similar applications, and which types of sensors seemed the most promising. For acoustic sensors to measure audible changes, acoustic emissions sensors and ultrasonic sensors seemed to fit this project the best. To measure vibrations of the build plate and determine cracking, displacement sensors and accelerometers would be best. Visual thermal sensors were investigated to monitor the weld pool energy and determine stress concentration areas.

Each of these sensors were rated against the design constraints and specifications. The constraints and specifications began with the requests from the sponsors, specifically that it must be safe for the operators, non-intrusive to the build process, not damage the machine, be simple and conclusive, and minimize wasted material. The first analysis and comparison of sensors was done through the Pugh matrix format, as shown below.

	Photodiode	Spectrometer	Camera	Accelerometer	Displacement	AE	Ultrasonic
Criteria							
Non-Intrusive	0	0	1	0	0	1	-1
Temperature	0	0	0	1	0	0	-1
Sensor ability	0	0	-1	0	0	1	1
Maintenance/Installation	0	0	0	0	-1	0	0
Σ+	0	0	1	1	1	2	1
Σ-	0	0	-1	0	-1	0	-2
ΣS	0	0	0	1	0	2	-1

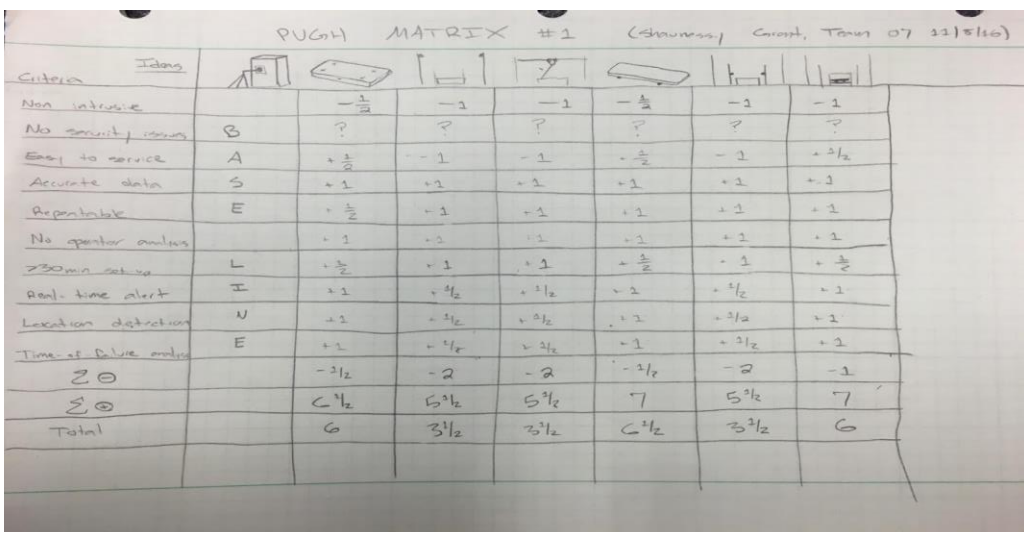
Table 2: Pugh Matrix for sensors

From this analysis, a general comparison was generated that showed the most promising sensors. As shown in Table 2, the accelerometer and AE (acoustic emissions) were the top results. Through a presentation and discussion with Lawrence Livermore National Laboratories, it was decided that this project should move forward using the accelerometer and acoustic emissions sensors.

In addition to comparing single sensors, another idea was to combine different types of sensors to integrate into the sensor system. This would provide an option of analyzing multiple types of output from the machine, and possibly give a wider range of data that would be able to detect cracks through various means. Each of the sensor options and compilation options are rated against the specifications listed in the Decision Matrix in Appendix C. The most heavily weighted categories were safety for the operators and the machine, accurate data in real-time, and non-intrusive (no change to the machine process or the operator process). The Decision

Matrix, helped determine that an accelerometer would be the best single sensor, and an accelerometer coupled with an acoustic sensor would be the best overall option. Because there is no research on what outputs from the machine could be measured, it is difficult to tell whether either of these sensors will be able to pick up valuable data useful for this application.

Another major aspect of the design is the location of the sensor(s). Cal Poly and Lawrence Livermore National Laboratory have different restrictions on where the sensors can be placed. Cal Poly does not want the system interfacing with the machine at all, while Lawrence Livermore National Laboratory intends to let the sensor system interact and alter more of the machine. From these constraints, initial research, and the recommendations of the sponsor, it was determined that the most apt location choices for the sensors would be: embedded in the base plate, located under the base plate, located on the side of the elevator shaft, located below the elevator shaft, attached to the machine walls, attached to the laser, or outside of the machine completely. In addition to each individual location, putting sensors in multiple locations was considered. From analysis based upon the same constraints and parameters as the sensor decision, it was determined that the ideal single location would be embedded in the base plate, and that multiple sensors could be embedded in the base plate and below the base plate. However, this particular analysis did not take into account that the different locations would provide different vantage points when compared with each other.



PUGH MATRIX #1 (Shaunessy Grant, Team 07 11/5/16)

Criteria / Ideas							
Non intrusive		− 1/2	−1	−1	− 1/2	−1	−1
No security issues	B	?	?	?	?	?	?
Easy to service	A	+ 1/2	−1	−1	+ 1/2	−1	+ 1/2
Accurate data	S	+1	+1	+1	+1	+1	+1
Repeatable	E	+ 1/2	+1	+1	+1	+1	+1
No operator analysis		+1	+1	+1	+1	+1	+1
>30min set up	L	+ 1/2	+1	+1	+ 1/2	+1	+ 1/2
Real-time alert	I	+1	+ 1/2	+ 1/2	+1	+ 1/2	+1
Location detection	N	+1	+ 1/2	+ 1/2	+1	+ 1/2	+1
Time-of-failure analysis	E	+1	+ 1/2	+ 1/2	+1	+ 1/2	+1
Σ −		− 1/2	−2	−2	− 1/2	−2	−1
Σ +		6 1/2	5 1/2	5 1/2	7	5 1/2	7
Total		6	3 1/2	3 1/2	6 1/2	3 1/2	6

Table 3: Pugh matrix for sensor locations

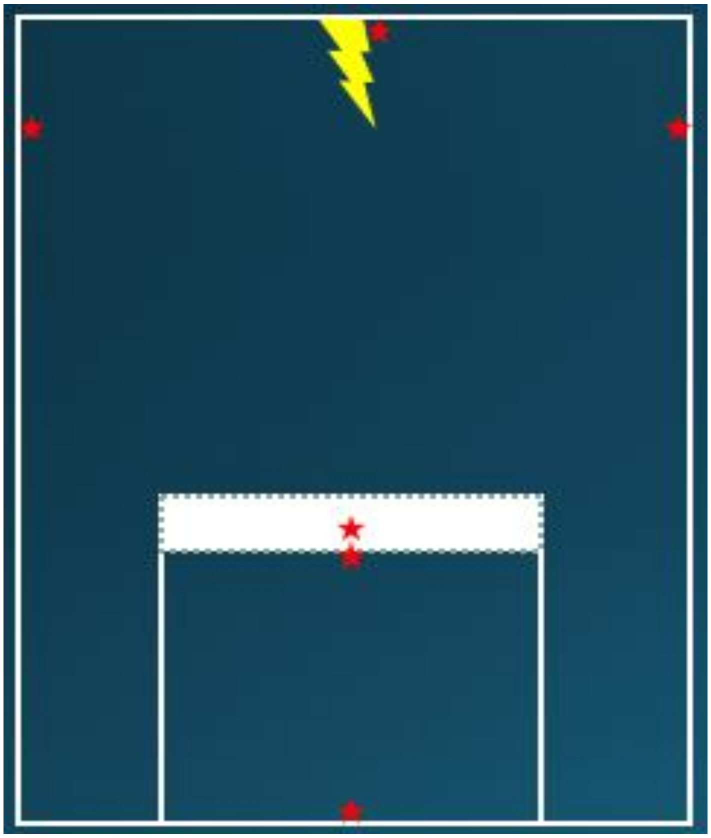


Figure 6: Layout of all potential Sensor location

Similarly to the brainstorming and initial design process with the different sensor types, the decision process for sensor location started with a Pugh matrix. Due to unfamiliarity with the machine, the constraints of different locations with different sensors was not taken into account. For example, a camera would not be useful under the base plate. Below is a sketch of our initial Pugh matrix regarding sensor location within the SLM machine.

Another aspect considered when determining the top location ideas was that certain locations will only work with certain sensor types. For example, a thermal sensor for monitoring the melt pool would not provide useful data mounted anywhere except above the melt pool. Accelerometers would not be of much use on the walls of the machine. This helped narrow down the sensor selection, due to the feasibility and intrusivity of each sensor location. Below is another Pugh matrix of the different sensors in appropriate locations for each.

Concept/Criteria	Accelerometer mounted in middle of baseplate	Accelerometers mounted in corners of baseplate	Accelerometers mounted on each side as supposed to corners	Microphone mounted on baseplate	Microphone mounted on upper wall in chamber	Camera Mounted outside of the chamber	Microphone and accelrometer mounted on the bottom of the baseplate
Non - intrusive	-0.5	-1	-1	-0.5	-0.5	B	-1
easy to service	1	0.5	0.5	0.5	1	A	-0.5
Cost	1	1	1	1	1	S	0.5
Installation	0	-1	-1	1	-0.5	E	-1
Data Collection	1	1	1	1	1		1
No security issues	0	0	0	0	0	L	0
Power usage	1	1	1	1	1	I	1
Equipmment required	1	0.5	0.5	1	1	N	0.5
Interface with alert system	1	1	1	1	1	E	1
30 > minute setup	1	1	1	1	1		0.5
Repeatable	1	1	1	0	0		1
+	8	7	7	7.5	7		5.5
-	-0.5	-2	-2	-0.5	-1		-2.5
0	1	1	1	2	2		1

Table 4: Pugh matrix for sensors integrated with location

From the selected top sensor types and locations, thermal monitoring sensors were eliminated from the idea pool, as they would not be appropriate for our design considerations. A thermal sensor would require hours of analysis before any build, as each build is unique and different, and would require different energy inputs, heat generation, and thermal emissions. This would also require constant operator interpretation of the data. As some of these builds can take up to 14 days of machine time, this was not a feasible option. Acoustic sensors and accelerometers would monitor the response of the part and machine, and could be compared to normal running data. This would allow the system to monitor anything out of the ordinary, rather than doing analysis on each build and interpreting real-time data against previous calculations. Both selected options could be wired to a Data Acquisition system (DAQ), and programmed with an algorithm to alert the operator when a failure has occurred, or machine behavior is out of the ordinary.

Acoustic emissions sensors and accelerometers can also be integrated into the base plate, either embedded or mounted below, which were the leading location ideas. CAD drawings of these options are shown in Figure 7 and Figure 8.

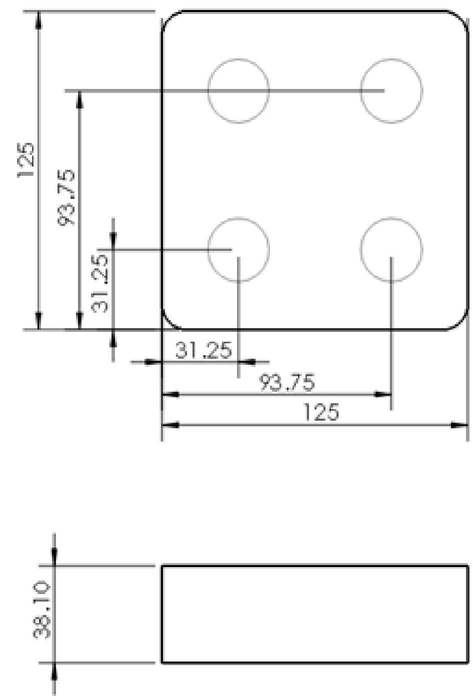


Figure 7: Sensor underneath the build plate

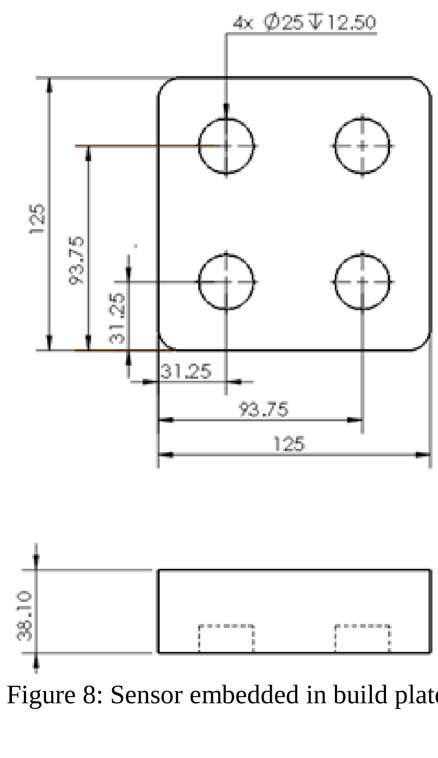


Figure 8: Sensor embedded in build plate

Once the more favorable solutions were determined, they were presented to the sponsor in an informal report. The sponsor agreed that thermal sensors were not practical for this application, and shared that they intend to do tests with similar sensor options for projects they are running. This project, run at Cal Poly, will work in parallel with what the Lawrence Livermore National Laboratories is doing in their lab, and results will be shared for mutual advancement. The Metal AM team at Lawrence Livermore National Laboratory has in their possession an acoustic sensor that they plan on implementing into their machine for preliminary data collection tests within the next two weeks. The Cal Poly team will be able to use the resulting data to gather more information as to what type of data is received from the machine in use. The Lawrence Livermore National Laboratory team recommended that the students at Cal Poly continue looking into specific models and brands of accelerometers and acoustic emissions sensors to determine exactly which sensors to could buy that would conform to all specs.

Moving forward, the Cal Poly team will begin designing a test plan for each of the sensors in various locations. The majority of the project will be testing and analyzing the sensor system implemented. It is anticipated that the bulk of the testing will be focused on determining the ideal placement of sensors around the part being manufactured. This may be one of the main challenges for the Cal Poly team, coordinating a testing schedule with the Cal Poly IME department and the restrictions that they have placed on the machine. Once the prototype has been tested to determine its capabilities, focus will be on ensuring that it is easy to manufacture, use, and implement in the machines at Lawrence Livermore National Laboratory.

Updates to Section 4 - Design Development

1) Final sensor decision was based upon which sensors Lawrence Livermore National Laboratory would be buying. After much discussion, it was decided that Cal Poly would purchase the same sensors and Lawrence Livermore National Laboratory. This would allow both teams to work together to find the best configuration for the sensors purchased. This decision was influenced greatly by the joint sensor research done by the Cal Poly team and the Lawrence Livermore National Laboratory Metals Additive Manufacturing team. Due to the security requirement (no wireless/bluetooth), high resolution, high frequency, and size constraints necessary for a complete analysis of the SLM machine function, only one manufacturer was considered. Kistler is a leader in the diagnostic technology industry, and was ultimately chosen as the vendor for the sensors purchased.
2) See Sections 4.2-4.3 for updates to the location decision. This was changed multiple times due to more information being released about the internal component geometry of the SLM machine and different components not be accessible.

4.2 - Second Iteration Design

During multiple conference calls with the machine manufacturer in the week of January 16th, the team discovered that the assumptions that had been an integral part of the initial design were false. Initially, all designs had been based off of a very similar Powder Bed Fusion machine that Lawrence Livermore National Laboratory was working with, designed and manufactured by Concept Laser. There was not much information given about the SLM machine that Cal Poly had on campus, and as it had not yet been installed, there was no way to determine what would be possible. The main assumption that proved to be false was that the build plate would be directly accessible from below. The implication of this assumption was that the sensors could be embedded in the bottom of the build plate, and then wires could be run directly from the sensors out the bottom of the build chamber, and hooked up to a Data Acquisition System external to the machine. However, once the initial plan had been finalized and approved by both Lawrence Livermore National Laboratory and the Cal Poly IME department, it was determined that that was not the case. On the SLM machines, below the build plate was another plate (the "mounting plate"), used for mounting the build plate to the lead screw that functioned to lower the build plate incrementally throughout the build. Below this mounting plate was a heating element that maintained the build plate a constant temperature input by the user, up to 200℃. There is no passage between the build plate and the mounting plate for any wires to pass through, nor any passage from the mounting plate to the external of the machine for wires to the Data Acquisition System. (See Figure 9 below).

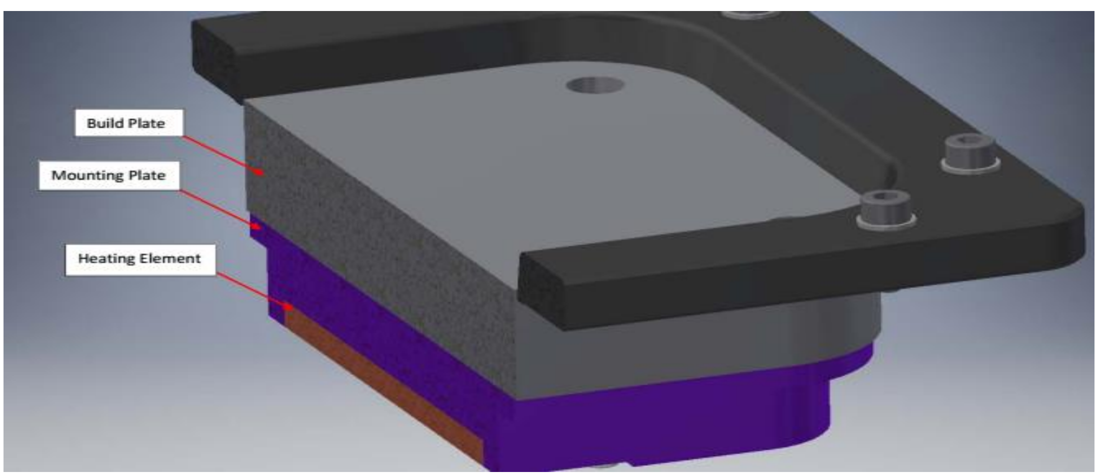


Figure 9: CAD layout of build plate, mounting plate, and heating element, provided by SLM

In addition to the new information regarding the layout and geometry of the build chamber, more information was given about the requirements of the build chamber at this time as well. The build plate is hermetically sealed off from the components below, to keep the Argon gas and metal powder particles out of the mechanical and electrical elements of the machine. According to SLM installation technician Dan Garman, it takes a very small amount of metal powder outside of the designated area to shut down the machine. Therefore, it is vitally important that the hermetic seal not be bypassed in any sensor system design, For this reason, the second design iteration would take place not in the base plate, but in the space below the mounting plate, under the plane of the hermetic seal.

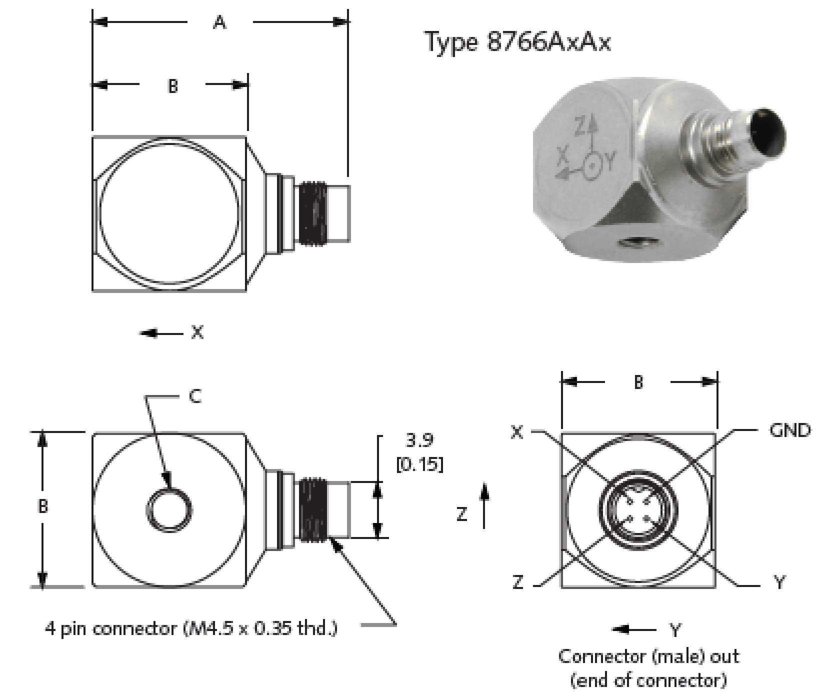
The second design would require the removal of the heating element beneath the mounting plate. The heating element is not required for builds made with steel, but it does add desireable qualities to the finished products of some materials. Cal Poly will be working primarily with steel powder, so removing the heating element should not cause any major impediments, and this design alteration was approved by the Cal Poly IME Department. Removing the heating element would open up a square volume under the mounting plate with a height of 7.5mm. While the available volume from removing the heating element would not be enough to contain the sensors, it would be possible to drill into the mounting plate and create pockets for the sensors. While this does go against one of the Cal Poly requirements, that this project must not permanently alter any part of the machine, SLM guaranteed that it would be possible to purchase a replacement mounting plate should the heating element be re-installed after the conclusion of this project.

At this point in the project, specific sensor models were identified and chosen. By far the most challenging specification to hit when determining specific sensor models was the high temperature requirement. Due to the wide frequency range and high sensitivity desired because there is no available information about the output of the SLM machine, there are not many manufacturers that produce such cutting edge diagnostic tools. The majority of sensors on the market do not reach above 165°C, and those that due cannot meet the rest of the requirements for this project. Kistler Group produces a high temperature (up to 165°C), lightweight, wide frequency range triaxial accelerometer that fell within the security requirements, as well as a high temperature, wide frequency range acoustic emissions sensor. Kistler is a Switzerland based company focusing on “dynamic pressure, force, torque, and acceleration measurement” (Kistler Mission Statement). Their 8766A500AH 500g PiezoStar® Triaxial Accelerometer was chosen as the ideal accelerometer for this application. The Kistler 8152C0050000 Piezoceramic Acoustic Emission Sensor was chosen as the acoustic emissions sensor for this project. In addition, because of the space constraint in the mounting plate, a single-axis accelerometer was added to

the sensors to be used in this project. Kistler's 8278A500SP5 500g Ceramic Shear Accelerometer was chosen in addition to the triaxial accelerometer and acoustic emissions sensor listed above. This single-axis accelerometer is one fifth the size of the triaxial accelerometer, and would not require any drilling into the mounting plate, being only 3.3mm in height. All three of these sensors were purchased, as outlined in the Cost Analysis section.

Due to the size of the sensors chosen, the alterations to the mounting plate would not be excessive. The accelerometer that was chosen is a 10.9mm cube with a protrusion that reaches 7.6mm further (see Fig. 10). This would require drilling a 10.9x10.9x4mm pocket into the mounting plate. The mounting plate is 22mm thick, so this would be removing approximately 18% of the material between the sensor and the heating build plate. The acoustic emissions sensor is 16mm in height, and would require drilling a 15x23.5x8.5 pocket in the mounting plate (see Fig. 11), which is 38.6% of the height. This is more considerable, and would require close monitoring and analysis to ensure that there was no detrimental heat transfer effects from removing this much material in one spot. However, it is safe to assume that there will not be any heat transfer consequences because by removing the heating element, the bottom of the mounting plate should not experience a large temperature jump. The powder particles in the build chamber disperse much of the heat from the lasers, diverting the heat from reaching the bottom of the mounting plate, under the 1-inch steel build plate.

At this time, it was also assumed that all of the wiring and cables could be routed out through hole in the mounting plate already in place for the cables to the heating element, as shown in Fig. 12. The routing holes were reported to be 6mm in diameter, and should therefore be able to hold the wires for the designated sensors. However, as was discovered later, the diameter of the cables and orientation that they must be fixed in would not be compatible with the routing holes available.



	Type 8766A050/100Ax	Type 8766A250/500/1K0Ax
A	21.1 [0.83]	18.2 [0.72]
B	12.5 [0.49]	10.9 [0.43]
C	6-32 UNC-2B mtg. thd., Typ. 3	5-40 UNC-2B mtg. thd., Typ. 3

Dimensions are shown in mm [in], unless otherwise noted.

Figure 10: Dimensions of the tri-axial accelerometer, provided by Kistler

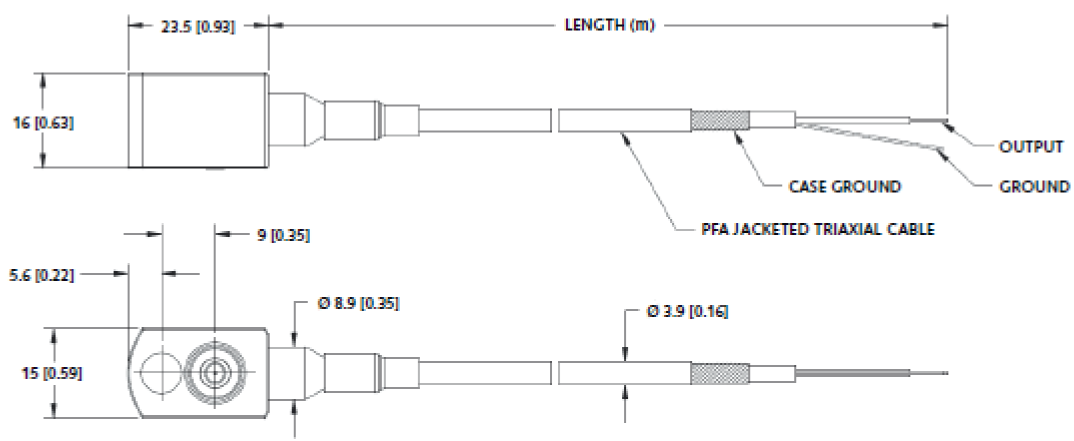


Figure 11:Dimensions of the Acoustic Emissions sensor, provided by Kistler

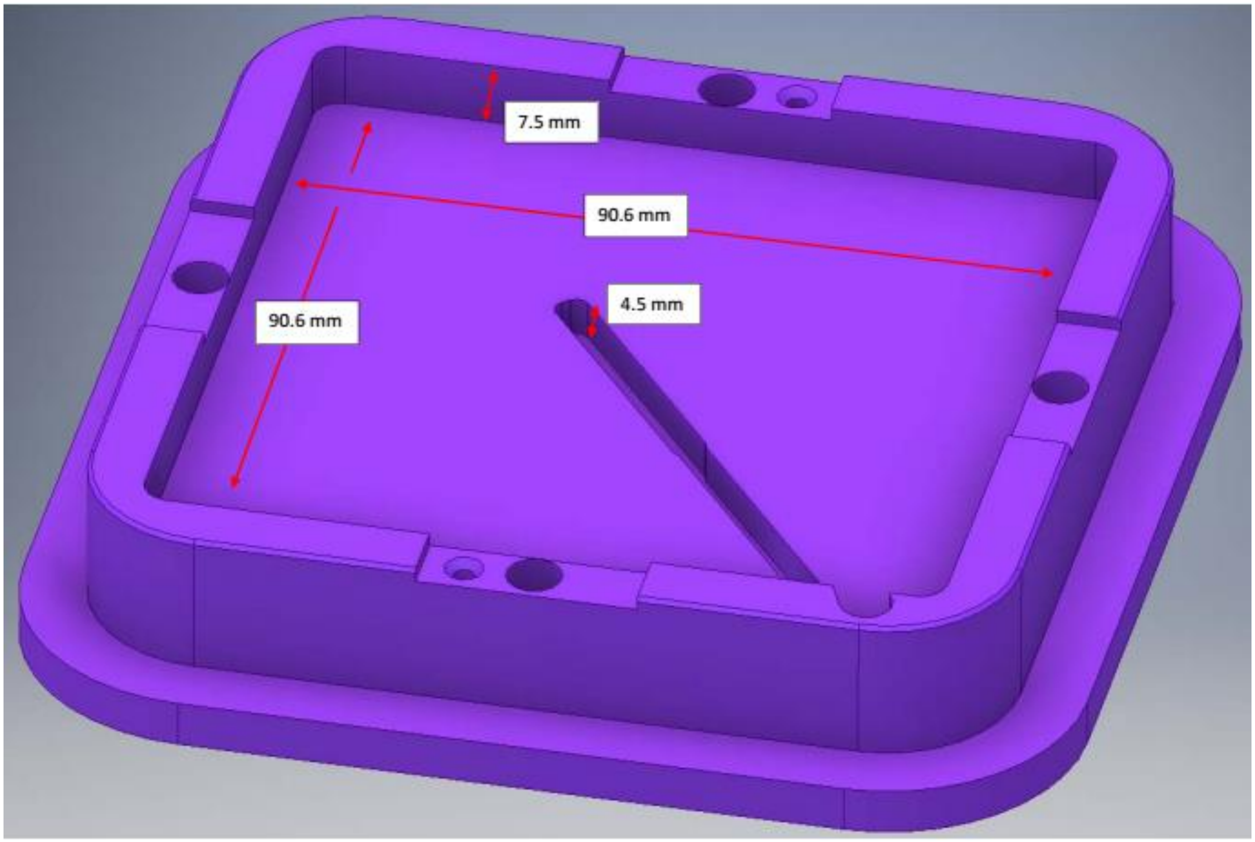


Figure 12:Dimensions of the mounting plate, provided by SLM

4.3 - Third Design Iteration

One week after the second iteration design was complete, the Cal Poly team was informed that the Lawrence Livermore National Laboratory Metal Additive Manufacturing team was no longer comfortable with the sensors being placed inside the build chamber, drilling holes in the mounting plate, and removing the heating element. There were many reasons for this decision, among the top being the fact that all SLM machines at Lawrence Livermore National Laboratory are run with the heating element on, due to the characteristics materials that are being used. Additionally, there was no guarantee of when the heating element could be re-installed, along with a new mounting plate. Re-installing the mounting plate could potentially cause down-time for the Cal Poly SLM machine, limiting future usage. Removing the heating element would also restrict the usage of the machine for the duration of this project, and could potentially create undesired characteristics in any parts made with this machine. Since the machine at Cal Poly is brand-new, there was a lot of hesitation making any alterations to the inside components.

The third design iteration has two separate components, dependent on the type of sensor. The accelerometers will be attached to the bottom of the ceramic plate, which lies below the heating element. Since there is currently no information on what the output of the SLM will be, or what a crack would look like, both sensors will be used to gather a larger amount of data, and therefore provide more information about the inner workings of the machine. Both the single-axis and triaxial accelerometers will be mounted using an adhesive, as is common in industry. The adhesive will put one side of the accelerometer in direct contact with the bottom of the elevator mechanism. Since the heating element can reach 200°C, the adhesive used must be able to withstand high temperatures. Silicone adhesives retain their properties and can have a glass transition temperature up to 300°C. This is ideal for the environment in which the accelerometers will be mounted. Kistler also recommended using this type of adhesive, as it will not do any damage to the accelerometers. Since the adhesive will have a slight dampening effect on the accelerometers, Kistler advised using the least amount of adhesive possible when mounting the sensors. As shown in Fig. 13 below, the sensors will be mounted on various locations, one on the circular plate and one on the square plate. Initially, the accelerometers would be moved around for each test, to determine the location where the best response came through. However, the adhesives being used will not allow for easy removal. Therefore, the triaxial sensor will be mounted at location 1, and the single-axis accelerometer will be placed at location 2. Location 1 is one layer closer to the build plate, and it is assumed that the vibrations will be stronger and therefore easier to register at this location. Since the triaxial sensor will be providing more data and has a higher resolution, it will be placed at location 1. In the figure, the cubes represent different options for the placement of the sensors, and the cylindrical studs represent the pre-existing studs on the plates to provide support and mobility for the entire build elevator.

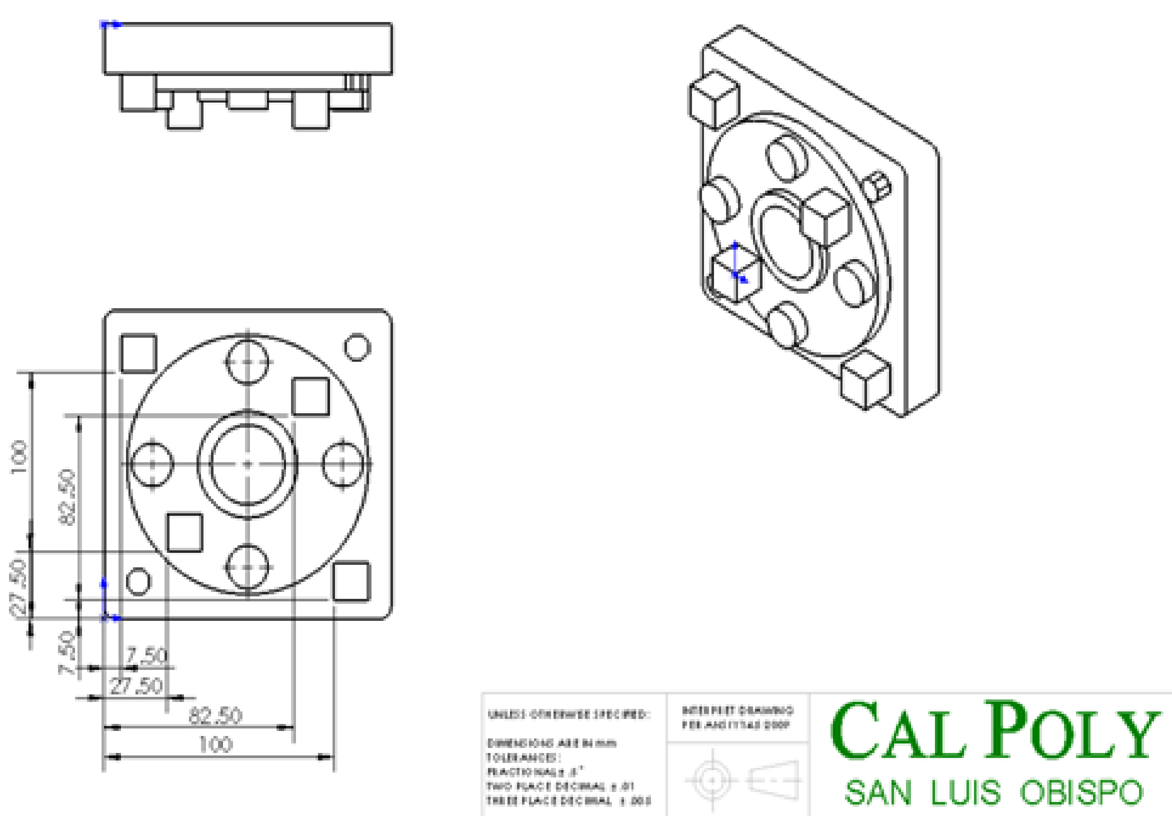


Figure. 13:Locations for accelerometers

Kistler recommended that the acoustic emissions sensor be mounted differently than the accelerometers to provide the best response data, as it gathers data in a very different fashion from the accelerometers. The acoustic emissions sensor has one particular side where the data is gathered. This data gathering mechanism consists of a pin connected to a diaphragm. The pin extends slightly beyond the surface of the side of the sensor on which it is placed. This pin needs to be in direct contact with whatever surface it is measuring from. The pin registers changes in the acoustic vibrations coming through the material which it is attached to, the signal travels to the diaphragm which triggers the sensor. As mentioned above, rather than transmitting a signal and analyzing the result, the acoustic emissions sensor simply waits for a major disruption from the background noise, which can be filtered out. The acoustic emissions sensor will be mounted directly to the external walls of the build chamber, within the machine. This is the closest to the part being built that a sensor could be placed without using an adhesive. Since the pin-side of the sensor needs to be in direct contact with the structure that it is monitoring, an adhesive will not provide the proper form of contact. There needs to be a force on the opposing side of the sensor to keep the pin in contact with the surface. Therefore, the sensor will be held in place with a

retaining ring, which will hold the sensor in place against the wall of the build chamber. This retaining ring will encompass the entire build chamber, and bolt onto itself to provide the pressure necessary to maintain the sensor in place. There will be silicone pads placed around the inside of the retaining ring to ensure that it does not slip out of place along the build chamber. The retaining ring will be made of 303 Stainless Steel, as it can withstand temperatures well above 200°C, and is inexpensive and easy to machine. The walls of this retaining ring will be 16mm thick, and it will be bolted onto itself using M5 bolts. Figure 14 below shows how the retaining ring will interact with the acoustic emissions sensor and the build chamber outer walls.

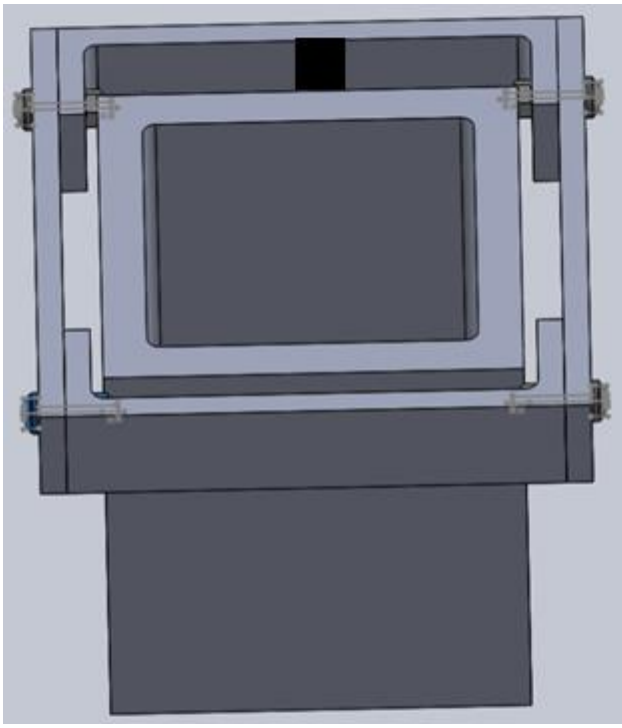


Figure 14: Model of the retaining ring and sensor

At the conclusion of this project, the sensors will be removed to the machine and returned to Lawrence Livermore National Laboratory. The accelerometers will be removed with a special tool provided by Kistler to aid with safe removal of sensors that have been attached using an adhesive. These sensors will be installed into the Lawrence Livermore National Laboratory SLM machines following the success of this project.

4.4 - Data Acquisition and Analysis

In order to analyze all of the data that will be taken using the sensors, in conjunction with the team at Lawrence Livermore National Laboratories, the Kistler LabAmp 5165A4 was chosen to be the data acquisition device. The main reason for this selection of this particular lab amp came down to a few critical factors. This lab amp allows for a very high sample of 625 kSps, but also the ability to be able to read very high frequency voltage input of 100 kHz. Another key feature is the ability to integrate a Piezotron Acoustic Emission sensor into the same Data Acquisition system in conjunction with the accelerometers that are usually used with the data acquisition device.

Since there has been nothing like this done before, one of the main objectives of this project was to have data about a cracking event and what occurs in the system when something like that occurs. The Kistler Lab-Amp provides two interfaces in order to do this. The first is a graphical user interface (GUI) that is integrated into the lab amp. It provides real time statistics as to what is happening in regard to the sensors. Other features included in this user interface are the ability to apply a high-pass or low-pass filter to the input signal, and to record the input signals to a CSV file. These features will provide a starting place in order to identify what happens when a part cracks. See Appendix F. for a more detailed look at the features provided by this user interface.

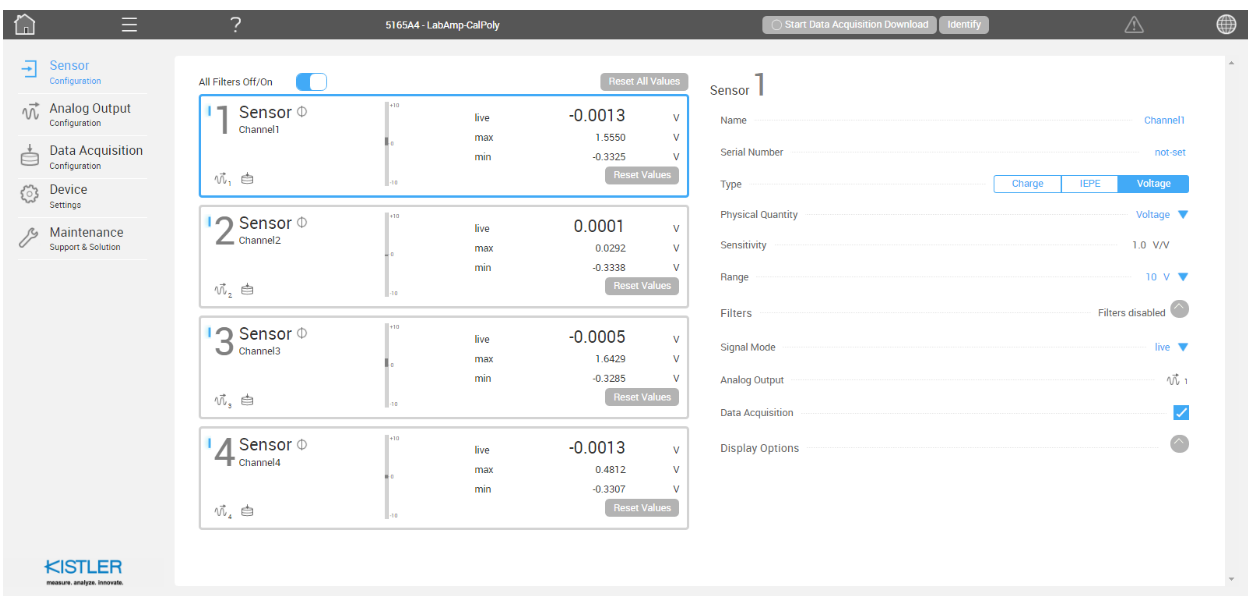
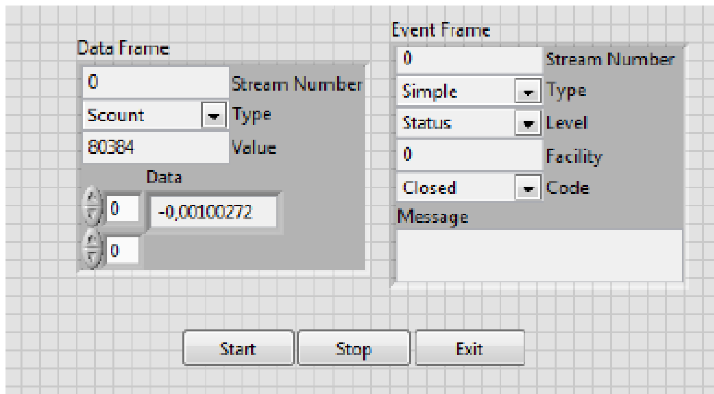
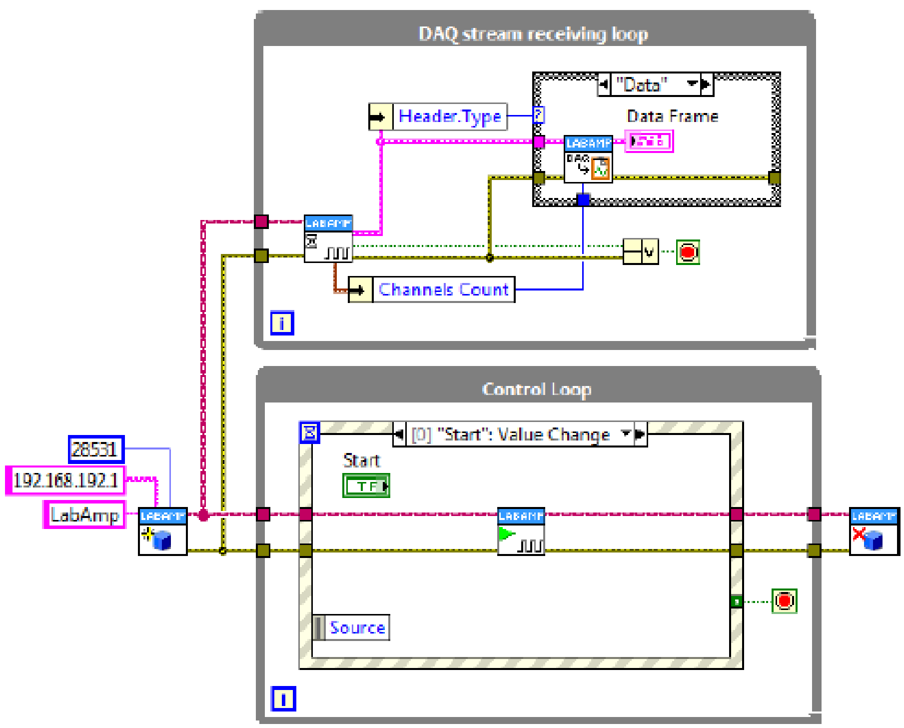


Figure 15:Home Screen of the GUI Provided with the Kistler Lab Amp

The second interface that is provided is the ability to integrate the lab amp into LabVIEW with provided drivers. This provides the best real time analysis option, but without first analyzing the results of the GUI, there is no telling what exactly in the data a crack looks like. The use of both of these interfaces will be critical in determining when a crack occurs and designing software that is able to detect a cracking event.



Picture 2 Front panel



Picture 3 Block Diagram

Figure 16:Sample LabVIEW VI provided by Kistler

5.0 Final Design

5.1 - Final Design Details and Drawings

The final design is dependant on the geometry of the SLM machine build chamber. Since the closest accessible point to the build surface is the ceramic plate that encompasses the lead screw (see Figure 9B below). Late in the design process, SLM revealed that it would not be possible to travel higher than the ceramic plate, as there is a hermetic seal that is imperative to maintain for machine function.. Both of the accelerometers will be mounted to the ceramic plate. The single axis accelerometer will be mounted with Loctite Silicone Sealant, High Temperature adhesive to the circular plate below the ceramic plate. After discussing the design more in-depth with Kistler, it was recommended that the triaxial accelerometer be mounted in the same area as the single axis sensor, but using an off-ground base. The triaxial accelerometer requires additional electrical grounding for peak performance, and the off-ground base would provide this. The off-ground base will be attached to the triaxial accelerometer via the 5-40 threads tapped into the accelerometer, as well as a threadlocker to secure it. The off-ground base will then be mounted to the ceramic plate using the same adhesive as the single-axis accelerometer.

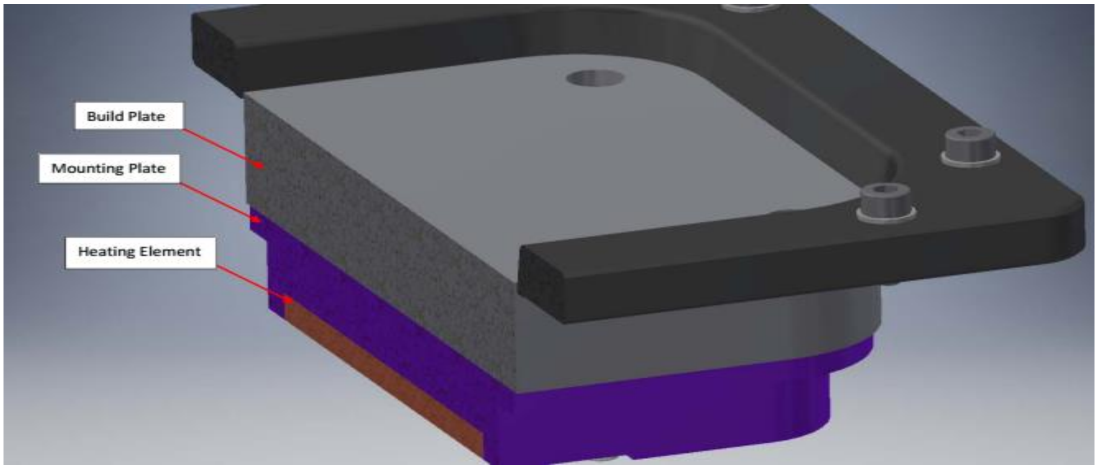


Figure 9B: CAD layout of build plate, mounting plate, and heating element, provided by SLM

The final design for mounting the acoustic emissions sensor has changed in the interaction between the sensor and the retaining ring. The retaining ring will remain unchanged

except for the side which houses the acoustic emissions sensor. Rather than placing the sensor between the retaining ring and the outer wall of the build chamber, the retaining ring will have a pocket that the sensor will sit in, and then a plate will be screwed on to the sensor from behind. This method was recommended by Kistler because the acoustic emissions sensor is designed to be attached to the surface which it is monitoring with a screw. A M6 screw will secure a top plate onto the sensor, which is attached to the retaining ring, as shown below. This will provide a constant, measureable pressure on the sensor, without creating an excessive force on the walls of the build chamber. The side of the retaining ring with the sensor will be the exact height of the sensor (16mm), to ensure that the top plate is in even contact with the sensor. The plate containing the sensor will be attached to the rest of the retaining ring using M5 bolts and a threadlocker.

5.2 - Final Design Cost Analysis

Already Purchased

Sensors
- Triaxial Accelerometer: $1,715.00
- Acoustic Emission Sensor: $705.00
- Single-Axis Accelerometer: $583.00

Sensor Equipment
- LabAmp: $2.924.00
- Acoustic Emission Coupler: $717.00
- Plug In Filter Set: $329.00
- Triaxial Output Cable: $253.00
- Connecting Cable: $68.00

Total Already Purchased: $7,294.00

Anticipated Costs

Material for mounting sensors
- Adhesive - $75
- Metal Enclosure - $50
- Extraneous - $125

Total Anticipated Cost: $250

Total Overall Cost: $7,544.00

6.0 Manufacturing Plan

The manufacturing for this project will consist of creating the retaining ring for the acoustic emissions sensor. The accelerometers will simply be glued on to the ceramic plate, so the only necessary “manufacturing” for that is to apply a very small amount of adhesive to the sensors, and place them carefully onto their desired location. The triaxial accelerometer will require the extra step of attaching the off-ground base to the sensor before adhering the off-ground base to the ceramic plate. This will be done by screwing the 5-40 thread of the off-ground base into one of the matching holes in the accelerometer.

The manufacturing for the acoustic emissions sensor retaining ring will be more involved. First, the material to build the retaining ring must be purchased. This will be a soft 303 grade stainless steel, so that it will not mar the outer walls of the build chamber. 303 stainless steel is easy to machine, which will simplify the machining process. Once the material arrives, The Cal Poly CNC machines will be utilized to complete all machining processes, as they are consistent and can produce parts to tolerances within 2 thousandths of an inch. Shaunessy will perform most of the machining as she is currently in a CNC machining class and has experience in machine shops. Both the retaining ring and the plate across the top of the acoustic emissions sensor will be made of 303 stainless steel, and machined on the Cal Poly CNC machines. The retaining ring and top plate of the sensor will be machined by 3/13/2017. The assembly will be fit onto the SLM machine by 3/14/2017 so that data can be collected by the 3/17/2017 test date. The front of the retaining ring, with the pocket for the sensor, will be bolted onto the side plates, and a threadlocker will be used to ensure a solid part. Then the front plate and the side plates will be slid around the outside of the build chamber, then the back C-channel will be attached using nuts and bolts. The nuts and bolts will be purchased from McMaster Carr, and the threadlocker will be purchased online.

6.1 - Proposed Manufacturing Timeline

3/3/2017 - Order all materials
3/13/2017 - Machine all parts
3/14/2017 - Install all parts into the machine

6.2 - Updated Manufacturing Timeline

3/8/2017 - Order all materials
3/13/2017 5/14/2017- Machine all parts, took longer due to difficulties machining steel. During the machining process, stainless steel work hardens due to the thermal stresses associated with cutting metal. This creates a hard surface layer of steel that is prone to breaking tools when attempting to further machine.
5/15/2017 - Install accelerometers into the machine.

7.0 Management Plan

7.1 Tasks

Team responsibilities have been split up based off of the project needs during the process. All members are responsible for gathering information and discussing amongst the team and creating agendas for sponsor meetings. Manufacturing processes shall also be handled collectively. Angel will be the treasurer, in charge of maintain the team's travel budget and materials budget. This includes working with the sponsor and ME department for purchasing materials. Shaunessy will be the correspondence between the Cal Poly team, the Lawrence Livermore National Laboratory Metals AM team, and the Cal Poly Mechanical Engineering Senior Project advisors. She the main point of communication with the sponsor, will facilitate all meetings, and maintain and organize the email account. During meetings with the sponsor, she will take written notes and maintain information repository for the team. Jake will be in charge of keeping the team on track and setting time limits for tasks. During meetings with the sponsor, he will take notes on the agenda and maintain organization of the Google Drive.

7.2 Deadlines

On November 18 the Preliminary Report is due, at which point the sensors to be used will be narrowed down to whichever are most compatible with the SLM machine. At this point, it has been decided both accelerometers and acoustic emissions sensors would be good options, so initial design work will be done for both. The location of the sensors has also been narrowed down to within or below the base plate. By December 2, the specific models of accelerometers will be researched, and the team will reach out to potential vendors. Following this will be the research of acoustic sensor models, which will be completed by December 8. A test plan will be presented to the sponsor on January 12, with preliminary analysis to validate the plan. Any modifications needed will then be completed by January 13. Test plan iteration and additional test plan analysis will be completed by January 27. By February 3 specific vendors and models of sensors will be decided. The Critical Design Report is due on February 7, which will be used as the basis for the Critical Design Review. The CDR report will include the final design, detailed drawings and cost estimations of the system, a design analysis confirming that the design meets the design specifications given by the sponsor, safety considerations, explanation and justification of material selection, fabrication and assembly instructions, maintenance and repair considerations. Using the feedback from the CDR, necessary adjustments will be made, and the initial build will begin. The initial prototype of the sensor system will be completed by

February 17. Preliminary tests outside of the machine environment will take place through February 25. These results will be analyzed through March 3. Modifications and adjustments will be made based off of the analysis from the first round of preliminary testing. A second round of preliminary testing will occur through March 10. This will be followed with analysis through March 17. Another set of modifications will be done and followed with the first round of machine testing which will be completed by March 24. Another set of Analysis will be completed by March 31. This will be used for further modifications. The following weeks will consist of one week of testing followed by analysis and modifications which will take place through May 12. By May 19 the overall results of the testing will have been analyzed and compiled into a final product where we will include recommendations and ideas to consider for future iterations of the sensor system. The information attained will then be used in the final report and presentation. The Final Design Report and Expo are both on June 2nd, by which time we will have drawn final conclusions on the success and recommending the system for industrial use. This will be followed by discussing lessons learned as a result of the process on June 8.

Thu 11/17/16	PDR Report	Thu 11/17/16
Mon 11/28/16	Research acccelerometer models	Fri 12/2/16
Mon 12/5/16	Research acoustic sensor models	Thu 12/8/16
Thu 12/8/16	Dead Week/Finals Week	Fri 12/16/16
Mon 1/9/17	Devise Test Plan	Fri 1/13/17
Thu 1/12/17	Present Test Plan to LLNL Team	Thu 1/12/17
Mon 1/16/17	Reiterate Test Plan	Fri 1/27/17
Mon 1/30/17	Finalize Sensor Types	Fri 2/3/17
Tue 2/7/17	CDR Report and Presentation	Tue 2/7/17
Wed 2/8/17	Build Sensor Systems	Fri 2/17/17
Sat 2/18/17	Preliminary Tests (without machine)	Sat 2/25/17
Mon 2/27/17	Analyze Initial Results	Fri 3/3/17
Mon 3/6/17	Second Round of Preliminary Tests	Fri 3/10/17
Mon 3/13/17	Second Round Analyzing Results	Fri 3/17/17
Mon 3/20/17	Initial Testing in Machine	Fri 3/24/17
Mon 3/27/17	Analysis of Initial Machine Testing	Fri 3/31/17
Mon 4/3/17	Second Round Machine Testing	Fri 4/7/17
Mon 4/10/17	Analysis of Second Round Machine Testing	Fri 4/14/17
Mon 4/17/17	Third Round Machine Testing	Fri 4/21/17
Mon 4/24/17	Analysis of Third Round Machine Testing	Fri 4/28/17
Mon 5/1/17	Fourth Round Machine Testing	Fri 5/5/17
Tue 5/2/17	Hardware Safety Review/Demo	Tue 5/2/17
Mon 5/8/17	Analysis of Fourth Round Machine Testing	Fri 5/12/17
Sat 5/13/17	Analyze Overall Results	Fri 5/19/17
Mon 5/22/17	Create Final Report and Presentation	Thu 6/1/17
Fri 6/2/17	FDR Presentation/Expo	Fri 6/2/17
Tue 6/6/17	Lessons Learned	Thu 6/8/17

Table 5:Gantt Chart excerpt with timeline dates

7.3 Updates to Timeline

As shown in the updated Gantt Chart the timeline has shifted, due to the availability of the SLM machine and the sensors. Below is an updated Timeline

Tue 11/15/16	PDR Presentation	Tue 11/15/16
Thu 11/17/16	PDR Report	Thu 11/17/16
Mon 11/28/16	Research acccelerometer models	Fri 12/2/16
Mon 12/5/16	Research acoustic sensor models	Thu 12/8/16
Thu 12/8/16	Dead Week/Finals Week	Fri 12/16/16
Mon 1/9/17	Devise Test Plan	Fri 1/13/17
Thu 1/12/17	Present Test Plan to LLNL Team	Thu 1/12/17
Mon 1/16/17	Reiterate Test Plan	Fri 1/27/17
Mon 1/30/17	Finalize Sensor Types	Fri 2/10/17
Thu 2/23/17	CDR Report and Presentation	Thu 2/23/17
Fri 2/24/17	Purchased Sensor System Parts	Mon 3/13/17
Mon 3/13/17	SLM Out of Order	Mon 4/17/17
Wed 3/22/17	Finals/Spring Break	Mon 4/3/17
Tue 3/14/17	Build Sensor System	Mon 4/24/17
Mon 4/3/17	Prep For Build 1	Tue 4/25/17
Fri 4/21/17	Development of LabVIEW Analysis Program	Tue 5/23/17
Mon 4/24/17	Temperature Test	Mon 4/24/17
Wed 4/26/17	Build 1	Wed 4/26/17
Thu 4/27/17	Prep for Build 2	Sun 4/30/17
Mon 5/1/17	Build 2	Mon 5/1/17
Tue 5/2/17	Prep for Build 3	Mon 5/8/17
Tue 5/9/17	Build 3	Tue 5/9/17
Tue 5/9/17	Hardware Safety Review/Demo	Tue 5/9/17
Wed 5/10/17	SLM Out of Order	Fri 5/19/17
Mon 5/22/17	Sensor Installation/Base Testing	Mon 5/22/17
Tue 5/16/17	Final Build Prep	Sun 5/21/17
Tue 5/16/17	Create Final Report and Presentation	Tue 5/30/17
Mon 5/22/17	Final Build	Mon 5/22/17
Tue 5/23/17	Data Analysis of Final Build	Tue 5/30/17
Wed 5/31/17	FDR Presentation/Expo	Wed 5/31/17
Wed 6/7/17	Lessons Learned	Wed 6/7/17

Table 6:Updated Gantt Chart

7.4 Proposed Testing Plan and Validation

Since real time fault detection is not a common practice in additive manufacturing, the biggest piece of being able to validate the system will be establishing a baseline to compare against. In fact, there will have to be several baselines that will have to be established due to the many parameters present in each build. The majority of the parts build by Lawrence Livermore National Laboratory are being built for the first time, so trying to compare build to build is not a realistic idea. Therefore, detecting part failures will have to come from detecting anomalies against the baselines established.

To establish the ability to detect cracks within the part, a few tests will be run in order to establish a baseline. First off, a test will be run with the system mounted inside with the SLM machine just being turned on, no part being manufactured. The purpose of this will be to measure the static noise that is generated simply by the normal operation of the machine even without a part being made. The second baseline test that will take place is measuring the emissions felt through the machine while the laser is operating. Since most parts are unique in shape and volume, there is not a set duration for the amount of time that the laser will be in use. This baseline will allow the system to distinguish normal laser operations from a crack occurring in the part being made. Another test that will need to be run in order to establish a baseline will be to have the elevator recede with a fresh layer of powder being added to the top. This will allow the sensor to establish the baseline noise created when a fresh layer of powder is being laid during a build. Together, these three tests will establish a strong baseline in order to compare real time data against. These initial tests will be completed by

The next sets of tests to be conducted will involve the construction of parts that crack, and ones that do not crack. With no previous data being available on the forces exerted on the environment around a part when it cracks, these tests will be used to examine what exactly happens when a part cracks. Based off the analysis of this initial data, the team determine what testing route is appropriate and move ahead with those series of tests. These tests will be building basic geometric shapes to predict the results for in order to fine tune the system, along with parts that will crack in order to test the functionality of the system and make adjustments as needed.

As far as validation against the specifications from Lawrence Livermore National Laboratories, the system will be continually compared against their specifications to make sure that the system meets their need. Specifically, minimal waste of test materials, safe for human operators to use, integration into the SLM machine without affecting the functionality of the SLM machine, and a notification system when the build has failed. The system design will be fully validated when a part can be manufactured and the system produces an alarm during the process. The build will be completed, and a thorough structural analysis of the part will be done to determine whether or not the alert was at the time of a part failure.

7.5 Updates to 7.4 Test and Verification Plan

1) 3/3/2017 - The very first test with the SLM machine will be running the machine with a thermometer. This will establish exactly what sort of environment the sensors will be mounted in. This will be done with a laser thermometer while the SLM is creating a part.
2) 3/10/2017 - Preliminary Sensor Testing. The sensors will be tested externally from the machine to determine exact sensitivity and frequency response. These tests will include using known forces upon objects that the sensors are attached to
3) 3/17/2017 - Typical Build with Sensor System. This test will be running the sensor system during a part that has been previously proven not to fail. The part geometry and part file will be provided by Lawrence Livermore National Laboratory. The results from this test will help establish a baseline to compare to when the system is tested with parts that due crack. This baseline will represent a part that is being build successfully, and any large deviations would signify a crack or other part failure.
4) 4/14/2017 - Direct Comparison Between Similar Cracked and Uncracked Parts. This test will be comprised of two parts; one part will gather response data from a build that has previously run successfully, the other part will gather response data from a very similar geometry that has been previously proven to crack. The part geometry and part file will be provided by Lawrence Livermore National Laboratory. The data will be analyzed and compared, to determine if there is a great difference or distortion that occurs when a part cracks. The data for this test will be available by 4/21/2017.
5) 4/28/2017 - Guaranteed Part Failure. This test will analyze the response data from a part that is known to fail, and attempt to identify exactly when in the build the crack occurred. This will be cross-referenced with data provided about the part beforehand, and any design that was pre-evaluated to ensure that the part would crack in a given timeframe. The part geometry and part file will be provided by Lawrence Livermore National Laboratory, as well as a given time frame in which the part is expected to

crack.

6) 5/5/2017 - Unique Parts. This test will consist of running as many parts as are available to see if the sensor system can identify cracks forming in parts that are unique. This test can be done in conjunction with whatever other parts are being build by other teams using the Cal Poly SLM machine.

7.6 Final Verification Plan

1) 4/24/17- The SLM machine was up and running with a build so a laser thermometer was taken and point on the outside of the build volume where the sensor were expected to be placed in order to verify that the sensors had the capabilities of producing viable data.
2) 4/26/17- The first build was made in the SLM using the same stl file that Lawrence Livermore National Laboratory had used in order to verify that the SLM at Cal Poly could reproduce the results that had been shown before.
3) 5/1/17 - The same stl file as the first build was used but was ran with the heated build plate to see if the results that were seen at Lawrence Livermore National Laboratory could be reproduced.
4) 5/9/17- A different stl file was sent due to the first two parts not failing. The part was produced and failed in a manner different than what had been expected.
5) 5/22/17- The same part that had been previously produced was made again with the sensor system installed and under different parameters. The part again failed in a different manner than expected but more closely resembled the expected faile than build #3.

7.7 Expectations

In order to achieve the requests from Lawrence Livermore National Laboratories, the Cal Poly team will be relying on their sponsors and the IME department. The IME department is in charge of the installation of the SLM machine, and if the machine is not up and running by the promised dates, adjustments to the schedule and test plans will be made. The given plan is designed so that the team can continue working and designing the system until after the expected installation day of the SLM machine, thereby allowing some schedule leeway if the machine is not fully operational. If the SLM machine is not operational for the duration of this project, Lawrence Livermore National Laboratories has agreed to do some of the testing with the sensor system designed by the Cal Poly students. In return they will share the results so that analysis and adjustments can be made to the Cal Poly sensor system. As part of the Cal Poly Mechanical Engineering Senior Project program, financial sponsor for any sensors that are required as a result of the design process. The Cal poly team is confident that with the support of both

Lawrence Livermore National Laboratories and the IME department, they will be able to produce a successful sensor system.

7.8 Updates to 7.7 Expectations

Expectations from Cal Poly are as follows: Cal Poly will allow the sensor system to be integrated into the SLM machine. This is with the assurance from the Cal Poly Senior Project Team that there will be no permanent alterations made to the machine. The Cal Poly IME department will also allow the senior project team time with the machine to install the sensor system as well as run the parts specified in the Test Plan of section 5.4. Cal Poly will also provide the students access to CNC machines and similar manufacturing options to fabricate the mounting structures for the sensors.

Expectations from Lawrence Livermore National Laboratory are as follows: Lawrence Livermore National Laboratory will provide the Cal Poly senior project team with sensors determined by research and joint decisions. Lawrence Livermore National Laboratory will also provide the Cal Poly senior project team with the geometry (.stl file) for a part to be made on the Cal Poly SLM machine that will consistently break in a violent manner within a short period of time to test the capabilities of the sensors.

7.9 Hazards

When dealing with such an intense process such as SLM, there are going to be various hazards. Based upon the Design Hazard Checklist (Appendix C), these are the main hazards anticipated with this project:

- Hazard: There will be explosive or flammable liquids, gasses, or dust fuel as part of the system.
    - Corrective Action: Since the SLM process deals with very fine particles of metal, with some of the metals being reactive, there is the possibility of a reaction occurring. However, with the safety protocols that are followed at Lawrence Livermore National Laboratory and at Cal Poly, tests are done before any new powder is used in order to maintain a safe lab environment.

- Hazard: The system will be exposed to extreme environmental conditions such as fog, humidity, cold or high temperatures.
    - Corrective Action: The SLM process generates large amounts of heat, as high as 4000° C at the melt pool. With that being said, the system will only be exposed to

a max of 200° C. To be able to do this safely, the system will have components that will be able to handle a large amount of heat while still being able to accurately collect crucial data.

8.0 - Manufacturing

The manufacturing portion of this project was creating the containing ring for the acoustic emissions sensor. This was to be created out of stainless steel, as steel has a high melting point, and stainless is not magnetic and therefore would not interfere with the SLM machine. A ¾" x 2" x 3' bar of 304 Stainless Steel was purchased from McMaster Carr and cut into 6 pieces (5 pieces, 19cm, 17.5cm, 17.5cm, 16cm, and 7cm) using a bandsaw (both vertical and horizontal). Each piece was then milled down to size, drilled and tapped with M5-0.8 holes according to the CAD drawings (Appendix G). The 19cm steel piece was milled to create a pocket for the acoustic emissions sensor, and the top plate was milled with a shallow pocket to accommodate for the exact height of the sensor.

The material decision was made early on in the process, before temperature tests were run. Steel was chosen over aluminum because at the time, there was no information on how hot the sides of the build chamber could get. There was no real structural or weight requirement for the containing ring, the main decision factor was the temperature. The melting point of aluminum is approximately 660°C and the melting temperature of steel is around 1400°C, and depending on where the part was located during the build, the heat from the metal powder fusion could dissipate through the surrounding metal powder and permeate through the surface of the build chamber, creating a much higher temperature on the external build chamber walls. However, temperature tests were run approximately one month after the material was ordered due to the SLM machine being out of service, so steel was decided on as a cautious choice. Once the tests were run, it was discovered that the temperature of the external walls of the build chamber never reached above 50°C, so aluminum would have been a better choice.

In addition to being cheaper than steel ($45 compared to $133 for the desired size), aluminum is much easier to machine. During the machining process, steel "work hardens", creating a surface layer that is much more difficult to machine. This caused a large delay in the completion of the manufacturing, as many tools were broken on during this process. The difficulties machining steel accounted for approximately 2 additional weeks of manufacturing time.

9.0 - Testing

Initially, the test plan that was going to be executed included running the SLM with various part geometries while the sensor system was installed but not functioning, to ensure that the sensor system was not interfering with the SLM machine in any way that would be detrimental to the parts being built. Then the sensor system was to be tested by gathering data from a part that was designed not to crack and comparing it to a part very similar in geometry, but designed to crack, so that data could be compared between the two runs. This test would establish a baseline for the data, in addition to providing information to what a crack response would look like. Following the comparison between the two similar parts, a build would be run where the part was guaranteed to crack at a given time, to see if the sensor system detected the crack during the expected period. That would conclude the specific testing to validate the feasibility of using these sensors to detect cracking in additive manufacturing builds, but the sensors would remain installed to be used for future builds, to detect if and when parts cracked, so that forensic studies would be easier to perform and evaluate the design of the parts.

However, the machine was not available nearly as often as expected, which greatly reduced the amount of testing. Initially, the installation date was set for early November, and the Cal Poly senior project team was told that they would be able to run builds starting in December. Due to complications with installing the machine and requiring technicians from SLM to travel to Cal Poly to complete the installation, the SLM was not functioning until March. This drastically changed the testing plan. Rather than having time for multiple builds per test run, there was only time for 4 builds total. These builds were of the specific geometries that Lawrence Livermore National Laboratory provided with Cal Poly, that they had run on their machines. These parts were designed to crack, and had been run as part of a multi-part cracking study at Lawrence Livermore National Laboratory. The geometry was such that as the build progressed, the thermal stresses would pull the material away from the “legs” and crack at the smallest cross-sectional area (see Figure 17).

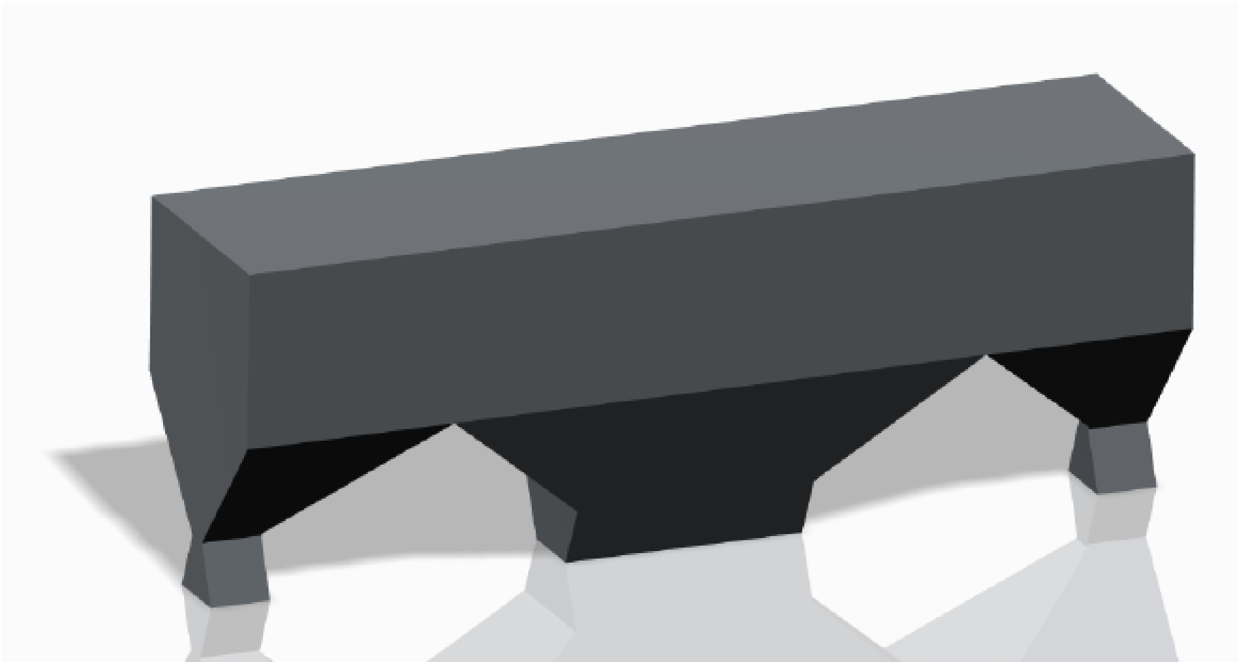


Figure 17:Geometry of parts intended to crack

The first two runs of this geometry did not produce any cracking, as shown in the following figures . The initial test took place on April 26th, 2017.

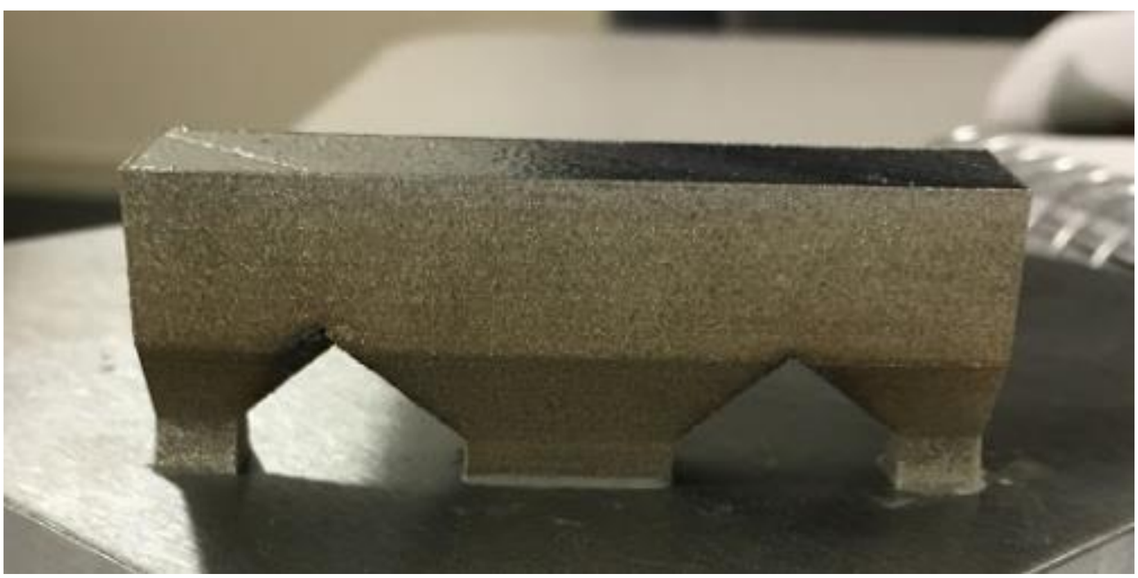


Figure 18: Final product of Run #1

As shown previously, there is no sign of cracking in this part. Cracking was expected along the line that denotes the first shift in geometry at the bottom, where the surface area begins to increase. While discussing why the part did not crack, it was determined that this particular run had been done with the heading element on, as was the standard procedure. However, the build plate increases stability of the build, and decreases the likelihood that the part will crack. As no crack occurred, the same part was run again without the heating element turned on. Run #2 was performed on May 10th, 2017, later than anticipated due to the machine running out of the Argon gas that is necessary for the machine to function. The results are shown in Figure 19.

Figure 19. - Final Product of Run #2

Even with the heating element disabled, this geometry did not crack. In discussing this result with Lawrence Livermore National Laboratory, a new geometry was suggested that had cracked successfully at Lawrence Livermore. This geometry had a smaller surface area at the point that the part was designed to crack, smaller leg sections. This area would be more affected by the thermal stresses, and more likely to crack. The third run was performed on May 17th, after receiving the new part geometry from Lawrence Livermore National Laboratory. The results are shown in Figure 20.

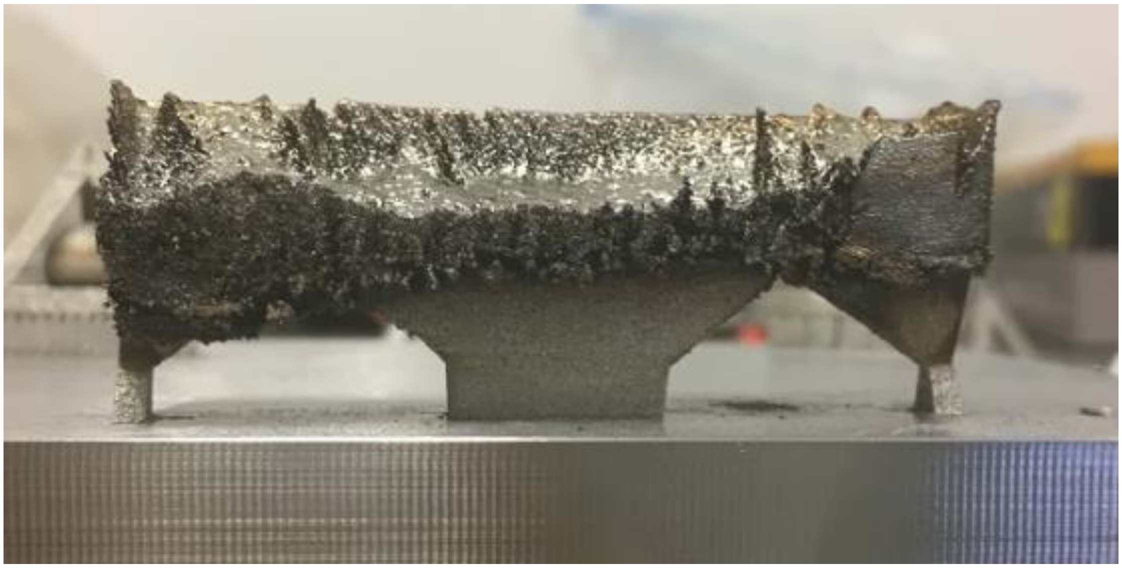


Figure 20. - Final Product of Run #3

Figure 21. - Final Product of Run #3

As shown in Figures 20 and 21, Run #3 did fail. However, this is not the failure mode that was expected. Despite compete catastrophic failure, there was no cracking across the intended section. In the forensic discussion that followed the discovery of this failure, it seemed as though the powder had been unable to spread across the entire build plate, creating a dam that did not allow full coverage. This created a hollow in the part, where the lasers ran over the same section without new powder being spread, creating the pocket of material welded to itself rather than the expected geometry. This would not produce the single crack response that was expected to be detected by the sensors. As this was not an acceptable result to run with the sensors, the same geometry was run again by itself in the middle of the build plate, to prevent any dams that could have occurred due to the part initially being placed towards the edge of the build plate, and ran with multiple other parts on the same build plate. The results from Run #4 are shown in Figure 22.

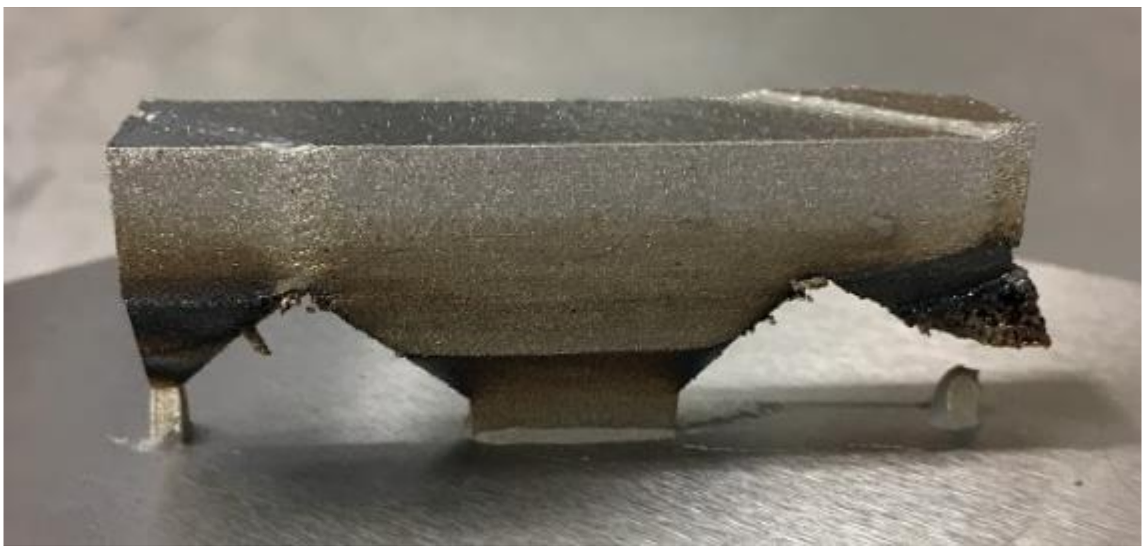


Figure 22. - Final Results from Run #4

While Run #4 did have failure at the expected design point, it was not the intended failure that Lawrence Livermore National Laboratory had produced. They had gotten a single crack across both “leg” portions, with no deviation in the rest of the part. As shown above, there is a large deviation from the intended part geometry after the crack on the right leg. This is most likely due to warpage, and then powder particles outside of the desired geometry being attracted to the heat of the warpage and welding on to the displaced material. The sensors were installed for both Run #4 and Run #3, and the data results are discussed in Section 10.

10.0 Results

As stated in the previous testing section, due to time constraints the full extent of testing, data collection and analysis was not able to be completed. However, the tests that were completed show promising results for being able to detect when a crack has occurred during the manufacturing process. Specifically, using the triaxial accelerometer mounted to the ceramic plate located under the build plate, data was able to be collected and analyzed, determining that there was an event that occurred during the build.

Results from the initial baseline sensor testing with the machine were limited. When this testing was taking place the SLM was not in full working order with the part of the powder re-coater removed for repair. Therefore, collecting data mimicking the exact natural motion and functionality of the SLM was not possible. Data was still able to be collected to baseline the movement of the elevator and limited functionality of the powder spreader and re-coater. These baseline tests allow for an automated program (LabView or another implementation) to be able to distinguish between individual events that are to be expected during the manufacturing process and events that are not part of the normal manufacturing process.

The first test that was completed with the sensors in the machine was designed to collect data during a build of a part that would crack. After collecting this data, comparisons were made between the baseline data and data collected during a build. However, the resulting failure mode of the part was outside of the scope of the part failure that is trying to be detected. The data collected, nevertheless, is valuable and will be used in order to create an even stronger baseline for comparison. See Appendix I for more graphs and analysis.

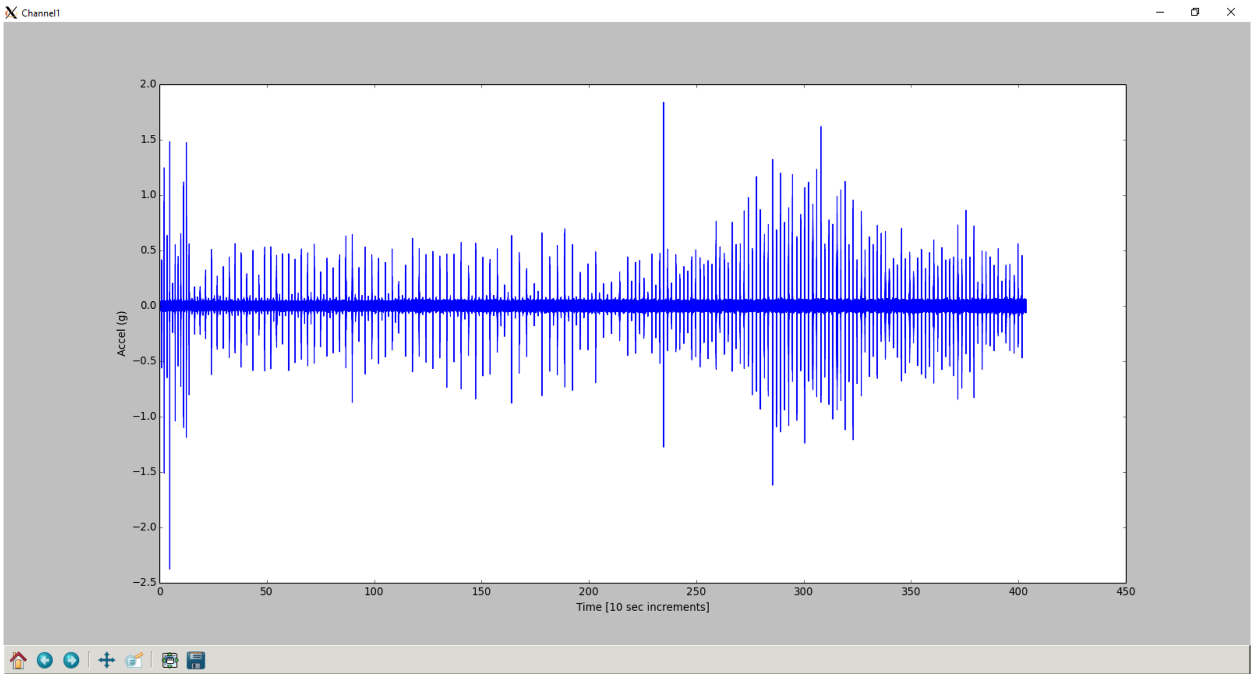


Figure 23: X-plane data from in machine test 2 (17:30 to 1:23:30)

Seen in figure 23 above, which is a section of data that was collected during the second in machine test, there is clearly an event around the 240 mark, which represents approximately 1 hour into the build. Given the nature of the failure of the part, seen below in figure 24, it can be deduced that an event occurred during the build process. However, since the mode of failure was not mode that was expected, the results cannot definitively be classified as detecting a cracking event occurring. What this data does show is that it was able to detect an abnormal event occurring, whatever may have caused it. Integrating the baseline testing to identify normal operations of the SLM machine and single out anomalies, such as the one pointed out above, will allow automated programs (LabView or other implementations) to detect a crack in the part during the manufacturing process.

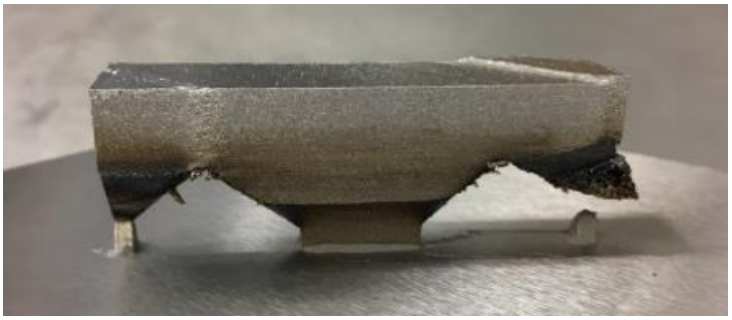


Figure 24: Part Failure

Overall, the results from testing were mixed. Given unforeseen issues with the SLM machine, and other complications such as issues with designing a part that will repeatedly crack, caused setbacks the ultimately affected the degree to which the test plan and analysis was completed. In terms of feasibility of being able to detect a crack that occurs during the manufacturing process, the integration of accelerometers and acoustic emission sensors into the SLM machine itself will be able to detect failure modes that do occur during the manufacturing process. Given proper signal analysis and integration with a LabView or some other interfacing program, the user could be alerted when an event occurs that is not expected.

11.0 Challenges

The main challenges in this project were coordinating between Cal Poly's Industrial and Manufacturing Engineering Department and Lawrence Livermore National Laboratory. This mainly stemmed from the nature of the project, being more research based as opposed to a true design project. The timeline that is used as the outline for this project is more conducive to a project that is not as research based, along with data collection and analysis. This project heavily relied on the availability of the SLM machine at Cal Poly, which was often out of service due to maintenance issues. As mentioned above, the machine was not functioning until March, and the team had been told that they would have access to it to begin running tests in November. Once the machine was running, the revised testing plan was often pushed back by a week due to different components of the machine breaking, most often the contraption that re-coats the powder layers. These delays led to there being only 4 builds run for this project.

Another major challenge was that there was no information available on the internal geometry of the SLM. As outlined in the Design Section of this report, the design for this project changed drastically over the course of a few months. Initially, the sensors were to be embedded in the build plate itself, and the altered build plate could be manufactured in-house at Cal Poly. However, it was then revealed by SLM that there was a mounting plate below the build plate, and the design was adapted to utilize the mounting plate in the same way. Once that design was complete, SLM said that there was a heating element under the mounting plate, that was necessary for certain materials. After discussing with the Cal Poly Industrial and Manufacturing department, the design changed to removing the heating element and placing the sensors in the cavity that held the heating element. However, SLM then said that there was a hermetic seal that could not be broken without compromising the performance of the machine. So the sensors were mounted to the lowest point on the chamber mechanism and the external walls of the build. The entire process of switching designs took about 4 months.

Once testing began in the Cal Poly SLM, it was difficult to replicate the single violent crack that Lawrence Livermore National Laboratory experienced in parts of the same geometry. This is most likely due to the make and models of the Cal Poly machine being different than the ones used by Lawrence Livermore National Laboratory. The settings and defaults are different between the machines, and it would have taken many trials to replicate the exact same results with the same machine parameters. The main part of this project was testing the sensors on a simple part that would crack in a predictable manner. This never occured on the parts produced by the Cal Poly machine. Because there was never a solitary crack in the parts from Cal Poly, it was impossible to analyze the results and see a single point where the sensors registered a crack, as was the initial expectation. However, despite the part geometry not performing as expected, enough information was available to determine that these sensors would be feasible in this application.

12.0 Next Steps and Recommendations

While this project did not provide the direct results expected, it did provide enough insight to show that the sensors chosen would be able to detect discrepancies in a build related to violent cracking. In order to further this project, the following plan has been recommended.

At Cal Poly: continue gathering data with the sensors installed, running a similar part geometry to Run #3 and run #4, changing the parameters on the machine until the part cracks successfully. It has been suggested that the part be run with the "grid" laser setting, as this could produce more drastic thermal stresses. It is also recommended to alter the laser power, scan speed, layer thickness, and to run the sensors currently installed with varying part geometries to continue to investigate what a baseline could be for different geometries. It would also be helpful to establish if there is an exact frequency with which the recoated passes across the build plate, as this could be used to normalize the data.

The acoustic emissions sensor was never able to be utilized at Cal Poly due to the required cabling not being specified or ordered. The acoustic emissions sensor will provide a more holistic approach to data collection and analysis. The acoustic emissions sensor should be installed into the Cal Poly SLM machine as soon as possible to further the progress of this project.

At Lawrence Livermore National Laboratory, it is recommended to install the accelerometers in the same way that they are installed at Cal Poly. If multiple sets of sensors can be purchased, it would be interesting to put them in different locations on the machines to determine if specific locations are better or more feasible than others. This could also aide in determining the location of any abnormalities with regard to the build plate, which would help with forensic analysis. This would lead to a better understanding of which features are more stable in the part design, and will help prevent failures in future parts. It is also recommended to place the sensors on different machine models, to see if there is a large variation in the data received when comparing the SLM machines to Concept Laser machines. There is expected variation between machines of the same model as well, so these tests would provide a more comprehensible understanding of whether these sensors are capable on all additive manufacturing machine or just certain makes and models.

For data analysis, it is recommended to implement a LabView VI that would be able to do real time analysis of the system. There are LabView drivers for the Kistler LabAmp that will allow for seamless integration with the device. Due to time constraints and a limited amount of data collection, there was not enough of a baseline that was able to be established in order to create an effective automated program. With a strong baseline for expected events, a LabView VI is a promising route that will be effective at analyzing real time data and alerting the operator if there is an anomaly.

13.0 Conclusion

Overall the Cal Poly Additive Manufacturing Failure Detection team was able to find sensors capable of detecting activity in the SLM during part builds. The team was able to see a response in the machine as it produced builds. The response was found through the use of the triaxial accelerometer and the research suggests that if an acoustic emission sensor were to be integrated into the SLM then it may be able to obtain better results for a baseline and may be better to detect failure than the current results provided from the accelerometer. Due to the time constraints more runs were not able to be completed that would have been able to produce a baseline of the response expected from the accelerometer. With a few more builds and setting parameter constraints during builds a successful baseline can be created. LabView VI will be useful with a fully integrated sensor system at detecting failure in real time once a baseline has been established.

14.0 Lessons Learned

The main take-away for the Cal Poly Students was that the scope of a project can change drastically over the course of a year. New information can be provided that completely changes the initial design. As outlined in the Design section, there were many design changes due to information being released that contradicted the initial assumptions. This changed the design, and nearly changed the entire scope of the project. The students learned that it is very important to be flexible with design changes, and be resilient when requirements are changed at the last minute. Another important lesson was not to rely on machines that are new and have not been fully implemented into a permanent program. It was difficult to schedule time to implement the proposed test plan when the machine was down for a week at a time every few weeks. Had this been foreseen, more effort would have been put into creating a backup plan to validate the sensors outside of the SLM.

15.0 References

[1] "SLM®125HL." SLM Solutions. SLM Solutions, n.d. Web. 23 Oct. 2016.

[2] Pluschkell, Thomas. Phone interview, 6, 13, and 20 of October, 2016.

[3] Hodge, N., R. M. Ferencz, and J. M. Solberg. *Implementation of a Thermomechanical Model in Diablo for the Simulation of Selective Laser Melting*. Tech. no. LLNL-TR-644936. N.p.: Lawrence Livermore National Laboratory, 2013. Print.

[4] Wang, Dr. Xuan. In-person interview, 11 October 2016.

[5] Paul, Ratnadeep, Sam Anand, and Frank Gerner. "Effect of Thermal Deformation on Part Errors in Metal Powder Based Additive Manufacturing Processes." *Journal of Manufacturing Science and Engineering*. ASME, 16 Jan. 2014. Web. 25 Oct. 2016.

[6] Tapia, Gustavo, and Alaa Ewany. "A Review on Process Monitoring and Control in Metal-Based Additive Manufacturing." *Journal of Manufacturing Science and Engineering*. N.p., 14 Oct. 2014. Web. 25 Oct. 2016.

[7] "Fundamentals of Ultrasonic Imaging and Flaw Detection." - National Instruments. National Instruments, 11 Feb. 2010. Web. 25 Oct. 2016.

[8] Sponsored by Olympus Scientific Solutions Americas - Non-Destructive Testing. "Ultrasonic Flaw Detection; Theory, Practice and Applications."AZoM.com. N.p., 10 Sept. 2013. Web. 25 Oct. 2016.

[9] "Community College Ultrasonic Testing." Community College Ultrasonic Testing. NDT Resource Center, n.d. Web. 25 Oct. 2016

[10] Nelligan, Tom. "Resources Ultrasonic Flaw Detection." An Introduction to Ultrasonic Flaw Detection. Olympus, n.d. Web. 25 Oct. 2016.

[11] "Acoustic Emission Testing." Acoustic Emission Testing. NDT Resource Center, n.d. Web. 25 Oct. 2016.

[12] Peter Mercelis, Jean-Pierre Kruth, "Residual stresses in selective laser sintering and selective laser melting", Rapid Prototyping Journal, Vol. 12 Iss: 5, pp.254 - 265.

[13] Leuders, S et al. "On the Mechanical Behaviour of Titanium Alloy TiAl6V4 Manufactured by Selective Laser Melting: Fatigue Resistance and Crack Growth Performance." International Journal of Fatigue, vol. 48, Mar. 2013, pp. 300–307. Science Direct, sciencedirect.com.

Appendix A

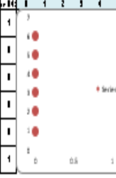
Quality Function Development Spreadsheet

Correlations	
Positive	+
Negative	−
No Correlation	

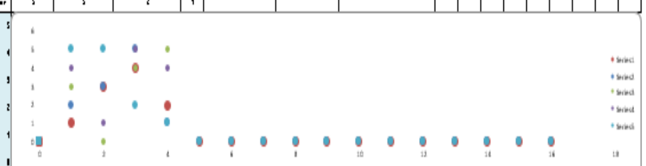
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

Row	Weight Chart	Relative Weight	LLNL Metals AM team	LLNL AM operators	LLNL Customers	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	Maintenance	low maintenance	Easy to operate	Safe	mobile/repeatable	Power Requirements	Withstand High Temperatures	Current Product Assessment						Row
							Column #	1	2	3	4	5	6	7							
							Direction of Improvement	▲	▼	◇	◇	▲	▼	▲							
1		57%	8	8	8	9	Diagnostic tool	▽	●	●	●	●	○	●	0	1	1	1	1		1
2		14%	2	2	2	9	Alarm system		○	●	●	○	○	○	0	0	0	0	0		2
3		29%	4	4	4	9	Location	▽	○	○	●	○	○	●	0	0	0	0	0		3
4		0%				9	Perception	▽	▽	▽	●	▽	▽	▽	0	0	0	1	0		4
5		0%				9	Power	▽	▽	▽	●	▽	▽	▽	0	0	0	0	0		5
6		0%				9	Time of Failure	●	●	○	●	●	●	●	0	1	1	1	1		6



	1	2	3	4	5	6	7
HOW MUCH: Target	Target for Specification #1	Target for Specification #2	Target for Specification #3				
Max Relationship	9	9	9	9	9	9	9
Technical Importance Rating	85.71428571	642.8571429	728.5714286				
Relative Weight	6%	44%	50%				
Weight Chart							
Our Product	1	3	4	2			
Competitor #1: Product Name	2	3	5	1			
Competitor #2: Product Name	3	0	4	5			
Competitor #3: Product Name	4	1	5	4			
Competitor #4: Product Name	5	5	2	1			
Current Product Assessment - Engineering Specifications							
Column #	1	2	3	4	5	6	7



Template Revision: 0.9 Date: 4/22/2008
Christopher Battles

Appendix B

Picture of the inside of the Cal Poly SLM 125 machine

This picture highlights some of the difficulties in working with the machine. The space available to work with is very small, and located below the large plate in the middle of the picture. The quality of this picture is poor because the small window that interfaces between the work space in the machine and the operator is heavily tinted. This could be an obstacle for optical sensors from the external of the machine.

Appendix C - Design Matrix

Design Criteria	Non-Intrusive	Security	Servicability	Repeatibility	Accurate data	Operatation	Easy Set-up	Real-time alert	Location Detection	Temperature	Safety	Cost	Total
Weighting factor	0.2		0.05	0.1	0.2	0.1	0.05	0.2	0.1			0.05	1.05
	0.190476		0.047619	0.095238	0.190476	0.095238	0.047619	0.190476	0.095238			0.047619	
Sensor Ideas													
Acoustic	8		7	9	7	8	9	9	4				8.52
Vibrations	8		7	9	8	8	9	9	6				8.90
Thermal	9		7	9	5	5	8	5	5				7.33
Multiple - Acoustic and Vibrations	8		7	9	9	8	7	9	8				9.19
Multiple - Acoustic and Thermal	8		7	9	7	7	6	7	6				8.10
Multiple - Vibrations and Thermal	8		7	9	7	7	6	7	6				8.10
Location Ideas													
Embedded in Base Plate	9		6	8	9	8	8	8	9				9.71
Outside	9		9	6	4	6	5	4	2				6.00
Attached to walls of machine	3		7	8	7	8	7	7	4				7.14
Attached to laser	4		6	8	7	7	6	6	4				6.95
Under Base Plate	7		7	9	8	9	8	8	8				9.10
Inside Elevator	3		5	8	8	8	7	8	7				7.90
Bottom of Elevator	5		6	9	8	9	8	8	7				8.57
Multiple - embedded and walls	3		6	8	7	8	7	7	4				7.10
Multiple - embedded and laser	5		6	8	7	7	6	6	4				7.14
Multiple - embedded and under	6		6	8	8	8	8	8	8				8.67
Multiple - walls and laser	2		6	9	7	7	6	6	4				6.67
Multiple - walls and under	4		6	9	7	8	7	7	4				7.38
Multiple - outside and walls	3		6	6	4	6	5	4	2				4.71
Multiple - outside and embedded	6		6	6	4	6	5	4	2				5.29
Multiple - outside and under	6		6	6	4	6	5	4	2				5.29
Multiple - outside and laser	4		6	6	4	6	5	4	2				4.90

Appendix D - Safety

ME 428/429/430 Senior Design Project 2016–2017

DESIGN HAZARD CHECKLIST

Team: Team 7: Additive Manufacturing Fault Detection Advisor: Birdsong

Y	N	
☐	☒	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☒	2. Can any part of the design undergo high accelerations/decelerations?
☐	☒	3. Will the system have any large moving masses or large forces?
☐	☒	4. Will the system produce a projectile?
☐	☒	5. Would it be possible for the system to fall under gravity creating injury?
☐	☒	6. Will a user be exposed to overhanging weights as part of the design?
☐	☒	7. Will the system have any sharp edges?
☐	☒	8. Will any part of the electrical systems not be grounded?
☐	☒	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☐	☒	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☒	☐	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☒	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☒	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☒	14. Can the system generate high levels of noise?
☒	☐	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☐	☒	16. Is it possible for the system to be used in an unsafe manner?
☐	☒	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Figure 4: Design Hazard Checklist, Page 1

Design Hazard Checklist Page 1

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
The system will include powders that are know to be hazardous to humans if handles the wrong way.	Lawrence Livermore National Laboratory already has safety measure in place to make sure that any powder that they are using passes a rigorous safety protocol before used in manufacturing.		
The system will be exposed to high temperature due to the additive manufacturing process and residual heat (Max 200 C)	If the maximum temperature is reached we will have a system that is able to withstand that temperature. Whether through heat sinks or hardware that is able to withstand the harsh elements that it will be subjected to.	2/7/2017	

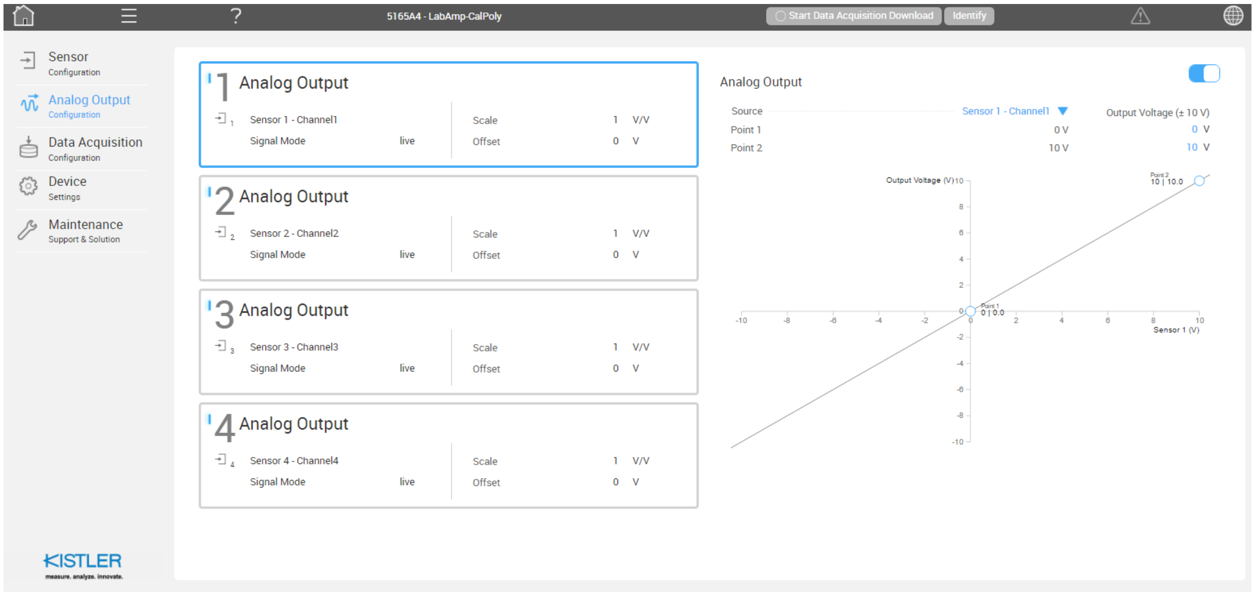
Design Hazard Checklist Page 2

Appendix E - Change Log from Project Proposal

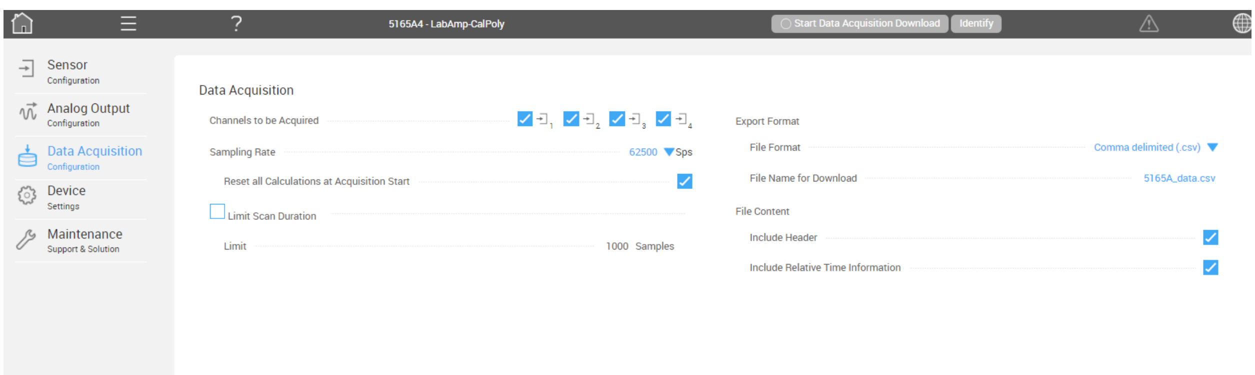
Edits for Report: (Check box)	PDR	X
	CDR	X
	FDR	X

Report Section #	Source of recommended edit (Sponsor, Advisor, Team, Reviewer)	Brief description of edit
1	Sponsor	Updated specific wording and added specific information given by the sponsor.
2	Sponsor	Added specific information regarding the machine and updated statistics.
2	Team	Reworked paragraph structure.
3	Sponsor	Edited based on feedback from sponsor about the objective of the project. Also removed information that was not needed.
4	Reviewer	Split Management plan up into sections based on deadlines and tasks.
7	Team	Included references that were mistakenly left off of report

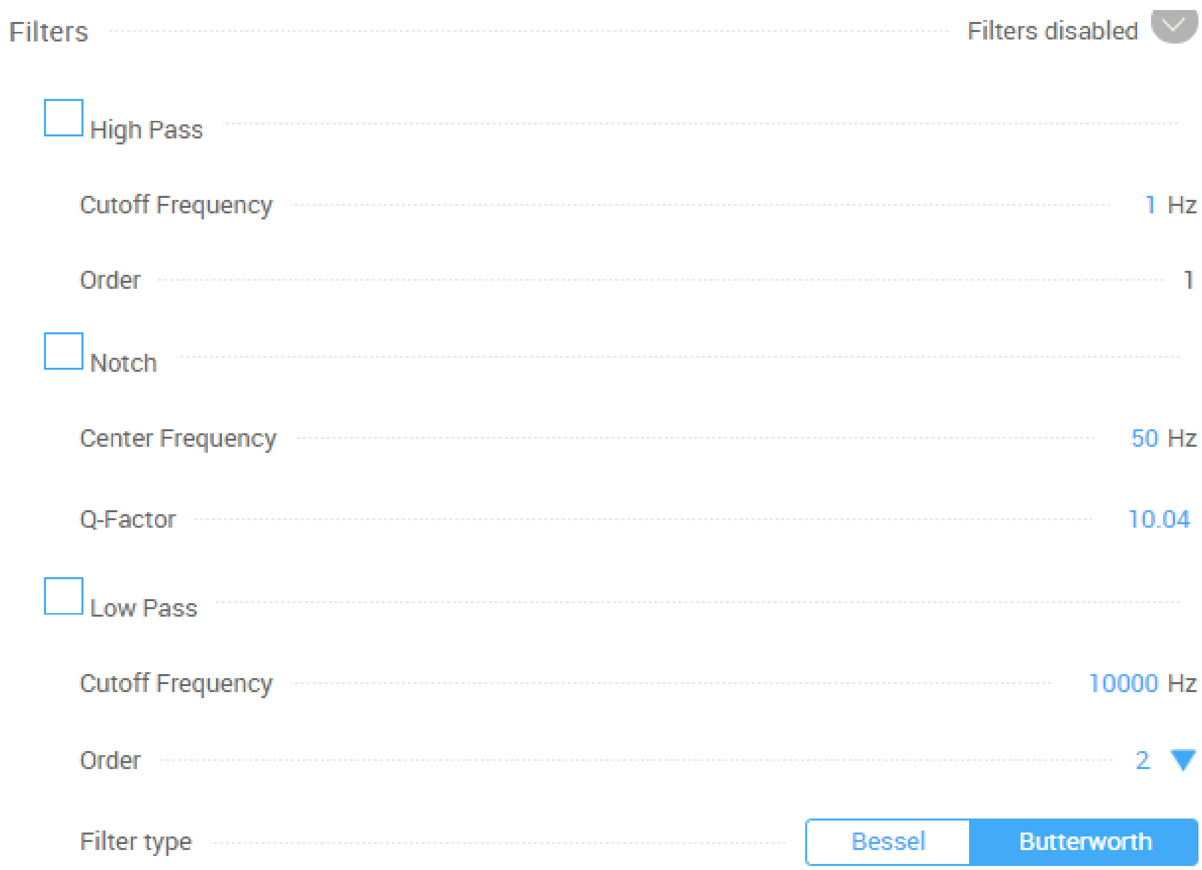
Appendix F - Data Acquisition GUI



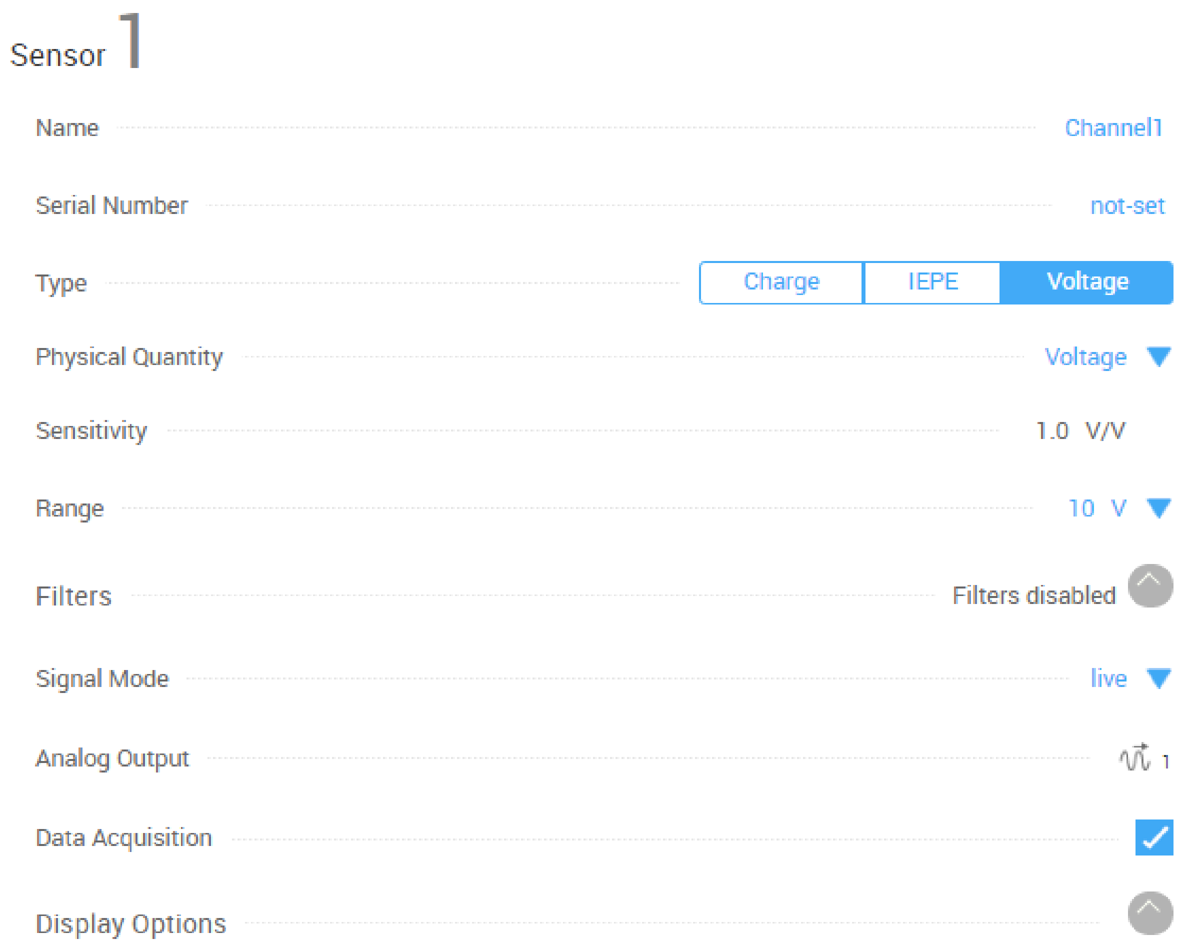
Analog Data Acquisition Screen



Data Acquisition and Export Screen

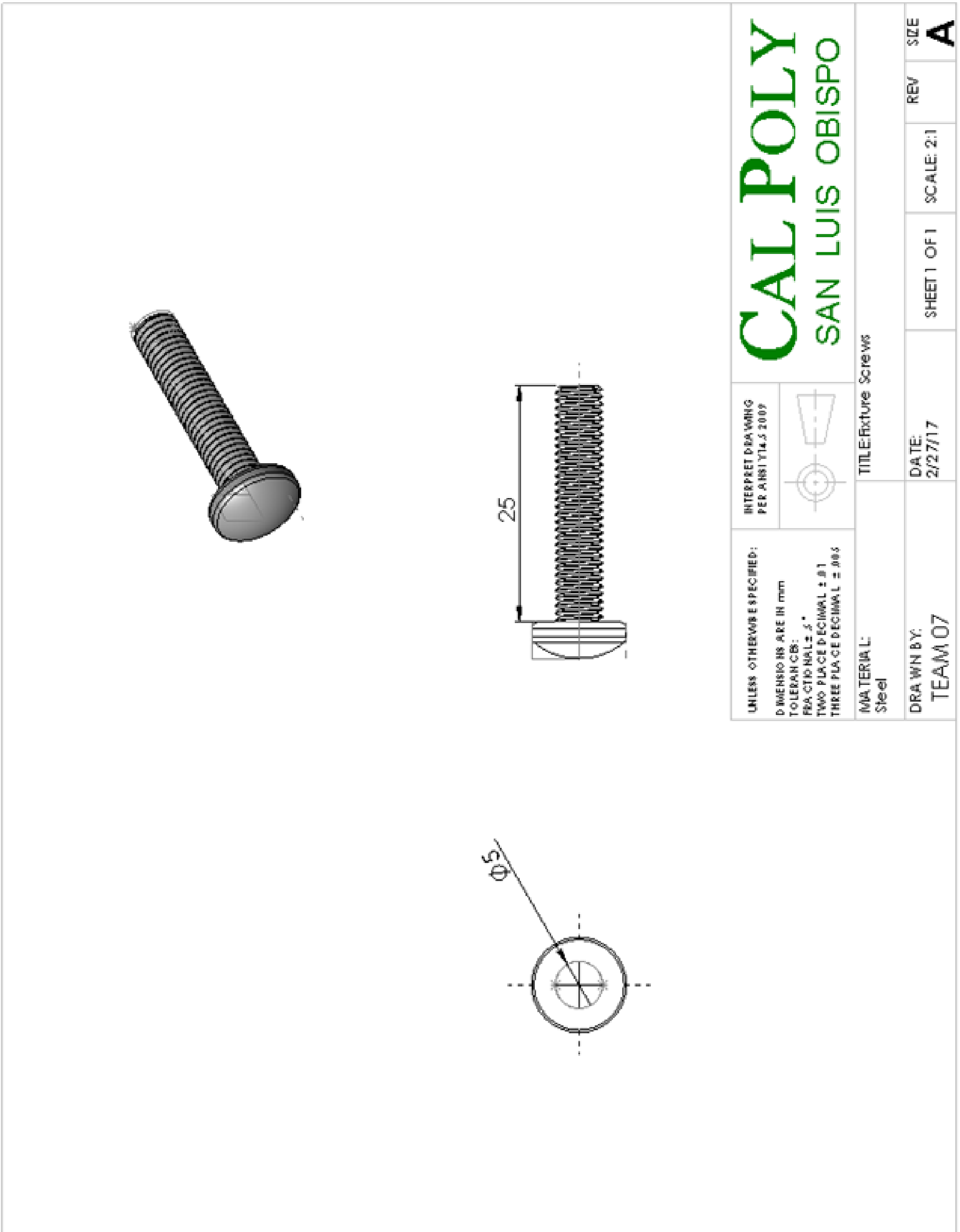


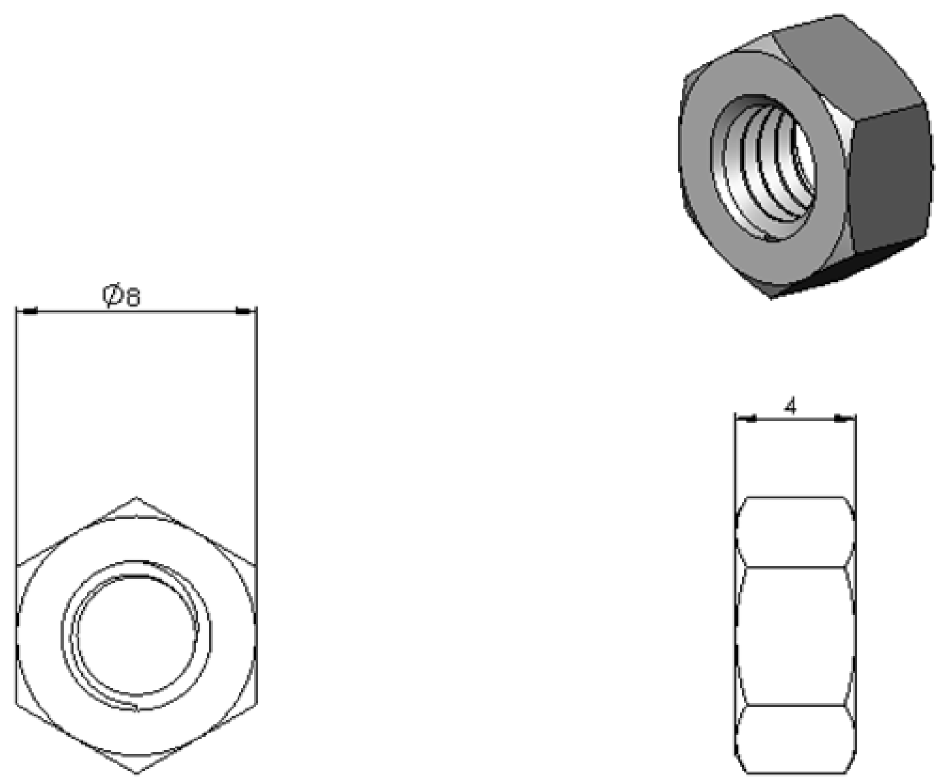
High-Pass, Low-Pass, and Notch Filter Setup Screen



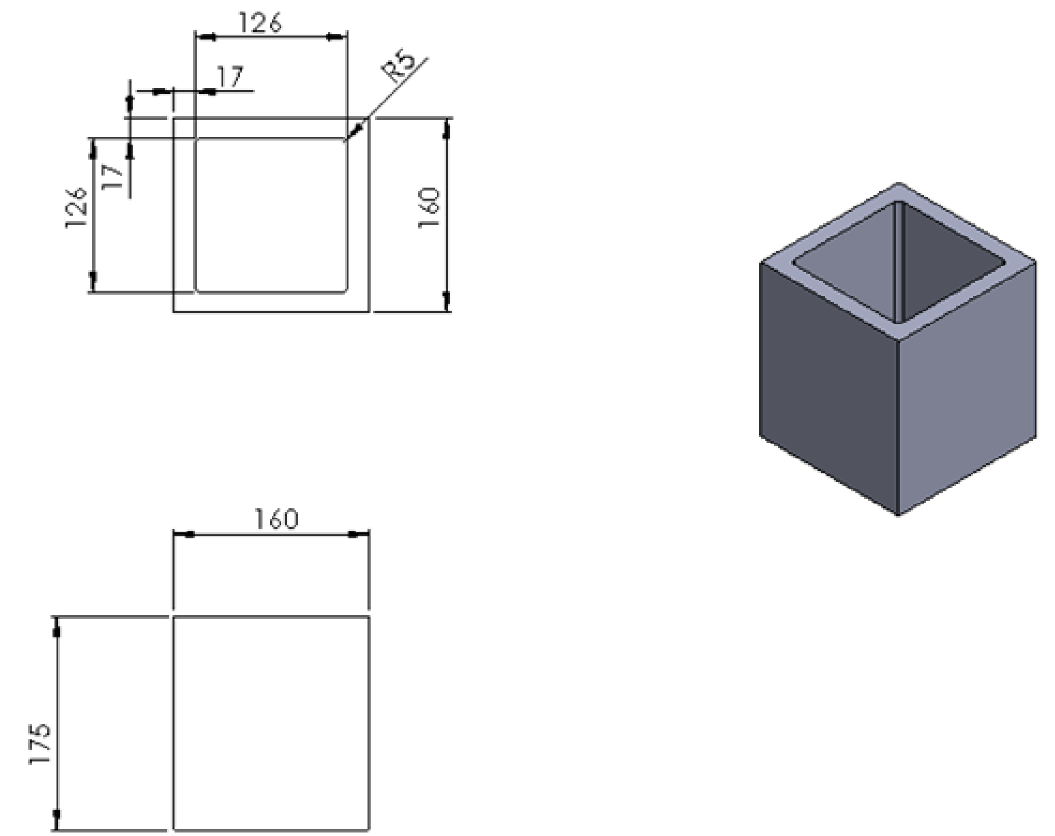
Individual Configuration Options for Each Sensor

Appendix G - Final Design Layout

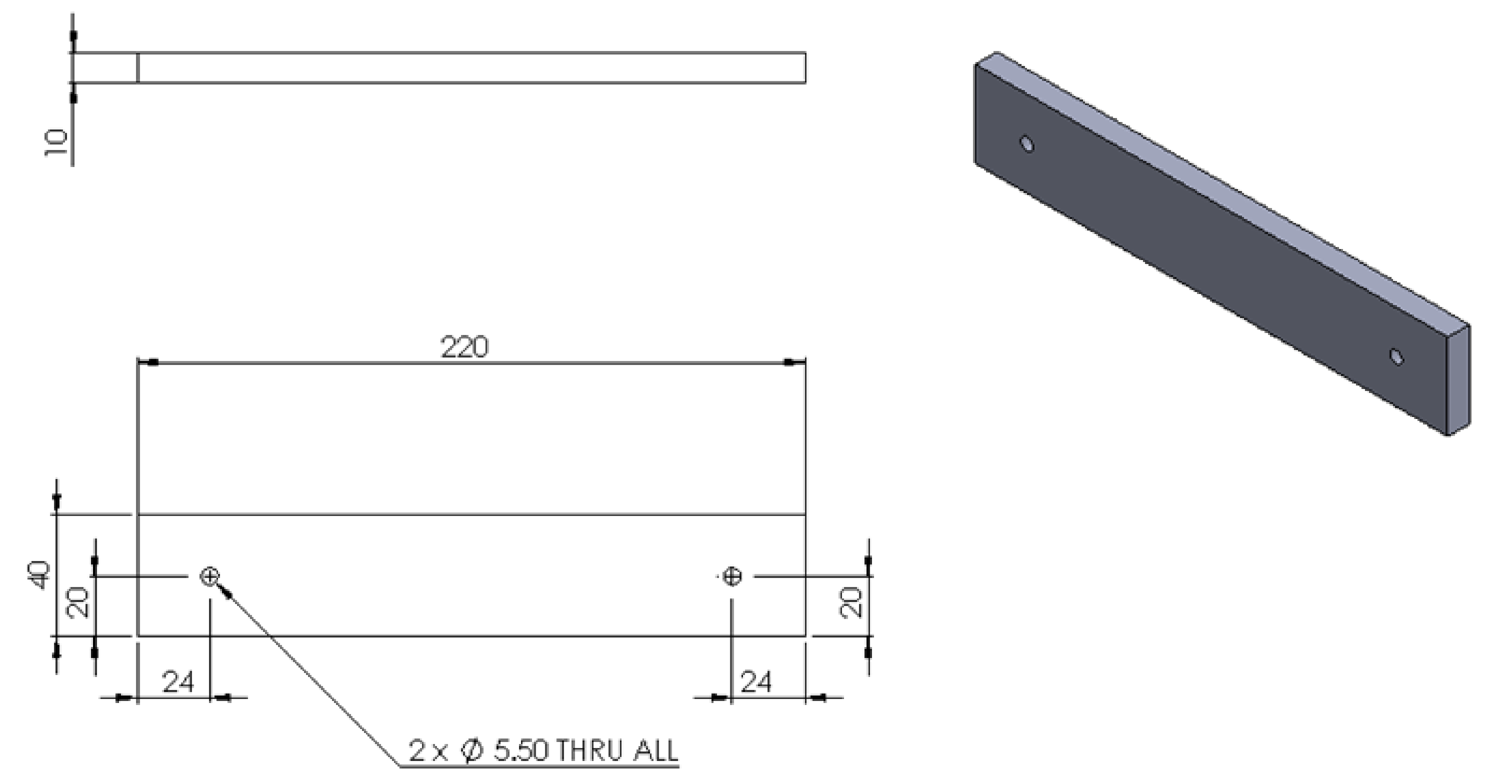




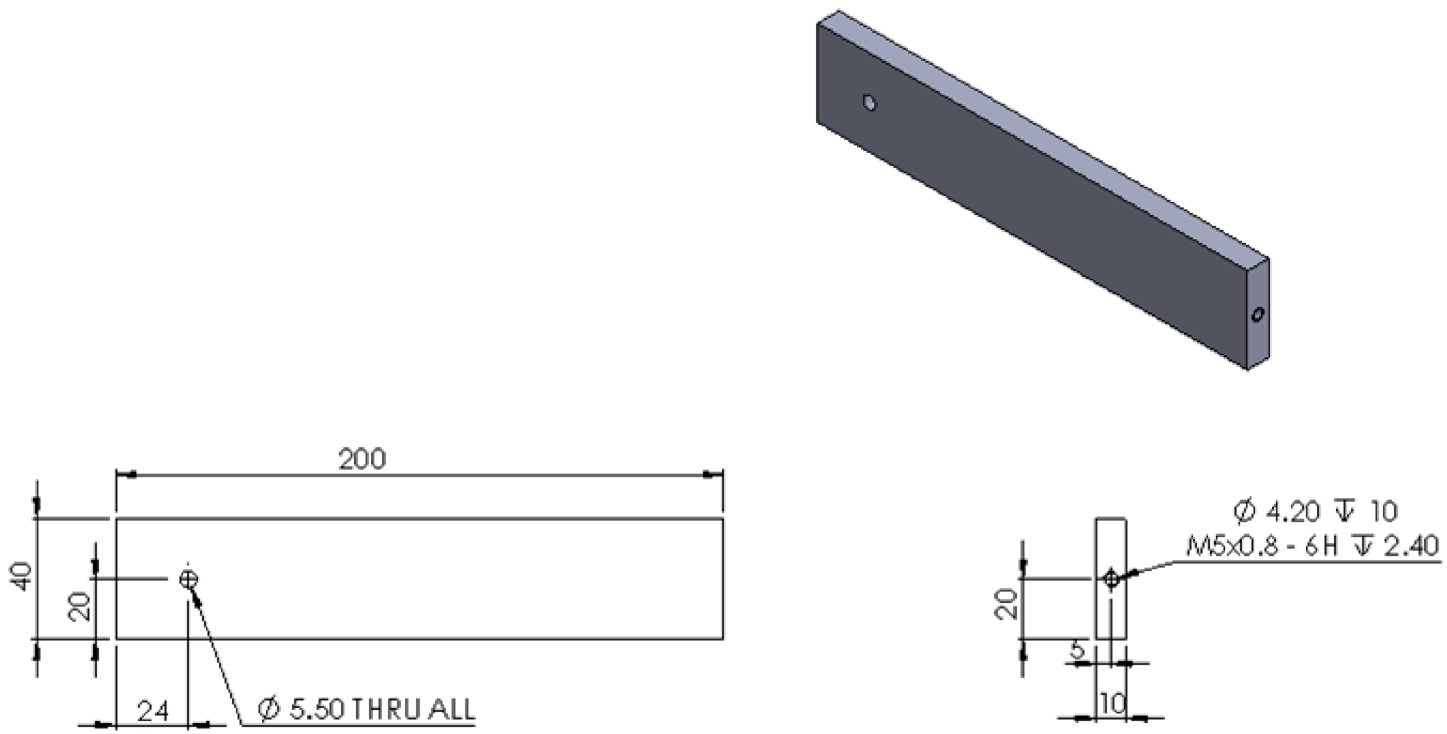
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN mm TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO
MATERIAL: Steel	TITLE: Fixture Nut	
DRAWN BY: TEAM 07	DATE: 2/27/17	SHEET 1 OF 1 | SCALE: 5:1 | REV | SIZE A



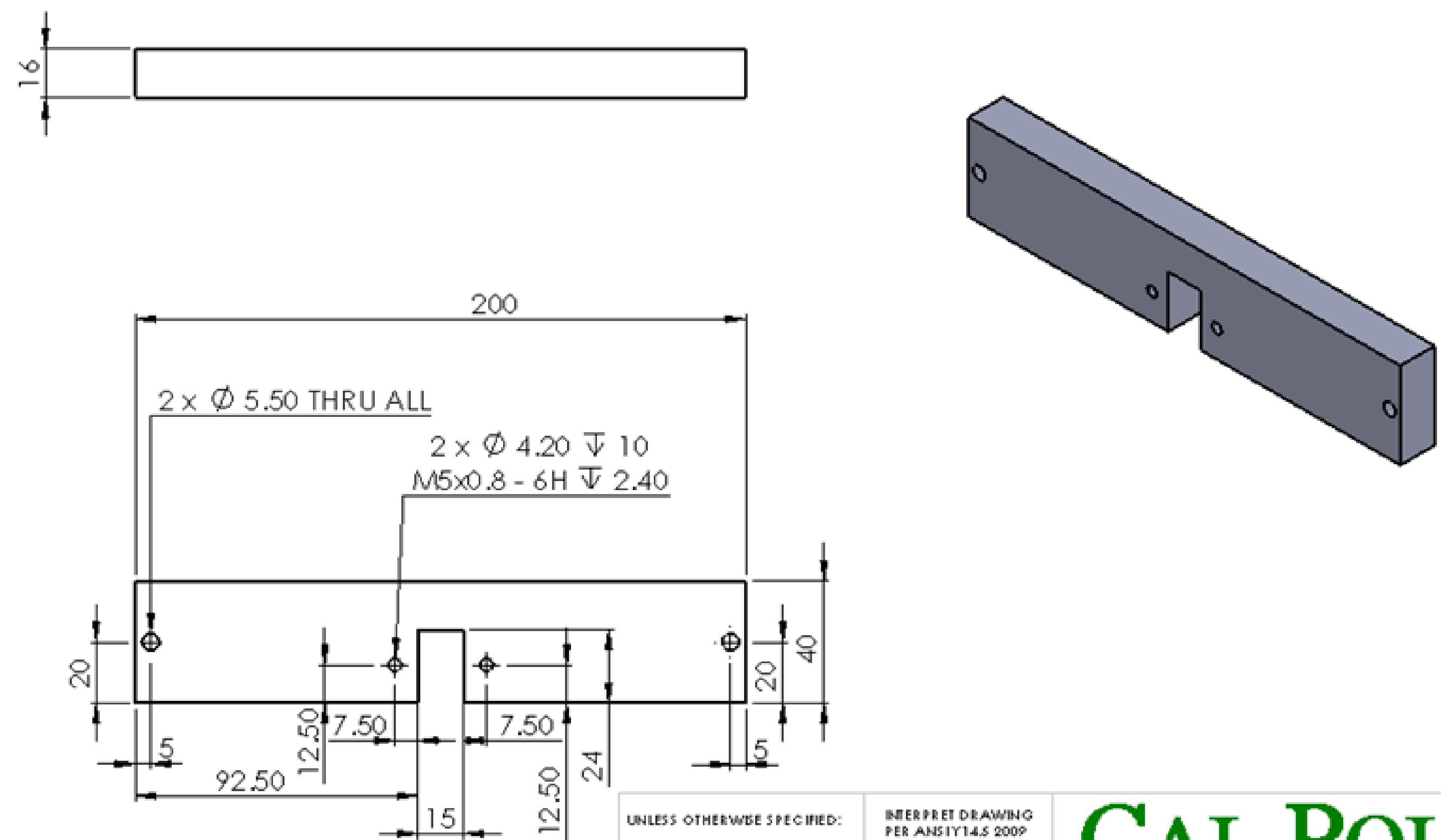
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN mm TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO
MATERIAL: Steel	TITLE: Bevator Chamber	
DRAWN BY: TEAM 07	DATE: 2/27/17	SHEET 1 OF 1 · SCALE: 1:5 · REV · SIZE A



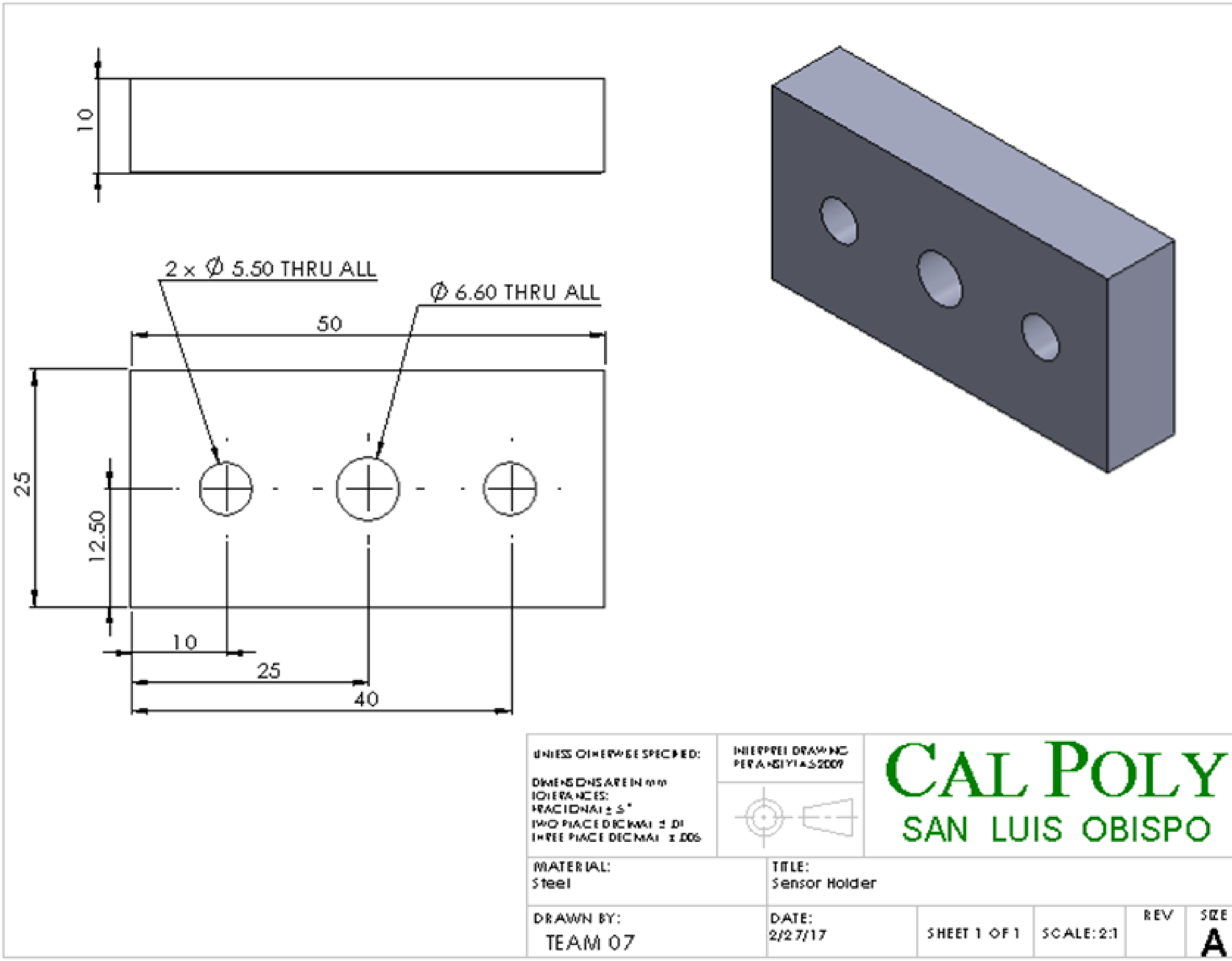
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN mm TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO
MATERIAL: Steel	TITLE: Connecting Bar	
DRAWN BY: TEAM 07	DATE: 2/27/17	SHEET 1 OF 1 · SCALE: 1:2 · REV · SIZE A

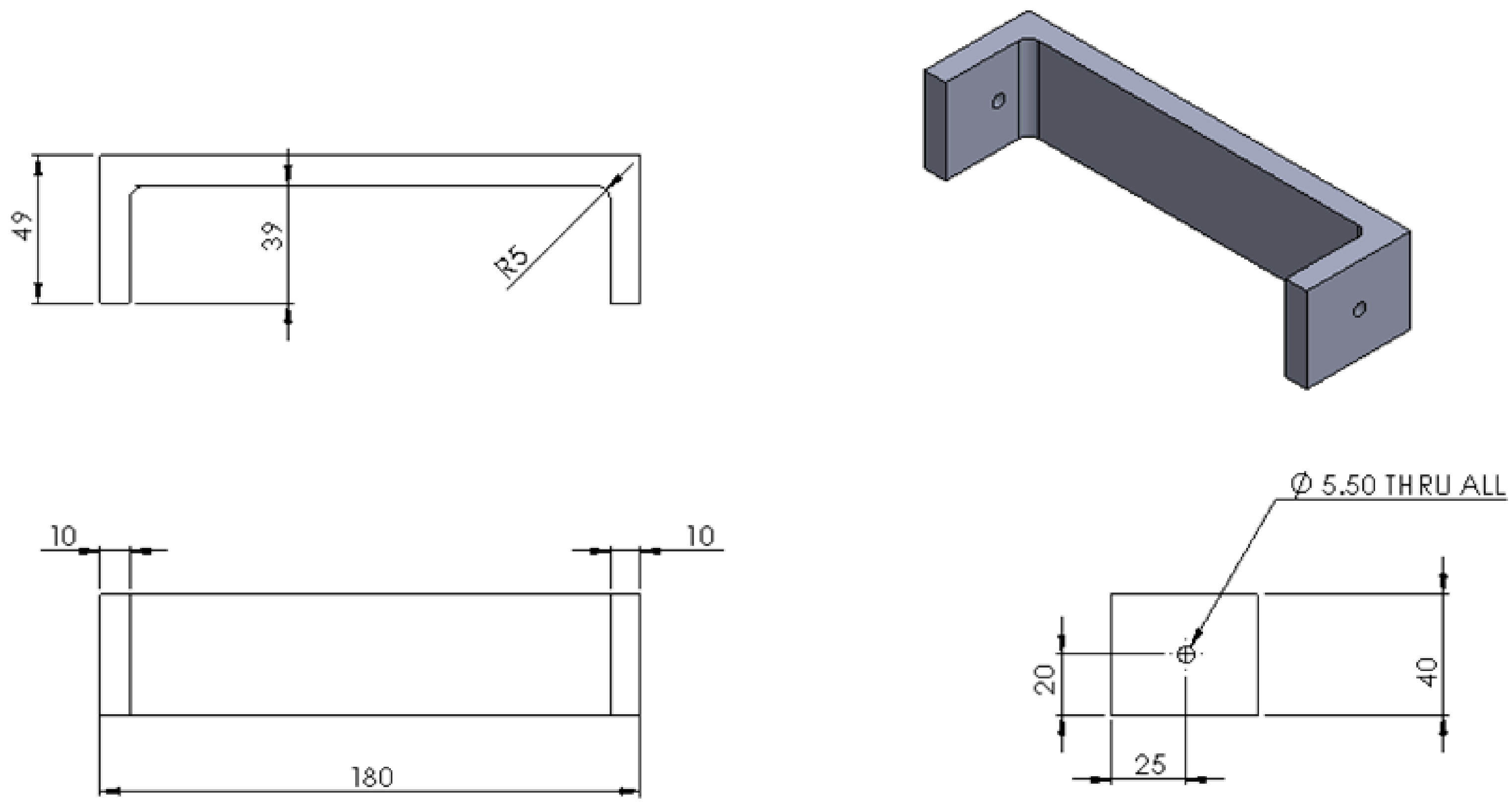


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN mm TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO
MATERIAL: Steel	TITLE: Connecting Bar	
DRAWN BY: TEAM 07	DATE: 2/27/17	SHEET 1 OF 1 · SCALE: 1:2 · REV · SIZE A



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN mm TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO
MATERIAL: Steel	TITLE: Sensor Bar	
DRAWN BY: TEAM 07	DATE: 2/27/17	SHEET 1 OF 1 · SCALE: 1:2 · REV · SIZE A


10
2 × Ø 5.50 THRU ALL
Ø 6.60 THRU ALL
50
25
12.50
10
25
40
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN mm
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005
INTERPRET DRAWING PER ANSI Y14.5 2009
CAL POLY
SAN LUIS OBISPO
MATERIAL:
Steel
TITLE:
Sensor Holder
DRAWN BY:
TEAM 07
DATE:
2/27/17
SHEET 1 OF 1
SCALE: 2:1
REV
SIZE
A

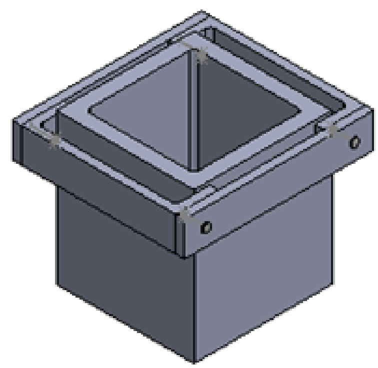


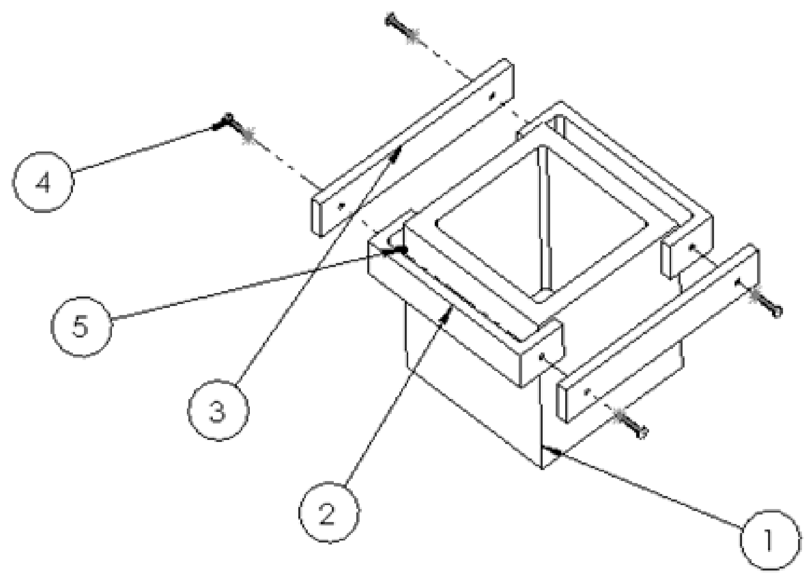
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN mm TOLERANCES: FRACTIONAL ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009
MATERIAL: Steel	TITLE: U-Bar
DRAWN BY: TEAM 07	DATE: 2/27/17

CAL POLY
SAN LUIS OBISPO

SHEET 1 OF 1	SCALE 1:2	REV	SIZE A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	101	Elevator Chamber	1
2	102	U-Bar	2
3	103	Connecting Bar	2
4	106	Screw	4
5	107	Nut	4





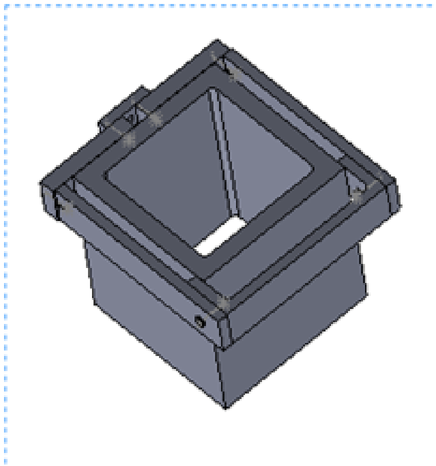
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN mm
TOLERANCES:
FRACTIONAL ± .5°
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005

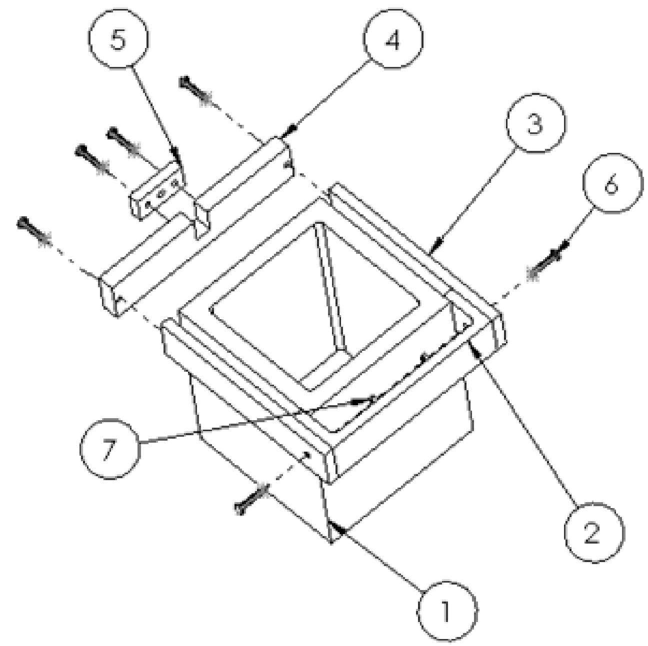
INTERPRET DRAWING PER ANSIY14.5 2009

CAL POLY SAN LUIS OBISPO

MATERIAL: Steel	TITLE: Elevator Chamber Fixture				
DRAWN BY: TEAM 07	DATE: 2/27/17	SHEET 1 OF 1	SCALE: 1:5	REV	SIZE A

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	101	Elevator Chamber	1
2	102	U-Bar	1
3	103	Connecting Bar	2
4	104	Sensor Bar	1
5	105	Sensor Holder	1
6	106	Screw	4
7	107	Nut	4





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN mm TOLERANCES: FRACTIONAL: ± .5° TWO PLACE DECIMAL ± .01 THREE PLACE DECIMAL ± .005	INTERPRET DRAWING PER ANSI Y14.5 2009	CAL POLY SAN LUIS OBISPO

MATERIAL: Steel	TITLE: Elevator Chamberr Fixture Version 2				
DRAWN BY: TEAM 07	DATE: 2/27/17	SHEET 1 OF 1	SCALE: 1:5	REV	SIZE A

Appendix H - Kistler Purchase Order

KISTLER
measure. analyze. innovate.

Delivery Note

Page 1 of 3

80317868

Ship-To-Party
California Polytechnic State Univ
c/o IME
Attn: Xuan Wang
1 Grand Avenue
San Luis Obispo CA 93410
USA

Information

Document Number	**80317868**
Document Date	02/02/2017
Customer No.	1042567
VAT No.	
Administrator	Darlene Roskwitalski
Telephone No.	+1 716 213 5779
email	darlene.roskwitalski@kistler.com
Delivery information	Complete Delivery

Customer
Lawrence Livermore National Labs
Attn: Aaron J. Ruch
L-782
7000 East Avenue
Livermore CA 94550
USA

Purchase Order No.	U1967371-VISA		
PO Date	01/31/2017		
Sales Order Number	252290	**Sales Order Date**	01/31/2017
Terms of delivery	FCA, Incoterms 2010 Amherst NY		
Delivery mode	Courier express,		

Shipping instructions
MARK AIRBILL: BILL RECIPIENT'S
FED EXP PRIORITY OVERNIGHT
10:30 AM ACCT #0941-0205-7

DO NOT INSURE OR DECLARE VALUE

COMPLETE

PH: 925/422-1670

Item	Material/Description		Quantity	DG Code
10	18027175		1 PC	
	8152C0050000			
	Piezoceramic Acoustic Emission Sensor with IEPE Output			
	High Sensitivity, Wide Frequency Range, High Temperature			
	Order/Item 252290/10			
	Serial No.:	5076054		
	Country of origin	US		
20	18028309		1 PC	

Kistler Instrument Corp.
75 John Glenn Drive
Amherst, NY 14228-2171

Telefon +1 716-691-5100
Telefax +1 716-691-5226
info.us@kistler.com

HSBC BANK USA
One HSBC Center
Buffalo, NY 14203
Acct.: 718-74452-7
Swift: MRMDUS33

ISO 9001
Certified Quality System

www.kistler.com

California Polytechnic State Univ

KISTLER
measure. analyze. innovate.

80317868

Delivery Note

Item	Material/Description		Quantity	DG Code
	5125C0			
	Acoustic Emission Coupler			
	Input : sensor 8152C with cable gland			
	Order/Item 252290/20			
	Serial No.:	5116896		
	Country of origin	US		
30	18029270		1 PC	
	5330A2			
	Plug In Filter Set			
	Consisting of 1ea of following:			
	Order/Item 252290/30			
	Country of origin	US		
40	18028549		1 PC	
	8278A500SP5			
	500g Ceramic Shear Accelerometer with Charge OutputWide Frequency Range, Miniature, Light Weight, High Temperature- Measurement range:			
	Order/Item 252290/40			
	Serial No.:	4991669		
	Country of origin	US		
50	18000523		1 PC	
	1631C1			
	Connecting Cable, Single-Core Coax, High Insulation			
	KIAG 10-32 pos. - BNC pos.			
	Order/Item 252290/50			
	Country of origin	US		
60	18029494		1 PC	
	1784B5K03			
	Signal output cable for triaxial voltage mode accelerometers			
	M4.5 4 pin neg. - 3 x BNC pos.			
	Order/Item 252290/60			
	Country of origin	US		
70	18011015		1 PC	
	8766A500AH			
	500g PiezoStar® Triaxial Accelerometer with IEPE Output			
	Wide Frequency Range, Miniature, High Temperature, Thermally Stable			
	Order/Item 252290/70			
	Serial No.:	5080199		

California Polytechnic State Univ

KISTLER

measure. analyze. innovate.

80317868

Delivery Note

Item	Material/Description		Quantity	DG Code
	Country of origin	US		

PO #U1967371

CALIFORNIA RESALE CERTIFICATE
RESALE PERMIT #SR CH 100-978248
ON FILE

EMAIL ACKNOWLEDGEMENT/INVOICE:
RUCH2@LLNL.GOV

PH: 925/422-1670

Before removing the padding material, kindly check the completeness of the goods.

Kistler Instrument Corp.
75 John Glenn Drive
Amherst, NY 14228-2171

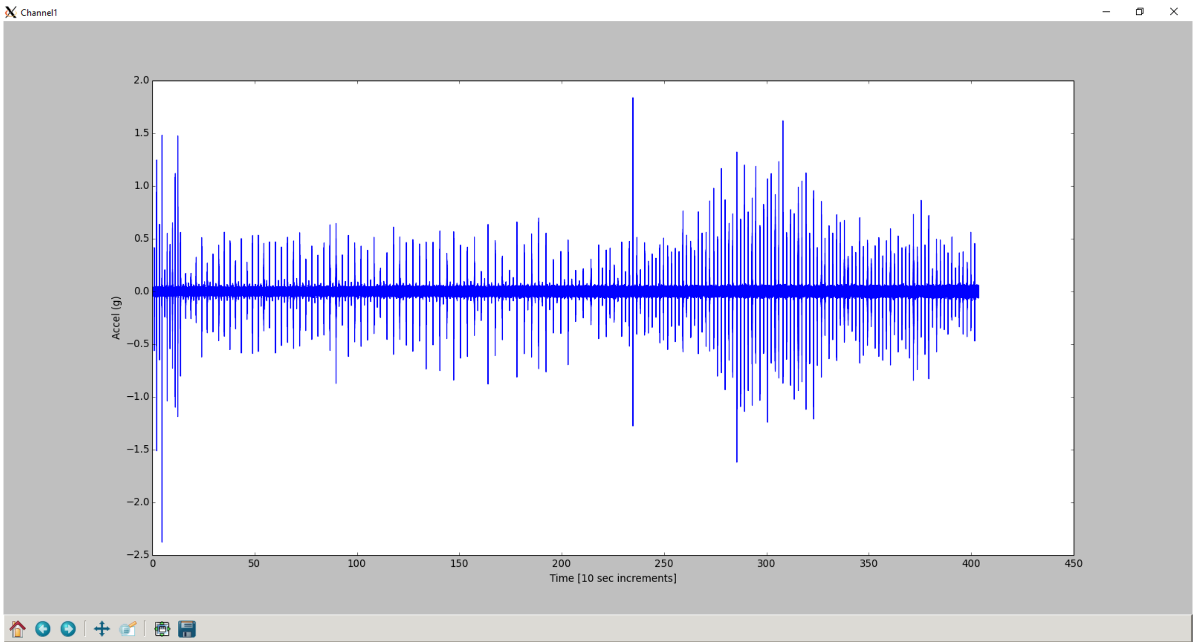
Telefon +1 716-691-5100
Telefax +1 716-691-5226
info.us@kistler.com

HSBC BANK USA
One HSBC Center
Buffalo, NY 14203
Acct.: 718-74452-7
Swift: MRMDUS33

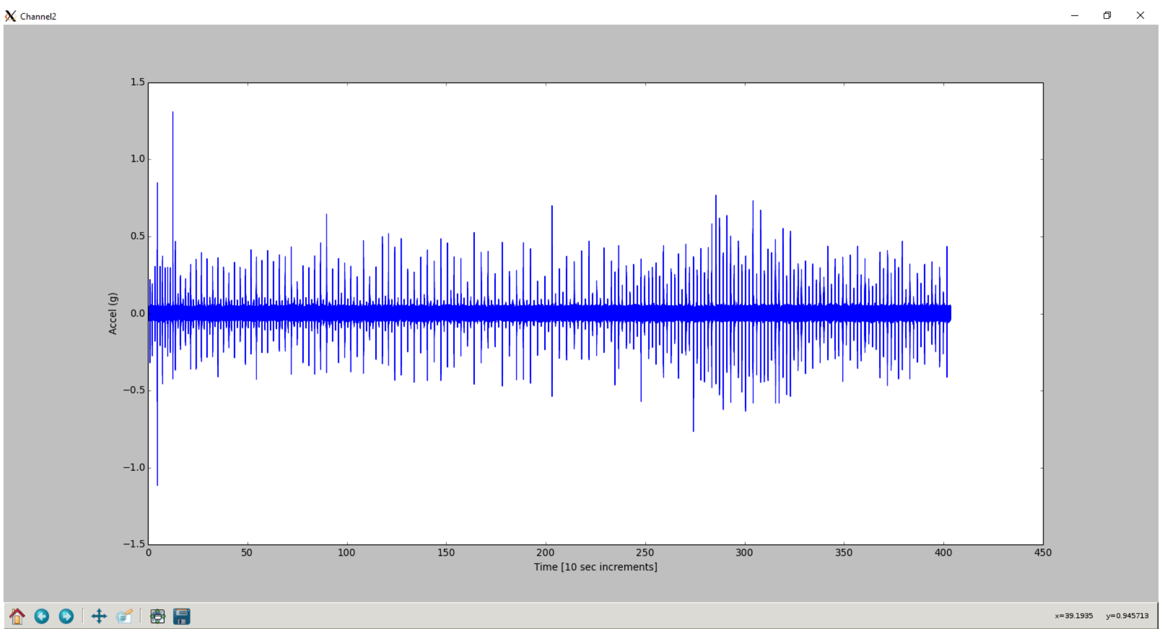
ISO 9001
Certified Quality System

www.kistler.com

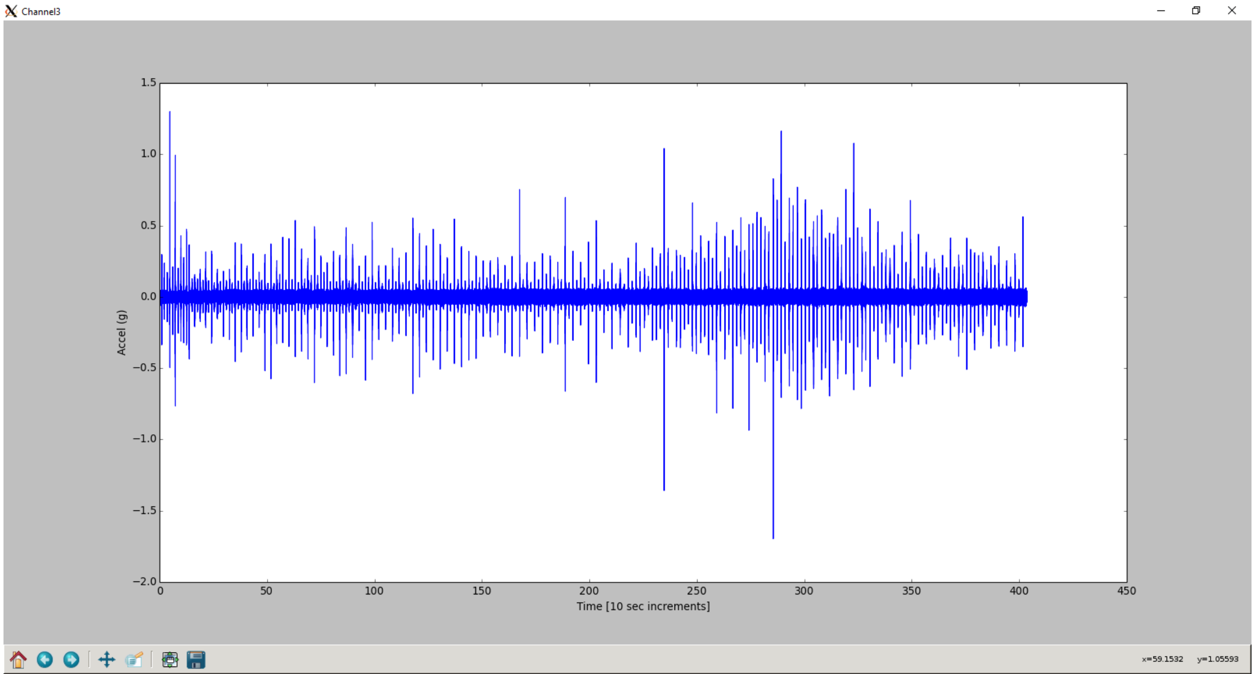
Appendix I - Analysis of Collected Sensor Data



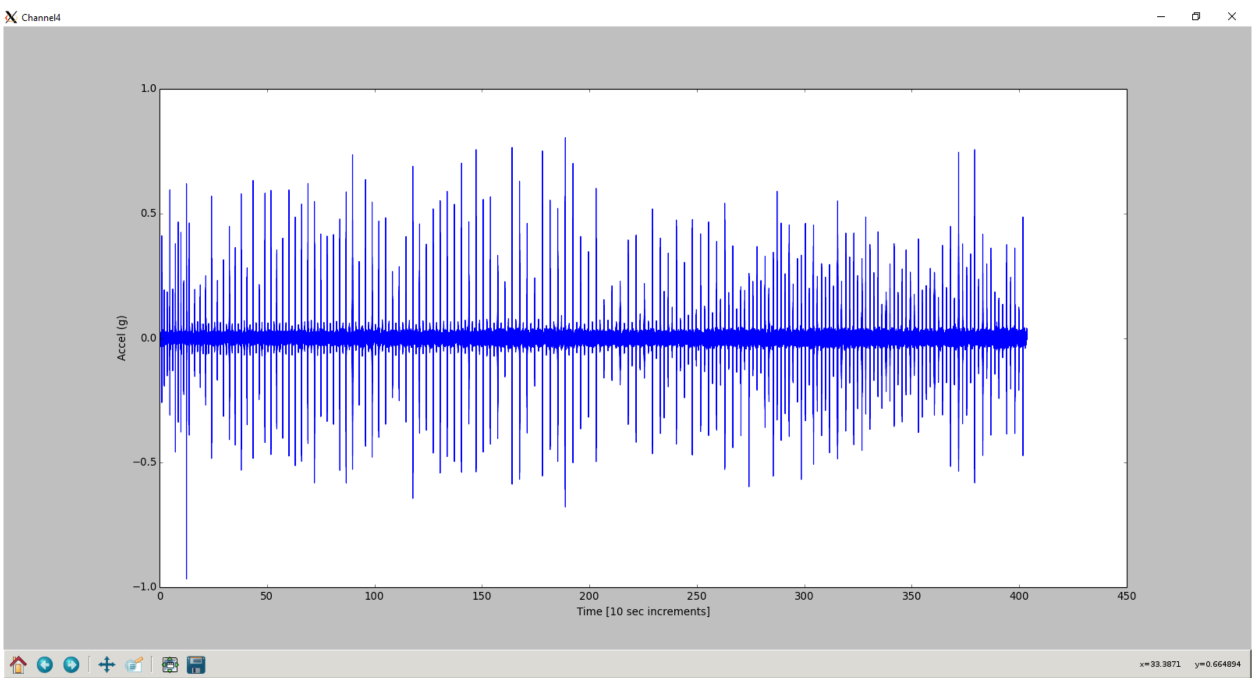
X-Axis



Z-axis

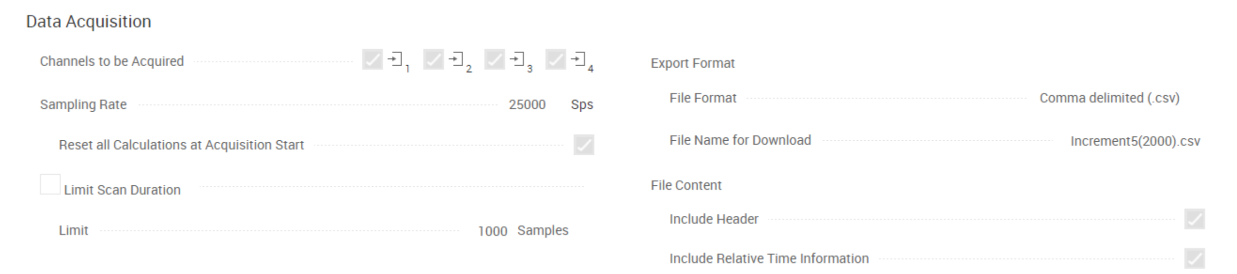


Y-Axis

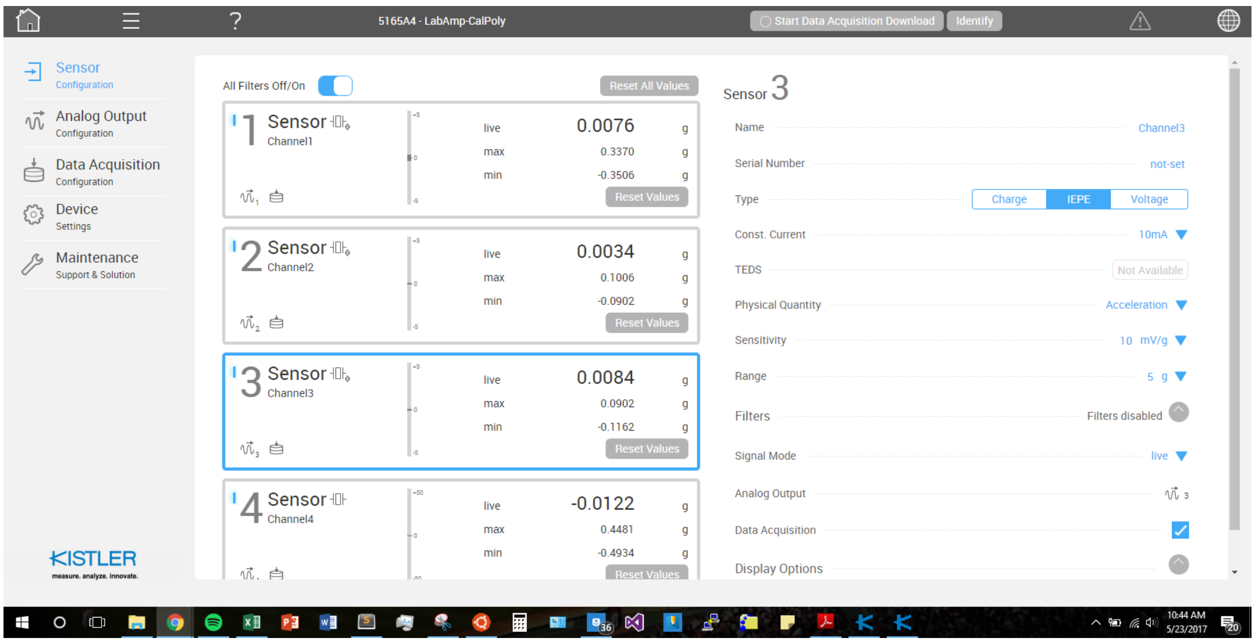


Single Axis

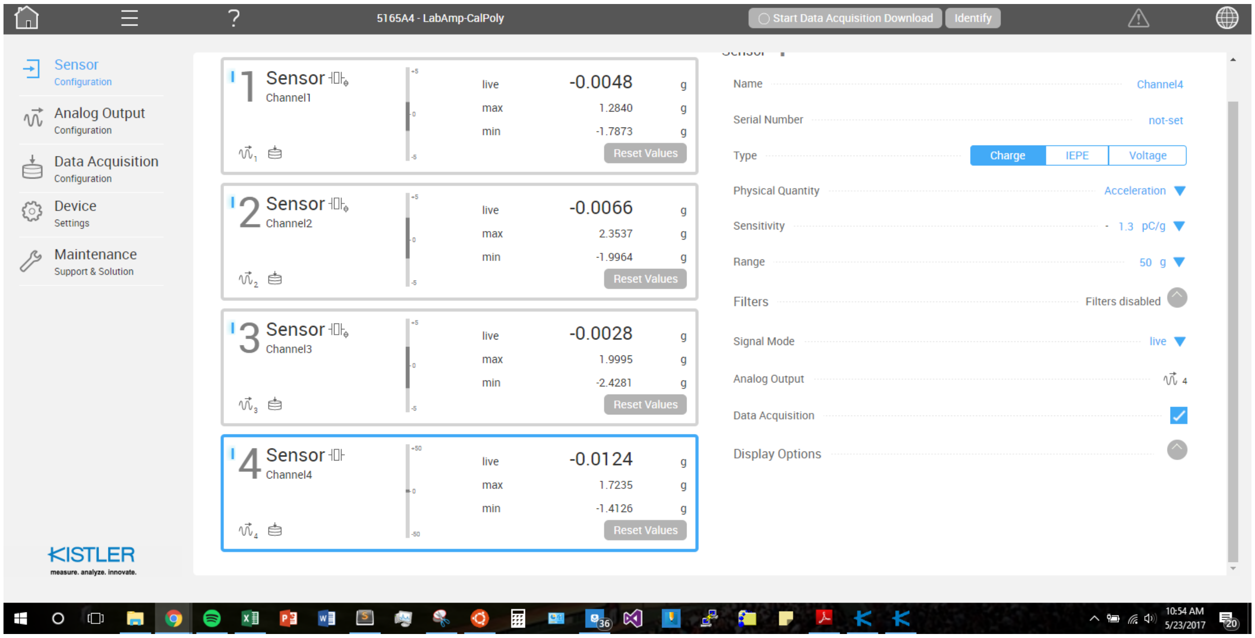
Appendix J - Acquisition Settings



Main LabAmp Settings



Triaxial Sensor Settings



Single Axis Sensor Settings

Appendix K-Gantt Chart