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2015 Summer Design Challenge: Team A&E (2241) Additively Manufactured Discriminator

Sarah E. Miller, Brandon J. Moore

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Sarah E. Miller
Advanced & Exploratory Systems

Brandon J. Moore
Advanced & Exploratory Systems

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1026

Abstract

Current discriminator designs are based on historical designs and traditional manufacturing methods. The goal of this project was to form non-traditional groups to create novel discriminator designs by taking advantage of additive manufacturing. These designs would expand current discriminator designs and provide insight on the applicability of additive manufacturing for future projects. Our design stretched the current abilities of additive manufacturing and noted desired improvements for the future. Through collaboration with NSC, we noted several additional technologies which work well with additive manufacturing such as topology optimization and CT scanning and determined how these technologies could be improved to better combine with additive manufacturing.

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NOMENCLATURE

UQS	Unique Signal
AM	Additive Manufacturing
3D Printing	A subset of additive manufacturing which includes AM processes that print material
SLS	Selective Laser Sintering
DMLS	Direct Metal Laser Sintering
PolyJet	Additive Manufacturing Process
SNL	Sandia National Laboratories
NSC	National Security Campus
STL	Stereolithography – The file type used to print or build additively manufactured parts
Printed Part	Additively manufactured parts printed using a printing process such as FDM or PolyJet
Built Part	Additively manufactured parts built using a building process such as SLS, DMLS, UC, LENS
Build Chamber	The area of the machine where the part is built, will either be the location of where the material can be extruded or where the laser can sinter powder
Build Volume	The build volume is the volume within the build chamber that parts can be produced, typically it is best to build parts in the center of the build due to temperature variations on the edges
Build Time	The amount of time it takes to build a part, often includes time for part to cool within the build chamber
Layer Thickness	The thickness of one layer of either powder or extruded material
Dogbone	Tensile specimens built in various orientations within a build which are then used to test the material properties of the part from that build

1. INTRODUCTION

Nuclear weapons are extremely powerful and capable of inflicting great damage meaning their use must be highly controlled. A nuclear weapon must always detonate when purposefully enabled and never detonate otherwise. The safe handling of nuclear weapons is paramount and thus it is important to design for protection against both normal and abnormal circumstances. Several events between 1950 and 1980 exposed nuclear weapons to extreme environmental conditions including fire, crush, and shock (Plummer). Though these events did not ever result in a partial inadvertent nuclear detonation, they did highlight the importance of designing safety mechanisms for nuclear weapons, especially in the case of abnormal environments.

Currently, there are few vendors capable of manufacturing the hundreds of precision tolerance, painfully scrutinized, long lead time sub components used in surety mechanisms. Additive manufacturing is a particularly fast method of manufacturing and is particularly attractive as a means of manufacturing surety mechanisms. Additive manufacturing also offers the opportunity to reduce the required assembly and the costly qualification and production process that comes with assembly. Additive manufacturing also has the benefit of reducing part count which in turn reduces the time and pull on vendor's contributions. The combination of these advantages highlights additive manufacturing as a new, viable method for producing surety mechanisms; however, producing mechanisms in additive manufacturing is more complicated than simply sending a vendor the same models to be built additively. The differences in material properties and design guidelines for additive manufacturing compared to traditional manufacturing mean that multiple design aspects need to be re-optimized. Full optimization will require new designs that take advantage of the capabilities of additive manufacturing.

One such surety mechanism is one that discriminates a unique input signal, UQS, and determines whether to allow a signal to progress or not. Current discriminator designs have many parts and are costly to assemble, making them good candidates for testing the applicability of additive manufacturing. Therefore, the goal of this project was to form non-traditional groups to create novel discriminator designs that take advantage of additive manufacturing.

2. MODEL DEVELOMENT

We began our process of designing a novel discriminator by reviewing the design criteria, selecting the top two designs to pursue, and then determining which of the top two should continue to manufacturing. This design process and the top two designs are detailed below.

2.1. Design Criteria

Each of the given requirements was ordered into a table where we added our derived understanding and selected appropriate verification methods.

Table 1: Design Criteria with equivalent derivation and verification methods

Customer Requirements	Derived Requirements
More than 50% of the discriminator is produced using Additive Manufacturing techniques	50% by volume of the discriminator shall be manufactured using Additive Manufacturing techniques
The device may use power and space as needed	The largest component shall fit within a 10"x10"x10" build volume
	The discriminator shall accept an input power of 28 VDC
The device must isolate charge through vibration and shock environments	The discriminator and shutter shall remain safe in 1000g static loading condition [TBR]
	The discriminator and shutter shall remain safe in a vibration environment of 10 GRMS [TBR]
Isolation of charge is defined as a voltage standoff of 500 VDC between input and output pins	With 500 VDC applied at the input, the maximum measured current at the output shall be 10 microamps
The device must discriminate a unique signal (as many as possibly up to 24 events)	The discriminator design shall include a discriminator that enables after receipt of the UQS (probabilistic equivalent of 24 unique signals)
The device must lock upon receipt of an incorrect signal	The discriminator shall lock upon receipt of the wrong signal, preventing further advancement towards enablement
The device can reset from the enabled position	The discriminator shall be capable of resetting from enabled to safe 1 time
The device must enable	The device must enable upon receipt of the correct UQS
The device must be rendered in prototype form	The team shall manufacture and demonstrate their design

Table 2: Design "Shoulds" with equivalent derivation and verification methods

Should Requirements	Derived Requirements
More than 90% of the discriminator is produced using Additive Manufacturing techniques	90% by volume of the discriminator should be manufactured using Additive Manufacturing techniques
The device can be used more than once	The discriminator should be able to be used a total of 20 times
The device can reset from the locked position	The discriminator shall be capable of resetting from locked to safe
The device can discriminate 24 events	The UQS to enable the discriminator should consist of a probabilistically equivalent 24 event signal
The device can be rendered in final form at NSC or commercial vendor	The device should be manufactured from metal by NSC or a commercial vendor
Additional Requirements from Scoring	**Derived Requirements**
Design Uniqueness	Different from existing discriminator
Flexibility of Design (UQS Changes)	Can handle different UQS changes
Additions to AM Roadmap	Can identify improvements in AM
Potential Reduction in Cost	Lower the cost of current discriminator
Predicted Reduction in Lead Time	Lower than the production of current discriminator
Flexibility of Design (Functional Channels)	ability to have different number of channels
Number of Parts (Fewer better)	Lower number of parts than current discriminator

2.2. Design Selection Process

Multiple design options were put forth in multiple brainstorming sessions including designs based on a corkscrew, Rubik's cube, environment sensing, magnetic gears, pressure burst disks, cantilevered beams, fluid valve system, and pegboard pathing. In order to determine which designs to progress, we scored each design idea based on the scoring criteria in a Pugh Chart. The top three designs are shown in Figure 1 below.

Team A&E AM Stronglink Competition							
Potential Alternatives							
Print Existing Mechanism		Option 2 - Pin Maze		Option 6- Wedge Shape Pin Drop		Option 11 - Knot	
Information	Score	Information	Score	Information	Score	Information	Score
Assume 90% can be printed	0	Design can almost completely 3D printed	0	Design can almost completely 3D printed	3	Design can be 3D printed but final will have more linear actuators	0
Standard 24 events	0	Design can discriminate 24 events or more events	0	Design can discriminate 24 events or more events	0	Design can discriminate 24 events or more events	3
	0	Design should be able to lock	0	Design will be able to lock	0	Locking will be more difficult	-3
	0	Design will be able to enable	0	Design will be able to enable	0	Design will be able to enable	0
	0	Design has ability to reset	0	Design has ability to reset	0	Design has ability to reset	0
	0	Design has free space for voltage standoff	3	Design has larger free space for voltage standoff	3	Design has free space for voltage standoff	3
	0	Design will be able to reset	0	Design will be able to reset	0	Not sure if this can be reset. How can is be reset once locked?	0
	0		**30**		**60**		**36**
Information	**Score**	**Information**	**Score**	**Information**	**Score**	**Information**	**Score**
	0	New unique design	3	New unique design	3	New unique design	7
	0	design will utilize AM capabilities	0	design will utilize AM capabilities	3	design will utilize AM capabilities	7
	0	Device can be scaled to same as baseline	0	Design will be able to scale	3	Should be able to scale	0
	0	Can have multiple ways to get through maze without modification	3	Design should be flexible	0	Not flexible would have to make new pattern	-3
	0	Design will push the AM capabilities	3	Design will push the AM capabilities	3	Design will push the AM capabilities	7
	0	Design has less parts so should be cheaper	3	Can be printed all together	3	design should have decreased cost	3
	0	Design will preform equivalent to baseline	0	Design may not have same reliability as mechanical devices	0	Design should have same performance	0
	0	Design does not have as many intricate parts so lead time should decrease	3	Design should be quicker since everything can be printed at once	3	same as baseline	0
	0	Design had capability to have flexibility in functional channels	0	Design had capability to have flexibility in functional channels	0	You would have create a new knot	0
	0	Design will be able to complete in allotted time	0	Design will be able to be completed in time	3	Can't be finished in time	-3
	0	Design will have less parts	3	A lot less moving parts	3	about the same number of parts	0
	0		**69**		**102**		**83**
	0		**99**		**162**		**119**

Figure 1: Pugh Chart For Top Three Designs

As risk mitigation, we chose to pursue the top two designs, the Wedge and the Knot, before selecting a final design.

2.3. Design Overview – Knot

The Knot design originated from viewing the complex shapes capable of being made in additive manufacturing. It was based on a 3D puzzle lock where individual puzzle pieces were interlocked and by moving each piece correctly in the correct order, a path would appear. The UQS code for this design would be the selection of the correct part as well as correct movement profile. This movement profile was intended to take advantage of the possibility for n-factorial movements. Thus, the piece could be directed to move translationally or rotationally along any prescribed axis. Once each piece was moved correctly, the next piece would be free to move. The shutter mechanism for this design was a set of holes in each piece, aligning to form an open path for an optical output. If the pieces were not moved correctly, then the path would be blocked by the pieces and the optical output would not pass through the mechanism.

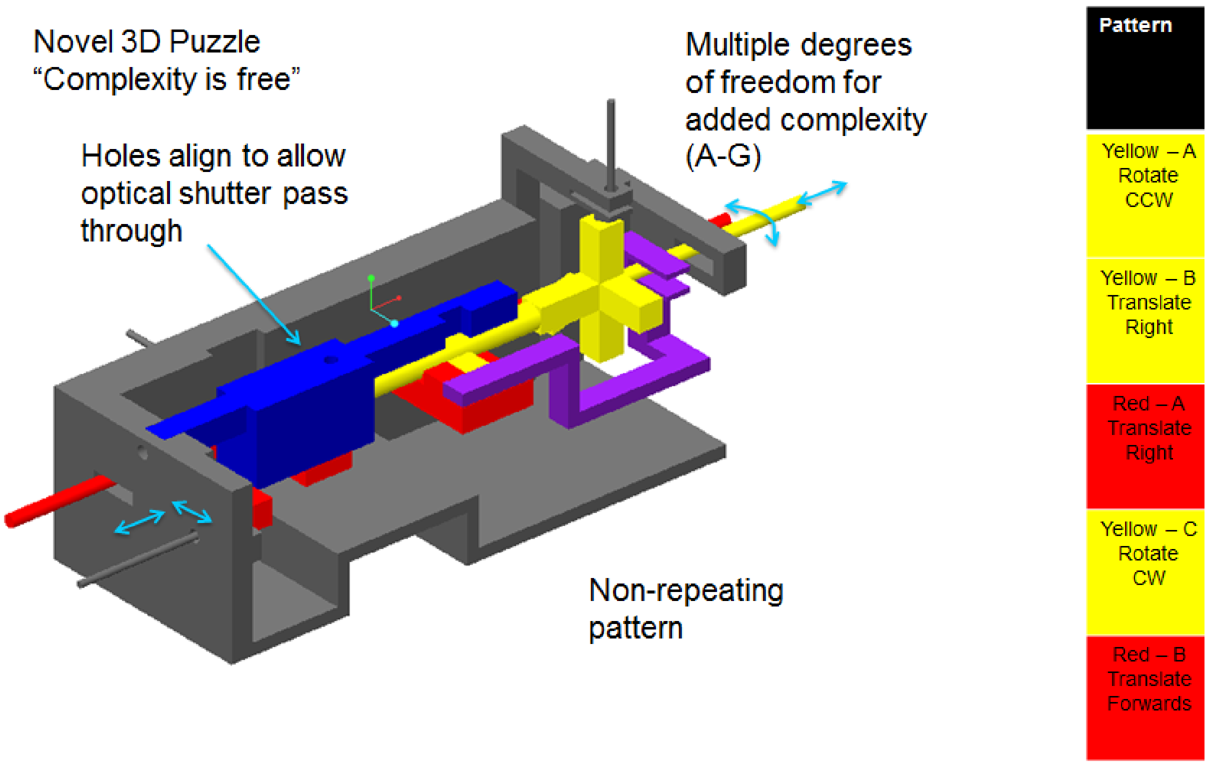

Figure 2: Knot Design Overview

One of the reasons we were drawn to this design was that it took great advantage of the “complexity is free” argument for additive manufacturing. The pieces could be designed in such a way that it would be impossible to create this device in traditional manufacturing. Additionally, current discriminator designs use a binary UQS mechanism – either A or B. The movement of these pieces could be link to not just A or B, but could extend far beyond – A through G or even Z. This added complexity to the UQS allowed for a reduced number of parts (for example, 8^8 is equivalent to 2^{24} so 8 parts with 8 movements could replace 24 movements in a binary design). Additionally, since the movement profile for each piece differed from the next, the UQS consisted of a non-repeating pattern. This meant that the A or B for one piece could be drastically different than the A or B for the next piece. This design factor was appealing in that a shock or vibration would not affect each piece in the same manner.

However, we did run into some limitations when continuing the Knot design. First, we discovered that conceptualizing the design was complicated. Due to the three dimensional nature of each part, it was difficult to coordinate the movement of each piece with the other pieces and even basic hand sketches of the design were complicated to construct. Additionally, we realized that locking the discriminator would be challenging. While an incorrect input would signal an incorrect movement of a piece and thus block the optical path and later pieces from moving, we still needed to prevent against retries. To do this, we constructed cantilever beam locks which would lock a piece upon and incorrect movement and reset the lock by pulling on the lock handle as shown in Figure 2.

Figure 3: Cantilever Beam Lock

While this prevented against retries for a specific movement, each potential movement needed to be accounted for as the device would need to lock for both an incorrect directional movement and an incorrect order of movement.

Additionally, we quickly discovered that attempting to CAD the original design was extremely complicated due to the organic nature of the knot pieces and the coordinate system of Creo (PTC Creo, Needham, MA). Most CAD programs were created with traditional manufacturing in mind and while they work quite well for these methods, they struggle to accommodate additive manufacturing. Due to these series of limitations, we decided to pursue the Wedge design described below as our final discriminator design.

2.4. Design Overview – Wedge

The Wedge design consists of a set of stacked plates or wedges that rotate by compliant springs on a set axis. Each wedge has two sets of holes: the locking rod holes and the shutter optical holes. The rod holes allowed a threaded rod to pass through the wedge and lock it in position after an input. The optical holes move relative to the input signal and align to form an open optical path when the input signal is correct. The optical signal is the “key” that unlocks the system and allows energy to pass. The top, or first wedge, has a handle that rotates about the axis to either the A or B optical hole in the second wedge and the threaded pin then rotates down, locking the second wedge to the top wedge. The top wedge then receives the input code for the third wedge and rotates to either the A or B optical hole for that wedge before the threaded pin rotates down to lock the wedge in place. Figure 3 shows a depiction of the wedge design where the purple top wedge moves each of the lower wedges by engaging the threaded pin.

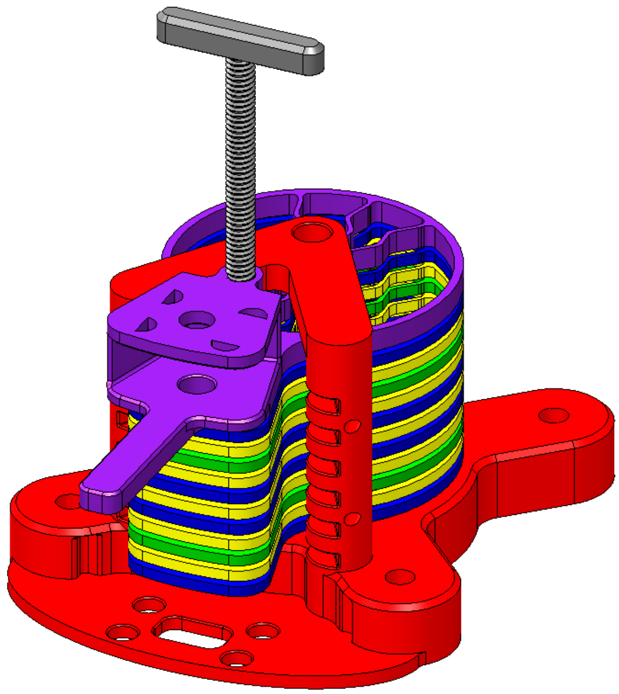

Figure 4: Diagram of Wedge Design

When the correct UQS is input to the device, each wedge has the open optical hole correctly aligned and the optical output would be able to pass through the wedges to a receiver on the bottom. If any signal is incorrect, the corresponding wedge blocks the optical signal from passing through it.

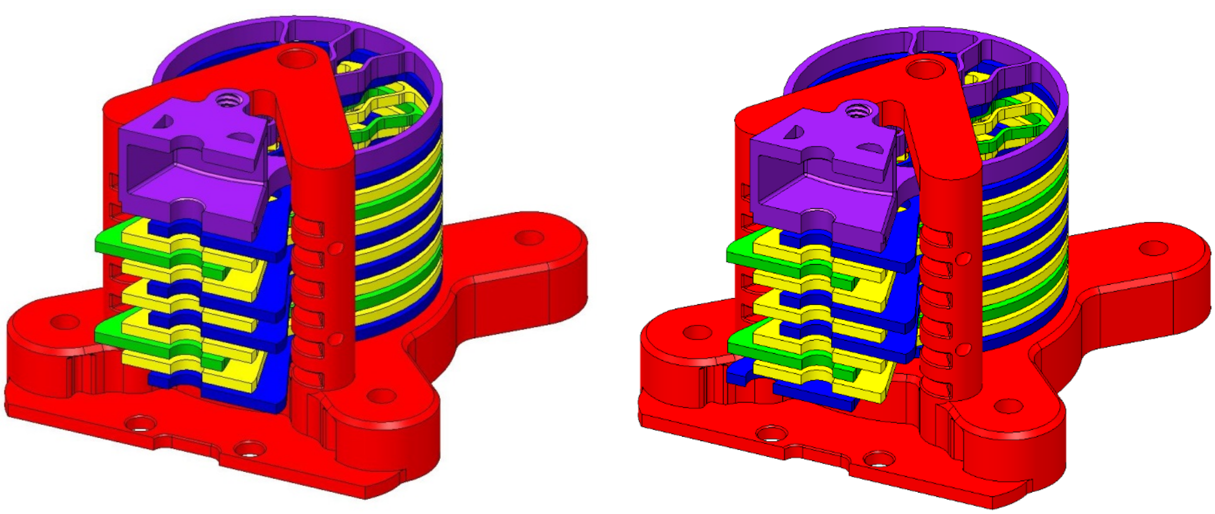

Figure 5: Depiction of optical path for Wedge design where (a) the correct UQS has been input and (b) an incorrect UQS has been input

In order to lock the wedges in place after an input and to prevent from retries, a threaded rod was created that passes through and physically locks each wedge regardless of the input. This threaded rod also allows the wedge to reset from either the enabled or incorrect positon simply by unscrewing the rod from the wedges.

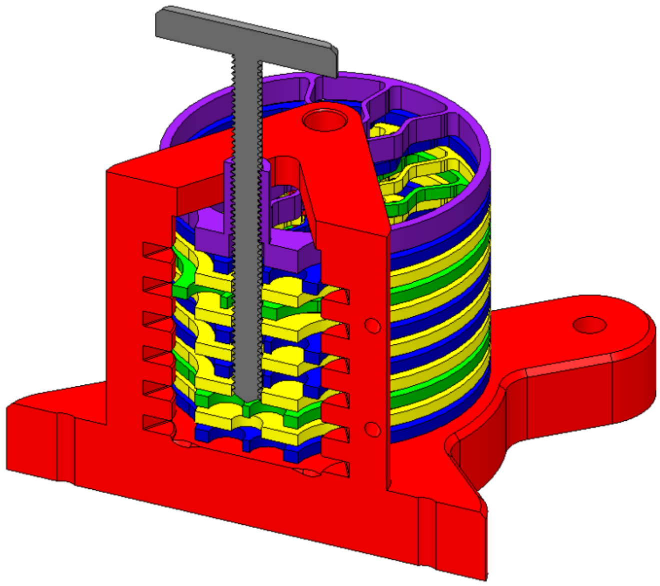

Figure 6: Section view of wedge with threaded rod. The threaded rod has passed through the holes in the top wedges and the last three wedges have yet to receive an input.

2.5. First Prototype – Analysis and Destructive Testing

We printed an initial prototype of this design at the 3D Print Lab at Sandia using the PolyJet process (Stratasys, Eden Prairie, MN) in order to get a visual of our design. We conducted destructive testing on this prototype and soon realized some areas for improvement in our design. For example, we realized that we had designed each wedge to rotate only 7 degrees. However, in order for the top wedge and locked lower wedges to rotate enough to lock the lower unlocked wedges, they would need to be able to rotate 14 degrees. We first checked that the printed compliance springs in the wedges would be able to withstand 14 degrees by removing the base columns and measuring the extent to which the wedges could be rotated before failure. The maximum rotation occurred at about 23 degrees which was more than enough for the design.

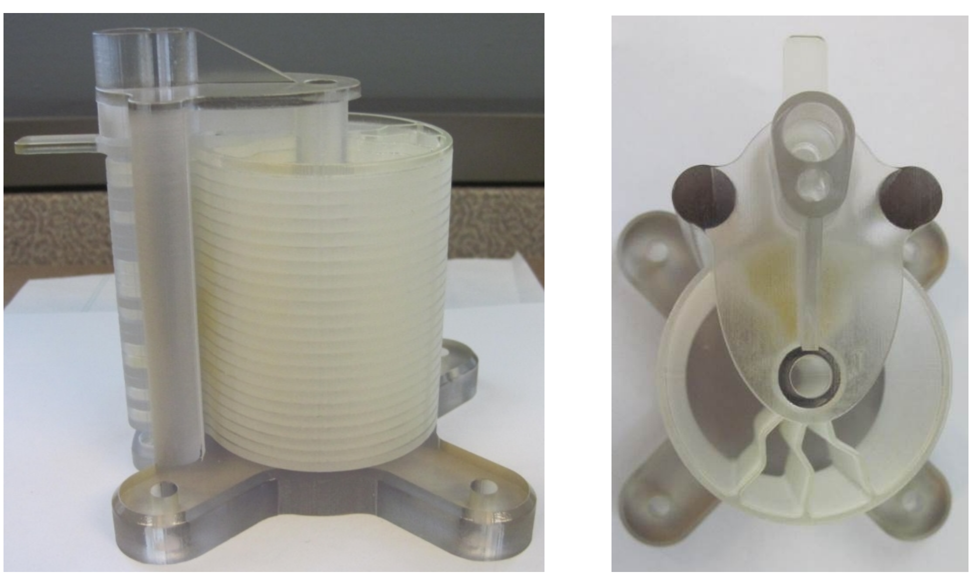

Figure 7: Pictures of First Prototype

Another design improvement we found was that depending on the set input for the wedges, the compliant springs could cause a fair amount of tension and make it difficult to rotate the top wedge. To address this, we added blank wedges between each event wedge to balance the forces on the top wedge and threaded rod. The blank wedges offered an additional benefit as they provided additional safety to prevent the threaded rod from passing through each wedge before the input for that wedge had been given.

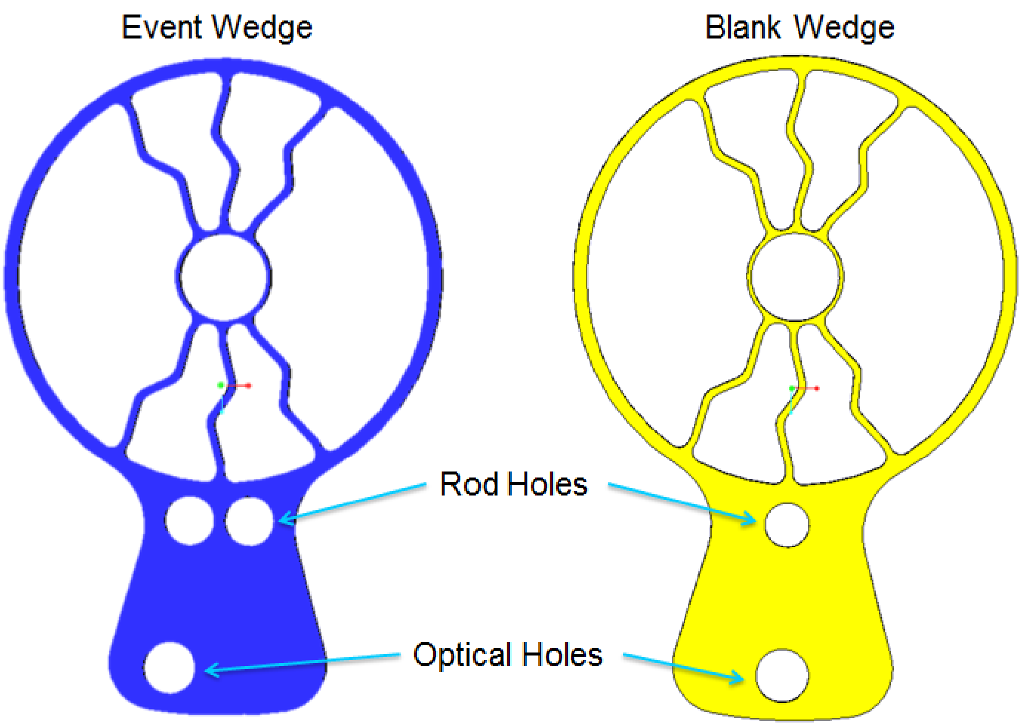

Figure 8: Depiction of (a) Event wedge and (b) Blank Wedge

3. REQUIREMENTS COMPLIANCE

While it was important to have the ability to think openly about design options, we also wanted to ensure that the chosen design complied with as many design requirements as possible. To be sure that our design met these requirements, we listed each given requirement and detailed how the design achieved these requirements. Below is a list of the specific requirements and how the Wedge design complies with each.

3.1. Ability to Discriminate and Unique Signal

One of the most important requirements for this project was that the discriminator be able to discriminate based on a unique signal, requiring an ability to differentiate between correct and incorrect inputs. The Wedge design meets this criterion in that each wedge accepts both an A and a B input, one of which will be incorrect when the other is correct. Also, the each wedge is independent from the others, guaranteeing that the input to one wedge has no effect on the other wedges.

3.2. Lock on Incorrect Signal

Aside from being able to discriminate a unique signal, the discriminator needed to lock upon receipt of an incorrect signal. The locking mechanism for the Wedge design consists of a threaded rod that rotates into a hole in each wedge after the signal input to that wedge had been received. Thus, the threaded rod locks each successive wedge to the handle and previous wedges regardless of the input. If the input signal is incorrect, the optical holes in the wedges will not align and an optical signal will be unable to pass through the device. The threaded rod also prevents against retries so once a signal has been input for a particular wedge, that wedge cannot be retried again until the discriminator is reset.

3.3. Enables on Correct Signal

In order for the Wedge design to enable on a correct signal, the optical holes in each wedge must align correctly so that an open path is formed through the wedges. After a complete signal is input and the wedges align and lock together in the correct position, an optical signal is able to pass through the device to a receiver placed below the last wedge.

3.4. Reset from Enabled and Locked Positions

The reset from the enabled and locked positions for the Wedge design is the same. The threaded rod simply rotates up and out of the wedges, allowing the compliant springs to bring the wedges back to their default position. Due to the design of the wedges and the threaded rod, the discriminator can be reset from any position in the device.

3.5. Use of Additive Manufacturing Capabilities

The main purpose for this project was to design a novel discriminator that would take advantage of additive manufacturing. Consequently, how well the new discriminator design uses additive manufacturing was highly important to our team. We wanted to ensure that design we finalized really pushed the boundaries of additive manufacturing. The Wedge design did this for us in multiple ways. For instance, the discriminator was designed to be built in two parts during one build. This design would have been impossible to manufacture in traditional methods with only two parts. Additionally, we were able to take advantage of the material properties available to us combined with the ability to incorporate unique internal structures to design the compliant springs within each wedge.

3.6. Design Uniqueness

To ensure that our design was novel, we contrasted it to previous discriminator designs to determine the similarities and differences. We quickly realized that our design differed quite dramatically from previous discriminators. These differences stemmed from our use of additive manufacturing. Instead of designing for two dimensions, we learned to design for three which enabled us to more easily contemplate a discriminator that moves in all three Cartesian coordinates. Most previous discriminator designs functioned in one plane, thus the Wedge design was quite unique.

3.7. Flexibility of Design – UQS

One of the attributes that drew us to this design was how simple it would be to adapt it to a new UQS. The correct input to the device depends on the pattern of wedges. The CAD model was designed so that reordering the wedges to create a different pattern would be very simple. Once the model is updated, we could simply send the new CAD file and within a few days a new fully functional devices would be ready for the next step.

3.8. Flexibility of Design – Functional Channels

Another flexibility of the Wedge design was its ability to add multiple functional channels. The Wedge discriminator was designed for one open optical path and a single threaded rod path, however, it could easily be modified for multiple optical paths so that a correct input would allow multiple channels to enable.

3.9. Scalability

An additional attribute of the Wedge design was that it was easily scalable in size, the number of wedges, and the number of input options. The device could be scaled smaller which would save on space, build time, and cost. Altering the number of wedges could alter the uniqueness of the UQS. Also, the wedges were currently designed for either an A or B input, but the wedges could easily be modified to include more options and offer greater uniqueness.

3.10. Reusability

We also wanted to ensure that the discriminator would be reusable. The Wedge device has no destructive components and the wedges can all reset to their default position, meaning that the Wedge device can be reused multiple times. We analyzed the wedges and determined that the compliant springs could be optimized to mitigate fatigue failure.

3.11. Percentage Produced Using Additive Manufacturing

The Wedge discriminator was designed to be made in two additively manufactured parts and is therefore 100% additively manufactured. We also planned on producing several parts using a variety of additive manufacturing processes such as PolyJet, SLS, and DMLS.

3.12. Cost Reduction Using AM and Predicted Reduction In Lead Time

Additive manufacturing offers reductions in both cost and predicted lead time due to the lack of necessary assembly. Only two parts are required for the Wedge design to function which dramatically reduced the amount of time used for assembly.

3.13. Number of Parts

As mentioned previously, the Wedge design consists of two parts. Traditional discriminator designs has 10s to 100s of parts that required delicate hand assembly and tight tolerances. This dramatic reduction in the number of required parts highlights one of the advantages of additive manufacturing.

3.14. Mechanical and Electrical Analyses

In addition to the above requirements, the new discriminator design was required to isolate shock and vibration as well as a voltage standoff of 500 VDC between the input and output. In order to determine if the Wedge design was capable of meeting these requirements, we conducted a variety of mechanical and electrical analyses.

3.14.1. Vibration Analysis

A simple closed form analysis was conducted to assess the wedge design in vibration environments. It is recommended that a more detailed analysis be performed, leveraging the structural dynamics computational tools at Sandia National Laboratories, before this design is considered for further applications

The vibration analysis was modeled as a sinusoidal force on a rigid and homogenous body using a spring-mass damper analogy. It was assumed that the kinematic boundary conditions included no bending moment, no shear force at the free end, and zero deflection at the base. The stiffness of each wedge was derived from Hooke’s Law. Figure 9 below shows the steady state amplitude response for the Wedge design.

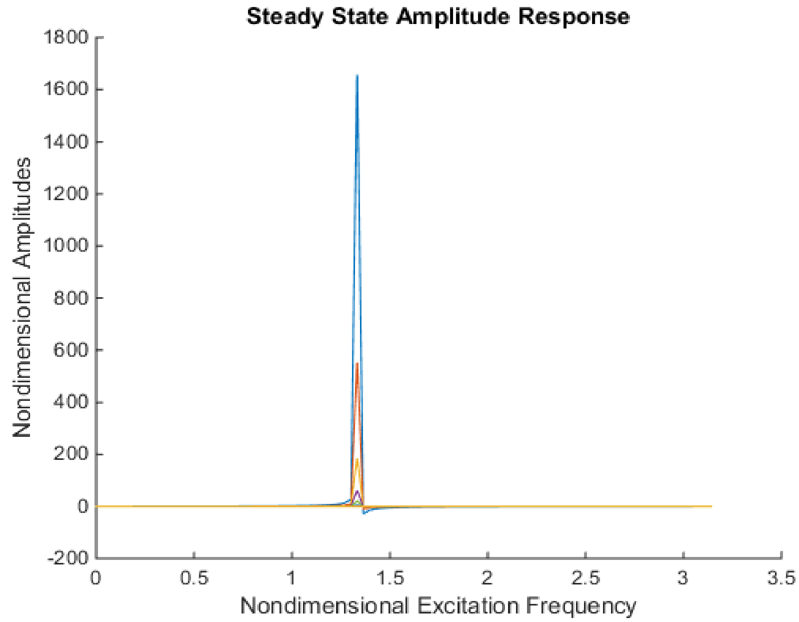

Figure 9: Steady State Amplitude Response

The amplitude response shown above indicates that there is one frequency at which the Wedge design would dramatically suffer. This result is quite desirable as the Wedge design and surrounding housing could be designed to mitigate this frequency and thus reduce the risk of the discriminator failing due to a random frequency input. The figure above shows the steady state response for the complete part while Figures 10 and 11 below depict the steady state responses for the top three individual wedges and last three individual wedges respectively.

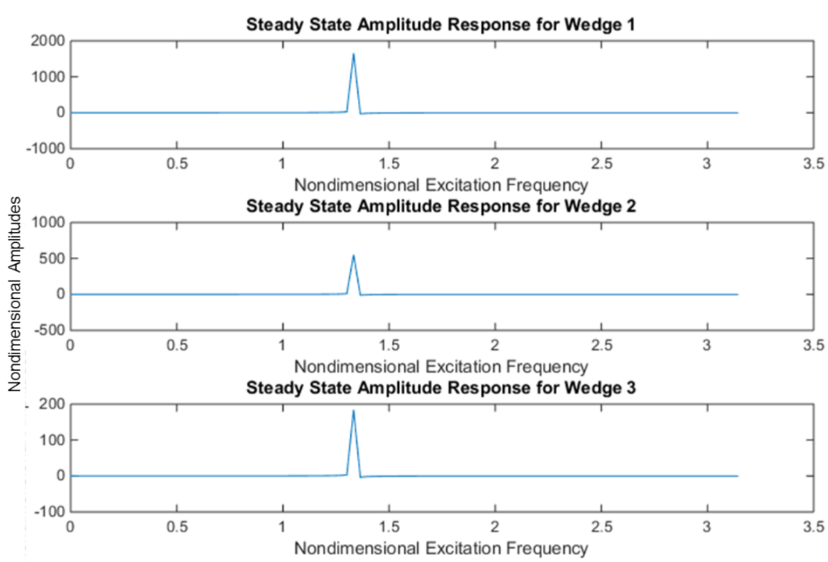

Figure 10: Steady State Amplitude Response for the Top Three Wedges

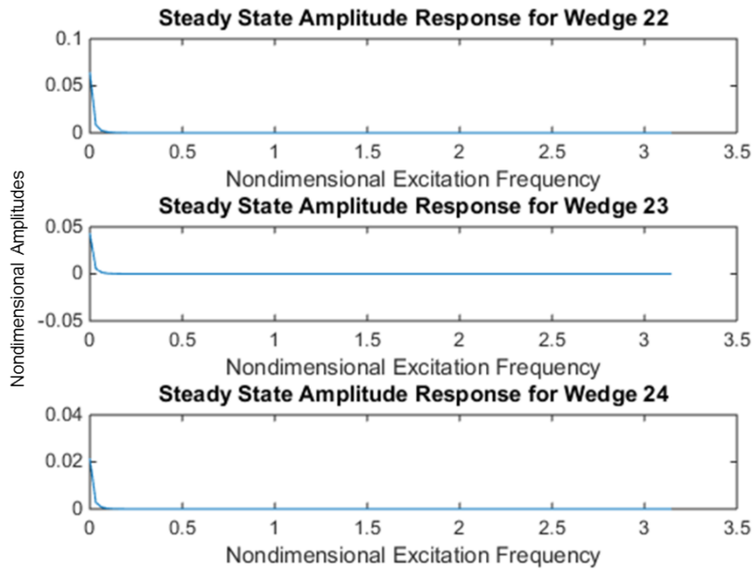

Figure 11: Stead State Amplitude Response for the Last Three Wedges

Figures 10 and 11 above show a much higher amplitude response to an input vibration from the top three wedges compared to the bottom three. This variation is most likely due to the fact that the bottom three wedges are furthest from the input vibration and closest to the stable base . The top three wedges were closest to the input vibration and furthest from the stabilizing base.

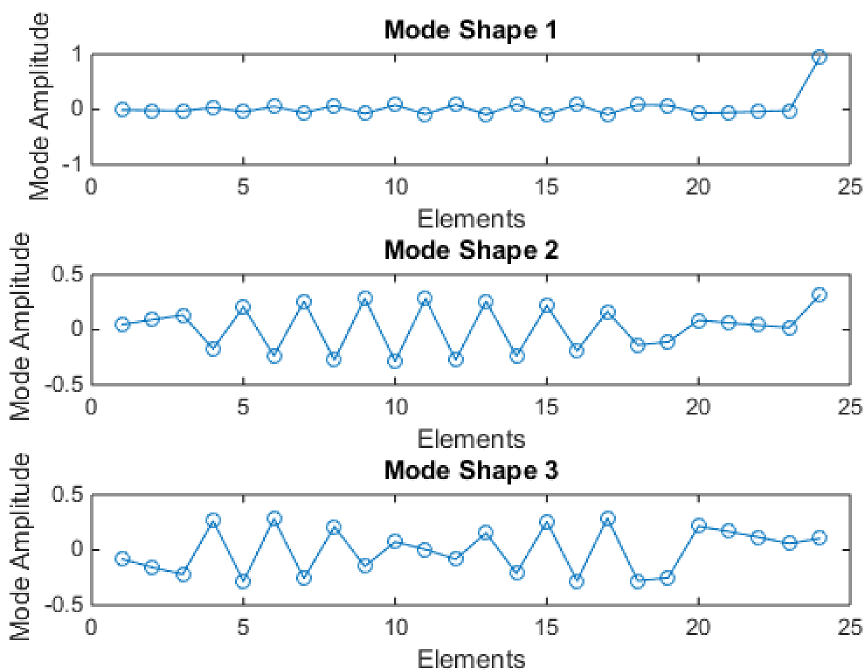

Figure 12: Modal Response of Top Three Wedges

We also found the modal response of the top three wedges as shown in Figure 12 above.

3.14.2. Static Analysis

Derived from the requirement “The device must isolate charge through vibration and shock environments “ we assumed the device must be able to tolerate a 1000g static load. We ran analyses on the base to discover the Von-Mises stress and total deformation of the base. We found the Von-Mises stress to be approximately 62 kPa with a total deformation of 8.5e-6 mm. Model images are shown in Figures 13 and 14 below. It is recommended that further analysis be performed on the individual wedges, although a failure in the wedges does not necessarily imply a failure of the device. Reliably failing is a safe condition when exposed to an abnormal mechanical environment is acceptable.

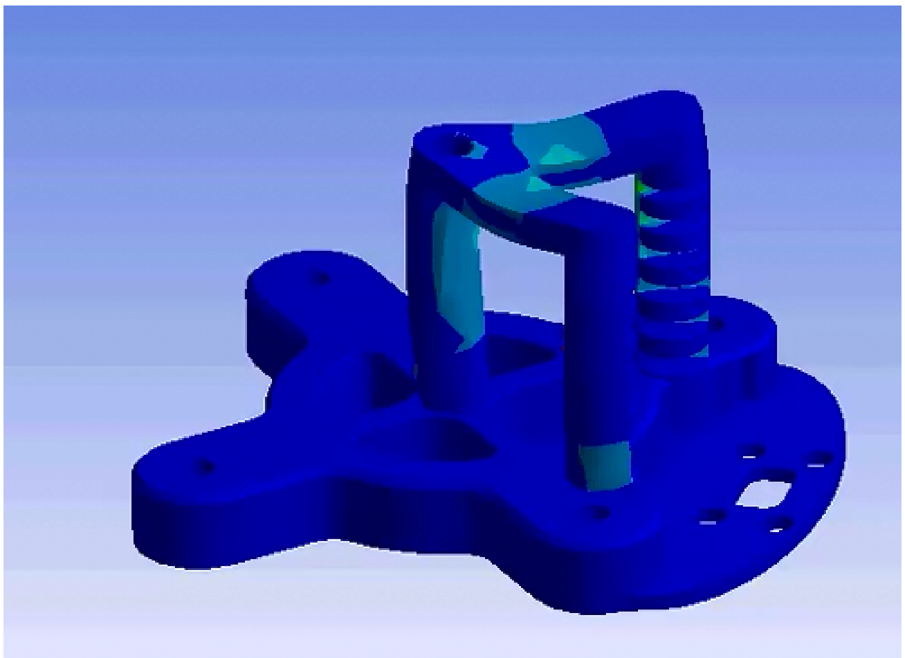

Figure 13: Von-Mises Stress of the Base

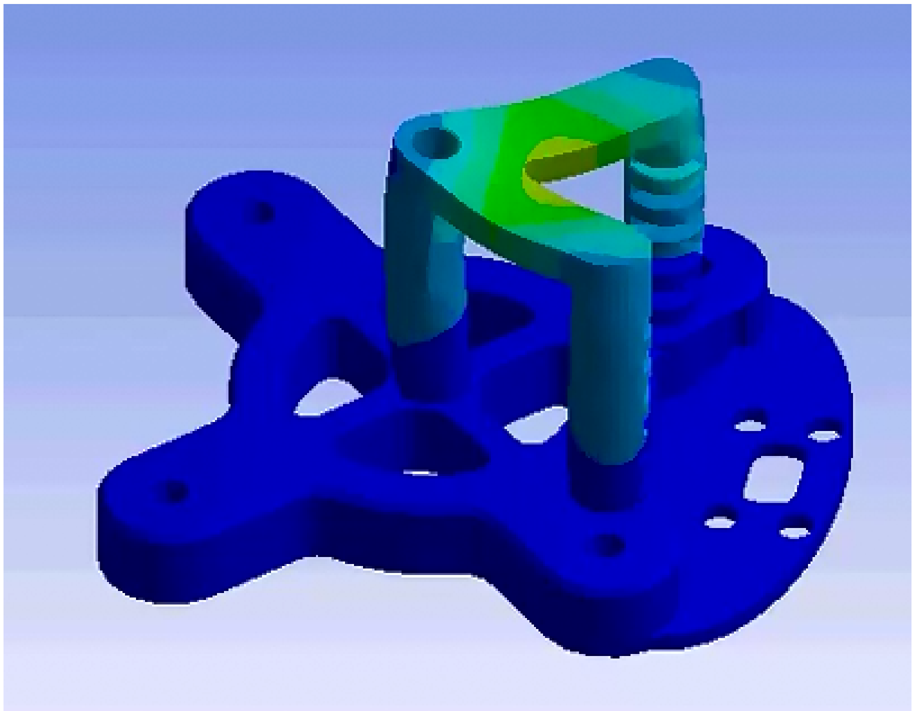
Figure 14: Total Deformation of the Base

Based on the information from these analyses, we concluded that with additional time we could redesign the discriminator to be more resilient to vibration and shock.

3.14.3. Voltage Analysis

Additionally, we wanted to examine how the Wedge design would react to 500 VDC. Each wedge was modeled as a resistor while the air gaps between the wedges were modeled as capacitors. The base was modeled as a single resistor. It is recognized that this is a simplified electrical analysis and that the boundary conditions for this analysis would impose design constraints on the discriminator. One constraint being hat the supporting rods must be constructed from a non-conductive material otherwise the current would pass through them. Figure 15 below shows the current profile for the Wedge design with a constant voltage of 500 VDC applied.

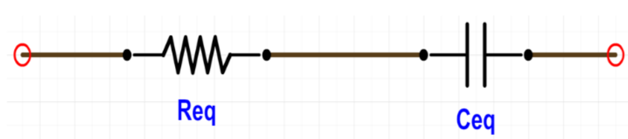

Figure 15: Resistor and Capacitor Analog

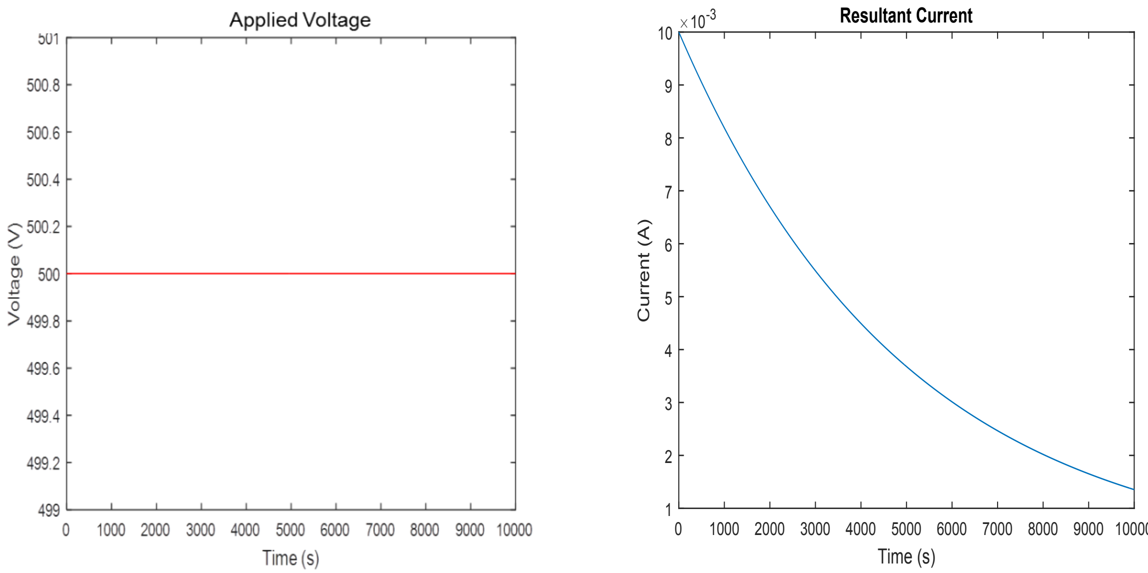

Figure 16: Voltage Response - Applied Voltage and Resultant Current

Further exploration into the electrical characteristics of this system and the resultant design implications are recommended.

4. ADDITIVELY MANUFACTURED BUILT PARTS

Once the Wedge design was completed, we sent the design to be printed at the 3D Print Lab at SNL and at NSC. SNL printed a part using PolyJet while NSC built two parts using Selective Laser Sintering (SLS), one stainless steel part in Direct Metal Laser Sintering (DMLS), and had two additional parts built using SLS at a third party supplier.

4.1. SLS Built Parts – NSC

The SLS parts built at NSC were very close to the CAD model and were functional. There were no areas of oversintering and the tolerances, as measured by CT scan and shown in Section 5.2, were quite good. The only drawback to this print was the material properties of the threaded rod. It was noticed after fabrication that the rod was fairly flexible which caused concern about proper operation because of the likely deformation in the part induced by the operation loads.

4.2. SLS Built Parts – Third Party Supplier

Two additional SLS parts were built at a third party supplier. While these parts did function, they were not as well built as the ones from NSC. The reasons for this are mostly likely related to the laser speed and laser power used in fabrication. Increasing laser speed can increase the speed at which a part gets built and reduces the build time and the cost; however, it can have some negative effects on the part. A specific amount of laser energy must reach the correct depth in the powder to sinter the new layer of powder to the previously sintered layer. If the laser speed is increased, less of the laser energy is transmitted to the powder. To address this, the laser energy is increased. However increasing laser energy also increases the risk of burning the surrounding powder (overburn), and sintering unnecessary surrounding powder (oversintering).

Both of these issues are visible in the SLS built parts from the third party supplier. It is apparent from the front of the wedges that they overburned and it was necessary to EDM them in order to fix the wedges to the correct shape. Additionally, inspection of the holes in the built parts showed that the NSC built part has crisp edges while the third party supplier part has rounded, deformed edges. The combination of high speed, high laser power, and small hole size meant extraneous powder was sintered to the third party supplied part.

4.3. PolyJet Printed Parts - SNL

Two PolyJet parts were printed for us at SNL, one as an initial prototype and another as a final part. This first prototype, mentioned above in section 2.5, was extremely useful in visualizing the model and determining what changes should be made. With the fist model we were able to conduct destructive tests to determine the range of rotation for the wedges, which was invaluable to our final design. The final part was also particularly useful as it allowed us to have a part where the wedges and threaded rod had been placed as if a correct UQS had been input. The quality of these two parts was comparable to the SLS parts built at NSC.

4.4. DMLS Built Parts - NSC

Even though we chose not to design for DMLS due to its limitations, we still wanted to build a version of the discriminator in DMLS to gain an understanding of the processes and learn how the model would need to be modified for a successful DMLS build. NSC built us a stainless steel part using DMLS and while this part was not functional, it did provide some great insight as to how the design could be altered to accommodate DMLS. One of the issues seen in this built part was overburn at the wedge handles and at the intersection of the wedges and their compliant springs. This overburn was most likely due to a combination of the geometry which was ill-suited for supports, and the laser power which may have burned the surrounding powder. Additionally, it was necessary to EDM some areas of this part in order for it to be close to functional. While this is typical of DMLS parts, it was still difficult to EDM certain sections of the part, specifically behind the base columns. The model would need to be redesigned in the future to avoid several of these issues.

5. ADDITIONAL TECHNOLOGIES

When we visited Kansas City, we were shown many of the other areas relevant to additive manufacturing. We primarily focused on topology optimization, CT scanning, and optical scanning. Topology optimization is a tool which alters the shape of a design in order to optimize set objectives, such as strength. The CT scanner can scan through layers of a part and compare the part with the CAD file to determine variation. Also, the CT scanner can be used to determine the state (reset or enabled) of the discriminator. We also considered the optical scanner which can create an STL file from a scanned object and could be a useful alternative for designing objects that are challenging to design in current CAD programs.

5.1. Topology Optimization

One of the additional technologies we used was topology optimization. Topology optimization optimizes the shape of a design in order to maximize or minimize a desired constraint while keeping other constraints constant. Since the final shape output by topology optimization is often unusual and difficult to manufacture with traditional techniques, this technology has the potential to work well with additive manufacturing.

While topology optimization has been successfully used to optimize other designs, there were some difficulties in applying it to the Wedge design. To optimize for compliance, the optimization software had to maximize the amount of allowable strain energy in the wedge. The first method to achieve this optimization was to set the prescribed rotation of each wedge and maximize the strain energy. However, the program was unable to converge on an answer. A possible reason for this lack of convergence is that traditional designs might not include parts that have sections meant to be compliant. Typically, the strength of a part is optimized rather than the compliance or flexibility. This difficulty was also seen in CAD programs that could not readily model compliant parts.

A second approach was to apply a constant moment and maximize the strain energy. While this optimization could give an understanding of the potential optimization for the wedges, it is not the ideal approach to optimizing the wedges. The moment on the wedges would vary depending on the shape and structure and therefore the set constant moment would not necessarily be correct. Even though the constant moment approach is not exact, it did converge and Figure 12 below highlights how topology optimization might be applied to this design.

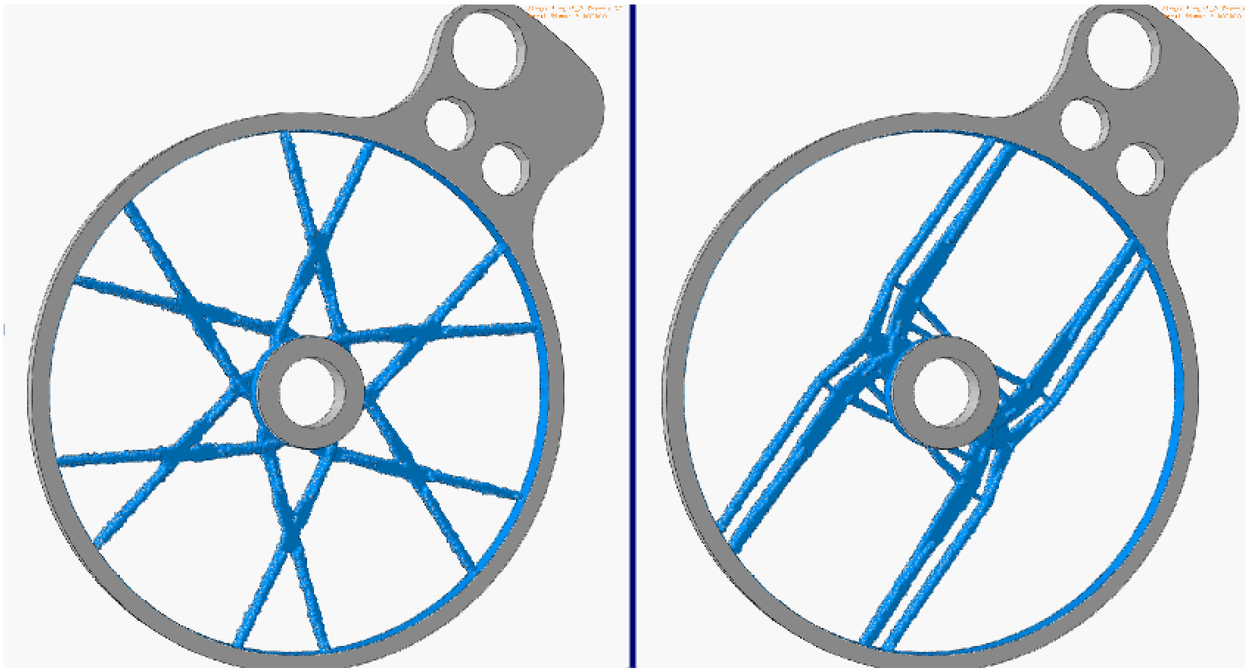

Figure 17: Topology Optimization for Wedge Design with (a) constant rotational symmetry constraint and (b) constant planar symmetry constraint

While the topology optimization struggled to converge for this design, it still showed great potential for optimizing designs in the future. The inability to converge for prescribed motion shows an area where topology optimization can be improved for future use.

5.2. CT Scanner

An additional technology used at NSC was the CT scanner. CT scanners have previously been used to inspect the state of discriminators to ensure they were in the reset position and to determine the variation between the built part and the CAD model. Since additive manufacturing still faces challenges with tolerances, CT scanners could be incredibly helpful in identifying design attributes that are challenging for additive manufacturing processes to build.

Example output images from the CT scanner are shown in Figure 17 below. Our part had relatively few variations between the CAD model and the as-built part. Most of the variations came from either the bottom of the part or the threaded rod and optical holes. These variations are consistent with typical issues in additively manufactured parts due to the nature of the additive process. The scanned part was built using SLS which can have tolerance issues with the base due to the machine attachment site. Additionally, the threaded rod holes and optical holes in the wedges were relatively small and may have picked up surrounding powder, sintering it to the part and causing the variation in part dimensions.

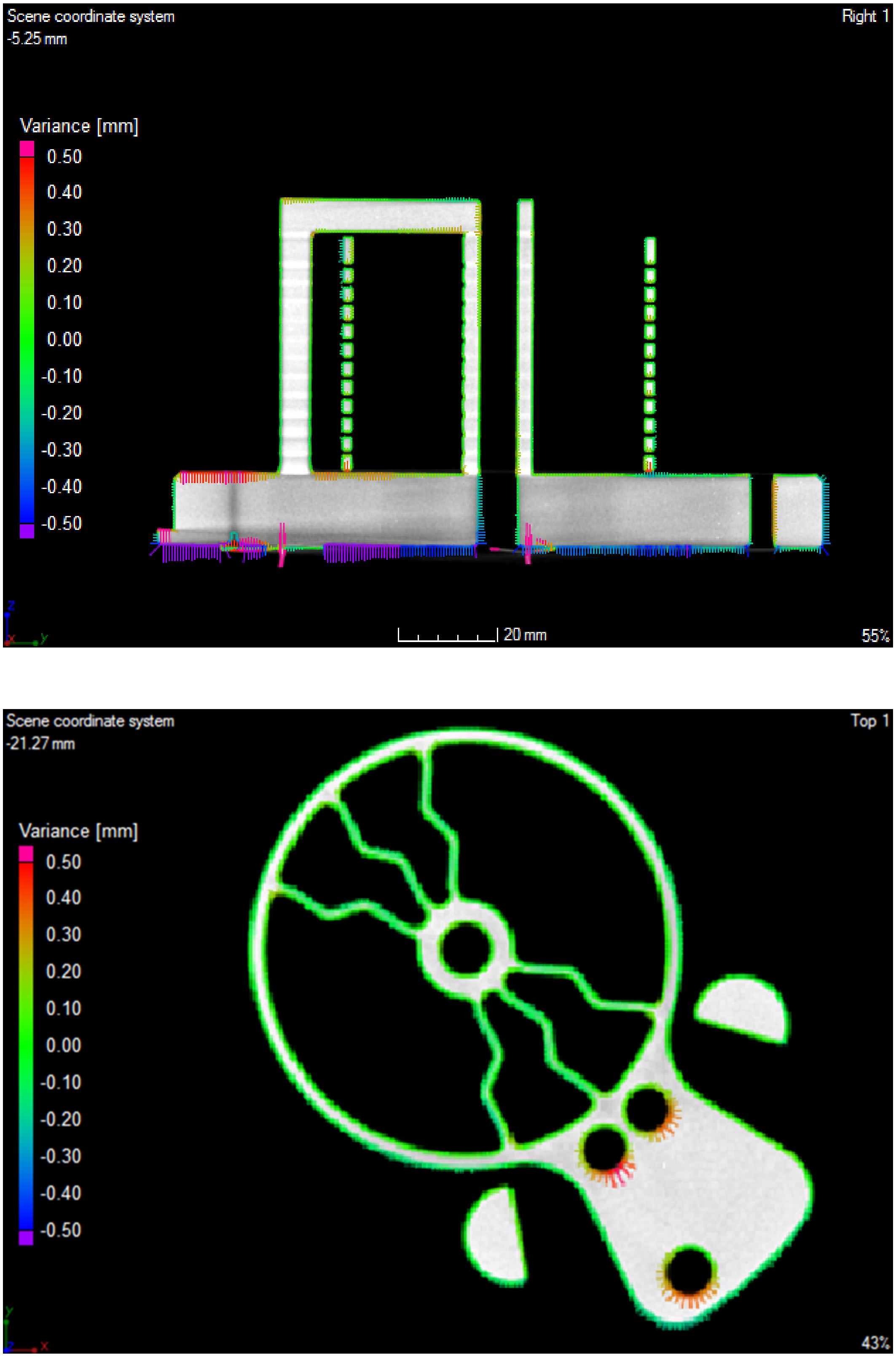

Figure 18: CT Scan Cross Sections of the NSC SLS built part

The issue of these variations could be circumvented by creating benchmark parts to determine the typical variation in a build. While there has been some work done on creating these benchmark parts, they are not universal. The variations in different machines and even different build settings can all cause changes in the benchmark part and make it difficult to determine the appropriate course of action.

CT scanning has the potential to be an inspection method for additively manufactured parts. Presently, the resolution is not adequate for very high tolerance applications (< 0.005 in.) but it is suitable for standard part tolerances. In addition to comparing the as-built geometry to the CAD model, CT scanning allows for the interrogation of internal voids and defects in the part. Challenges facing the adoption of this inspection technique are the capital equipment cost and the time to process.

5.3. Optical Scanner

An additional avenue we considered was using an optical scanner on a part in order to create an STL file that could then be additively printed. The main advantage of this technology is that it can create input CAD files based on hand-made parts without reliance on traditional CAD programs. Since one of the main limitations to the Knot design was the difficulty in creating CAD models for these organic shapes, creating a clay model of the design and scanning it to generate the STL file is a potentially useful workaround.

6. ROADMAP

6.1. Additive Manufacturing Roadmap

Additive manufacturing is an incredible new technology and offers many design avenues that were previously unavailable. However, because this technology is so new, its user community is still working on solving issues that have arisen. Below are some areas in which additive manufacturing could be improved that are specifically relevant to this project.

6.1.1. CAD

One of the difficulties in designing for additive manufacturing is that current CAD programs are optimized for traditional manufacturing, without additive manufacturing in mind. This limits the design potential of projects as the CAD programs work in Cartesian coordinates while additive manufacturing has no such restrictions on its abilities. Since current CAD programs are based on these Cartesian coordinates and traditional manufacturing, it is also difficult to model complex geometries. Additive manufacturing may allow for “free complexity”, but until the CAD programs also allow this functionality, complex geometries will still be difficult to model.

The discrepancy between CAD programs and the capability of additive manufacturing also affects the files of parts sent to be manufactured. Traditionally, two dimensional drawing are constructed which are then used as an aid in manufacturing parts. Additive manufacturing, however, opens the realm of designs to models that might not easily be dimensioned in two dimensions. Fortunately, steps are already being made to overcome this limitation. Instead of two-dimensional drawings, three-dimensional models with dimensions are now being used to dimension parts for manufacture.

Another important aspect to consider when converting between traditional manufacturing and additive manufacturing is that drawings sent for traditional manufacturing offer straight forward GD&T while the STL files sent for additive manufacturing lack this information. In order to accurately inspect additively manufactured parts, it will be necessary to create a method of maintaining GD&T for these processes. NSC is currently working this topic.

6.1.2. Direct Metal Laser Sintering (DMLS) Limitations

One of the goals of this project was to design a device to be built in metal using additive manufacturing but we quickly realized that the limitations posed by DMLS would restrict our design space so we instead chose to design for SLS. Some of the reasons we chose not to design for DMLS were the limitations of small overhangs, the chance of overburn, the time consuming need for post-process machining, and the need for support material.

6.1.2.1. Support material

Unlike in SLS, the support of the powder bed alone is not enough to support the built part. Thus, supports are required to be built into a part and removed after the build is complete. This need for support material limits the ability to take advantage of complexity as the design must be created to allow for post-machining access.

6.1.2.2. Post-process machining

DMLS parts also generally require post-process machining to improve surface finish in addition to support material removal. Because these post-processing machines are necessary, the advantage of complexity that additive offers is reduce since the requirement that post-process machines must have access to these areas is now added. Since these additive parts must be designed to allow for post-processing and since the required tolerances can only be achieved through machining, the advantages for additive are reduced for DMLS.

6.1.2.3. Overhangs

Since the powder bed cannot fully support the part in DMLS, if a part extends too far beyond an edge, it requires supports for these overhangs. Some other additive processes, such as FDM, require supports for overhangs but even in FDM the distance an overhang may extend before support material is required is much larger than that for DMLS.

6.1.2.4. Overburn

Another issue when building parts is the potential for overburn which occurs when excess laser energy is used and the powder sinters then burns. Overburn can occur for several reasons, including excess laser power, slow laser speed, and high build temperature. Further optimization in build settings would reduce the risk of overburn.

6.1.3. Part Tolerance

Another limitation of current additive manufacturing techniques is the inability to achieve tight tolerances. Often, additively manufactured parts require post-process machining in order to reach tolerances comparable to those achievable in traditional manufacturing. Tolerance is limited in additive processes by the layer thickness and laser spot size. Altering the layer thickness and laser spot size also alters the build time which impacts the cost.

6.1.4. Build Variability

The variability between builds in different machines or even different builds in the same machine needs to be minimized. Unlike traditional manufacturing, the kinks of manufacturing used additive have not been worked out and there are still some unacceptable variations between builds. This makes it difficult to predict the properties of additively manufactured parts. Often, dogbone specimens are placed in strategic orientations within a build in order to test and ensure the build quality. This variation in part quality needs to be minimized before additive manufacturing can be used for final parts.

6.1.5. Design Guideline

Design Guidelines are currently being constructed within the NNSA, and also in industry, to combat the issue of build variability. These design guidelines are currently in development, but may take several iterations before they are completely adopted by the additive manufacturing community. The variation seen between different machines for the same process or different builds within the same machine makes it difficult to apply one standard design guideline for all machines (Wohlers). It will take further investigation in the output of these machines in order to determine the correct guidelines for specific processes.

6.1.6. Material Selection

While the array of materials available for use in additive manufacturing has increased, additional options are needed. Of particular interest is the ability to use magnetic materials. An increase in the range of materials would expand additive manufacturing's utility in future projects.

6.1.7. Powder Reusability

For this project, we decided to focus on building parts in SLS since it offered fewer limitations than DMLS but SLS still has areas for improvement. For instance, plastic powder is not nearly as recyclable as metal powders. While metal powders used in DMLS can be reused many times, plastic powders can typically be reused only 2-3 times before the particle diameter becomes too large. Additionally, most builds need at least 50% virgin powder for proper sintering and desired material properties. Parts that are highly material dependent might require 100% virgin powder in the build.

6.2. Additional Technology Roadmap

In addition to additive manufacturing processes, we also worked with several additional technologies. From this interaction, we were able to discern how these additional technologies might progress for future design work.

6.2.1. Topology Optimization

As mentioned previously, the topology optimization users struggled to optimize for compliance. In order to allow for future compliant designs, it would be beneficial for the software users to further explore this space, and if there is a short coming in the software, identify and resolve it. It is unusual to design for compliance in traditional manufacturing and it may be new territory for topology optimization. Further work on understanding the capabilities of topology optimization in this area could enhance its use and further benefit additive manufacturing.

6.2.2. Optical Scanner

While the optical scanner could be quite useful in advancing the Knot design, it did have some limitations. Specifically, the optical scanner has difficulty with deep holes and inclusions. The inability to detect these features limits the features that optical scanners can detect and is an area that should be improved to broaden its applicability for additive manufacturing designs.

7. CONCLUSIONS

There were several lessons learned from this project. We reviewed the areas where additive provides an advantage and how additive could be improved. We also learned that adding uniqueness such as multiple solenoids in the Knot design led to an addition in complexity, especially for the locking mechanism. Also, we realized the importance of reviewing the initial design requirements not just at the beginning of the project, but also at a check point during the execution to ensure we stayed on task. We also realized that continued development of materials and part validation techniques is required and that collaborating with others, specifically NSC, was vital to our design success.

7.1. Future Work

Future work for this project would have several areas of focus: the Knot design, Wedge design, additive processes, and leveraging peripheral technologies. We would further the Knot design by creating a clay model of several parts and using the optical scanner at NSC to create an STL file for each part. We would then print these parts in SLS. We would also further the Wedge design by incorporating some of the additional design concepts generated during our meeting with NSC and build these designs to determine which structure best matches the given requirements. We would also continue higher fidelity mechanical and electrical analyses for both the Knot and Wedge designs. Also, we would make modifications to these designs in order to print functional parts using DMLS. As far as peripheral technologies, we would continue work on the topology optimization to determine the best method for optimizing the compliance and we would CT scan additional parts to determine the additive processes that build parts most similar to the CAD model.

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