Solid Propellant Additive Manufacturing

Printing Solid Rocket Motors

Cameron Brown, Erick Chewakin, Max Feldman, Tony Lima
Nick Lindholm, Caleb Lipscomb, Ryan Niedzinski, & Jon Sobol

Agenda

Purpose & Background

Design

- **CONOPs**
- **Laser**
- **Powder Bed**

Applying SLS

Results

Summary

Project Overview

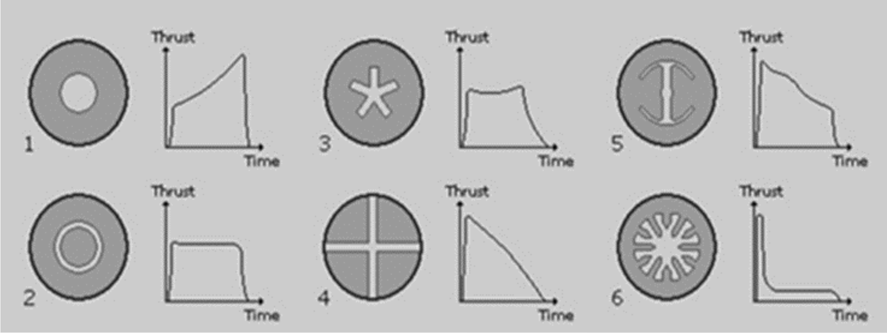
Purpose & Background

Project Statement

Design and integrate an additive manufacturing system such that it will print sucrose-potassium nitrate solid rocket propellant and compare the mechanical characteristics of the printed propellants to those manufactured by the traditional casting method.

Background
Solid Rocket Motors

- Cylinders of solid rocket propellant (fuel + oxidizer) with different cross sectional grain shapes
- Grain shape determines thrust profile through available surface area to burn
- Normally made by casting
  - Propellant cures in a cylindrical tube
  - Desired grain shape is bored through the middle



Example Grain Shapes and Thrust Profiles[1]

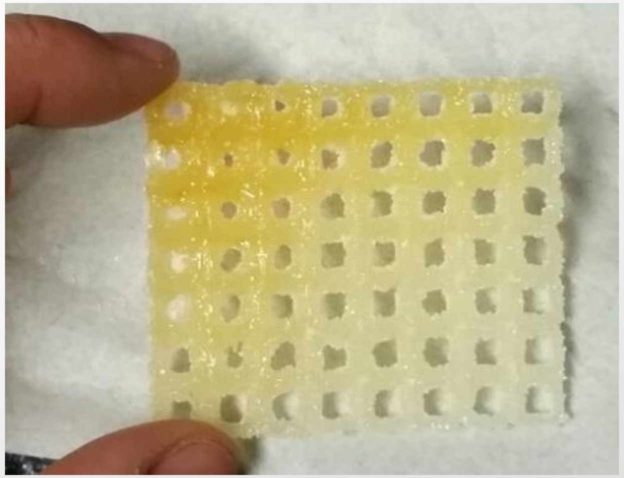

Cast Solid Rocket Motor

Additive Manufacturing

- 3D printing by stacking multiple thin layers into a desired shape or design
- Types of additive manufacturing include:
    - Fused deposition modeling
    - Stereolithography
    - Selective Laser Sintering
- Benefits include: greater flexibility of designs, higher degree of automation, and greater accuracy

Casting vs. Additive Manufacturing

- Traditional Casting Limitations:
  - Limited number of grain shapes
  - Air bubbles in cast
  - Nonuniform setting
- 3D printing can improve the traditional casting method:
  - Produce complex grain shapes and new thrust profiles
  - Does not need to manufacture a different cast for each design



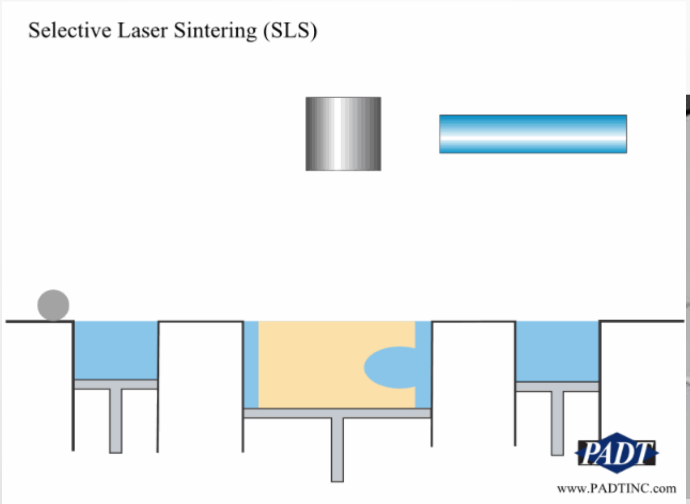
Example complex shapes produced from 3D printing

What is Selective Laser Sintering?

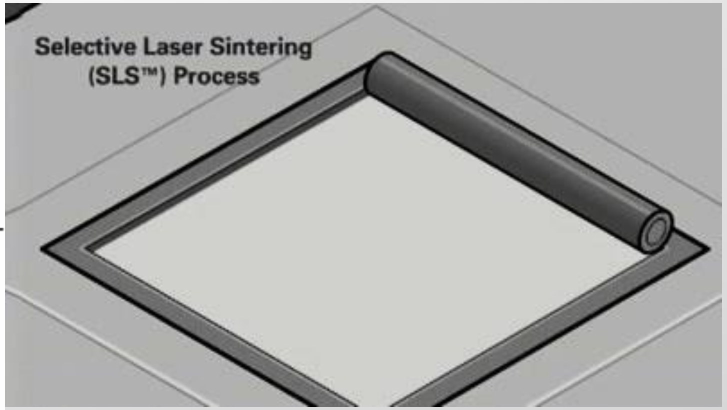
Selective Laser Sintering (SLS): a type of Additive Manufacturing which sinters/melts powder with a laser

Operation:

1. A CAD file is uploaded to the printer
2. CO_2 laser heats a specified area of the powdered material
3. Heated material binds together forming a solid
4. Powder bed is then lowered by one layer thickness
5. New layer of powder is then swept on top of the previously fused layer



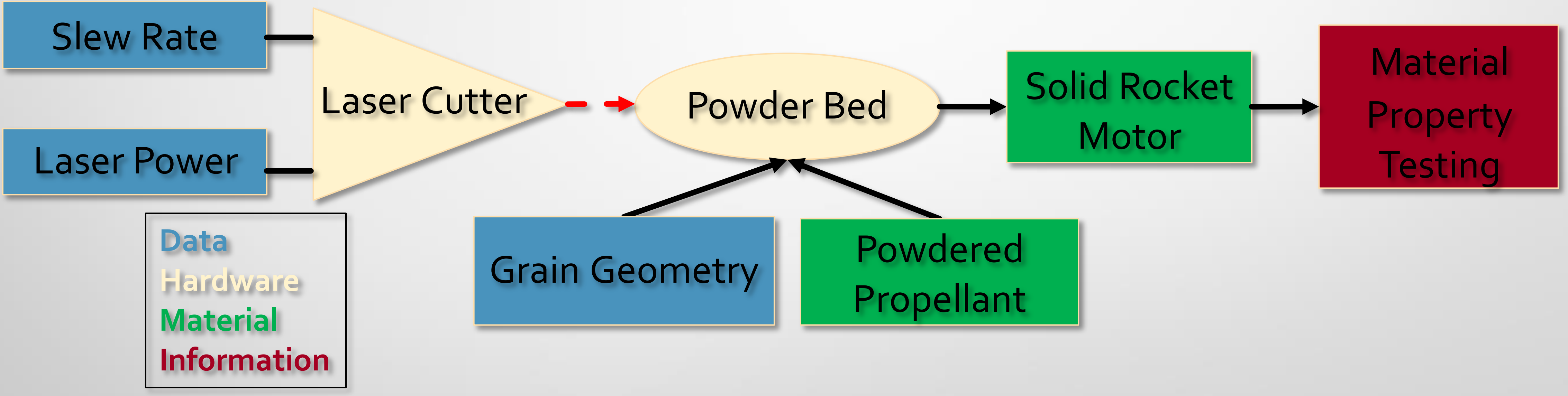
SLS Process (Profile View)[4]



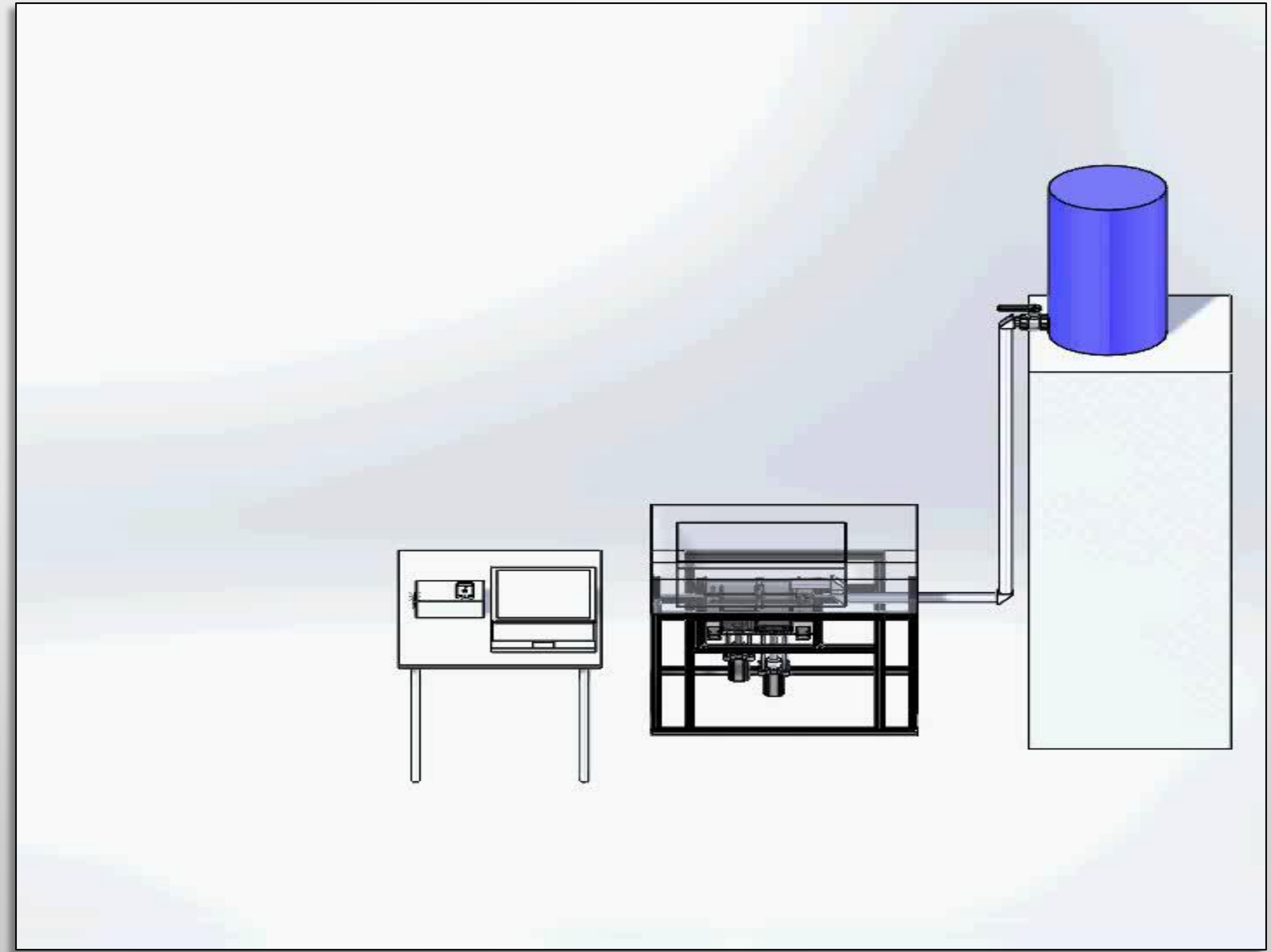
SLS Process (Top View)[5]

Project Concept of Operations

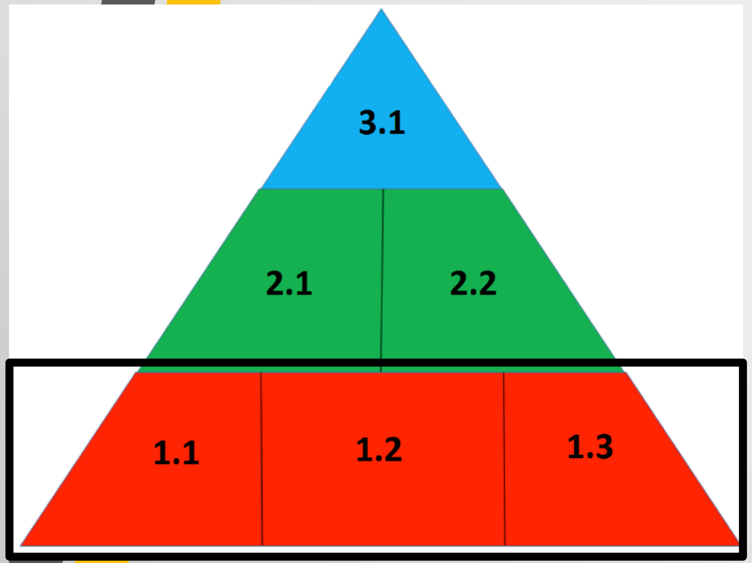
Sinter multiple layers of Sucrose/KNO_3 powder using SLS



Concept of Operations

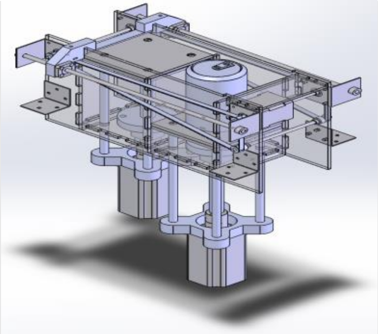
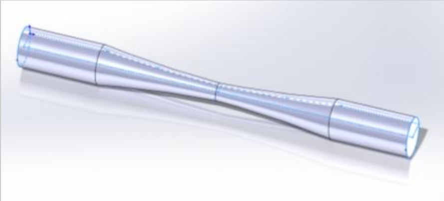


Levels of Success



Level	Description	Status
1.1	Design 3D Printing System for Sucrose-KNO_3	Achieved
1.2	Characterize a Thermal Model for Propellant	Achieved
1.3	Use Analogous Method to form Solid Propellant	Achieved
2.1	Compare Material Properties (Casted vs Printed)	Not Achieved
2.2	Print a Solid Rocket Motor Cylinder	Achieved
3.1	Manufacture 5 Different Grain Shapes	Not Achieved

Critical Project Elements

CPE	Description
Laser Sintering Sucrose and KNO_3	 • Verify Thermal Model and Laser Energy Control
Powder Bed	 • Component Integration and Tolerance Verification • Full Powder Bed Cycle Test
Material Property Testing	 • Validate Material Properties Between Casted and Printed Motors

Design

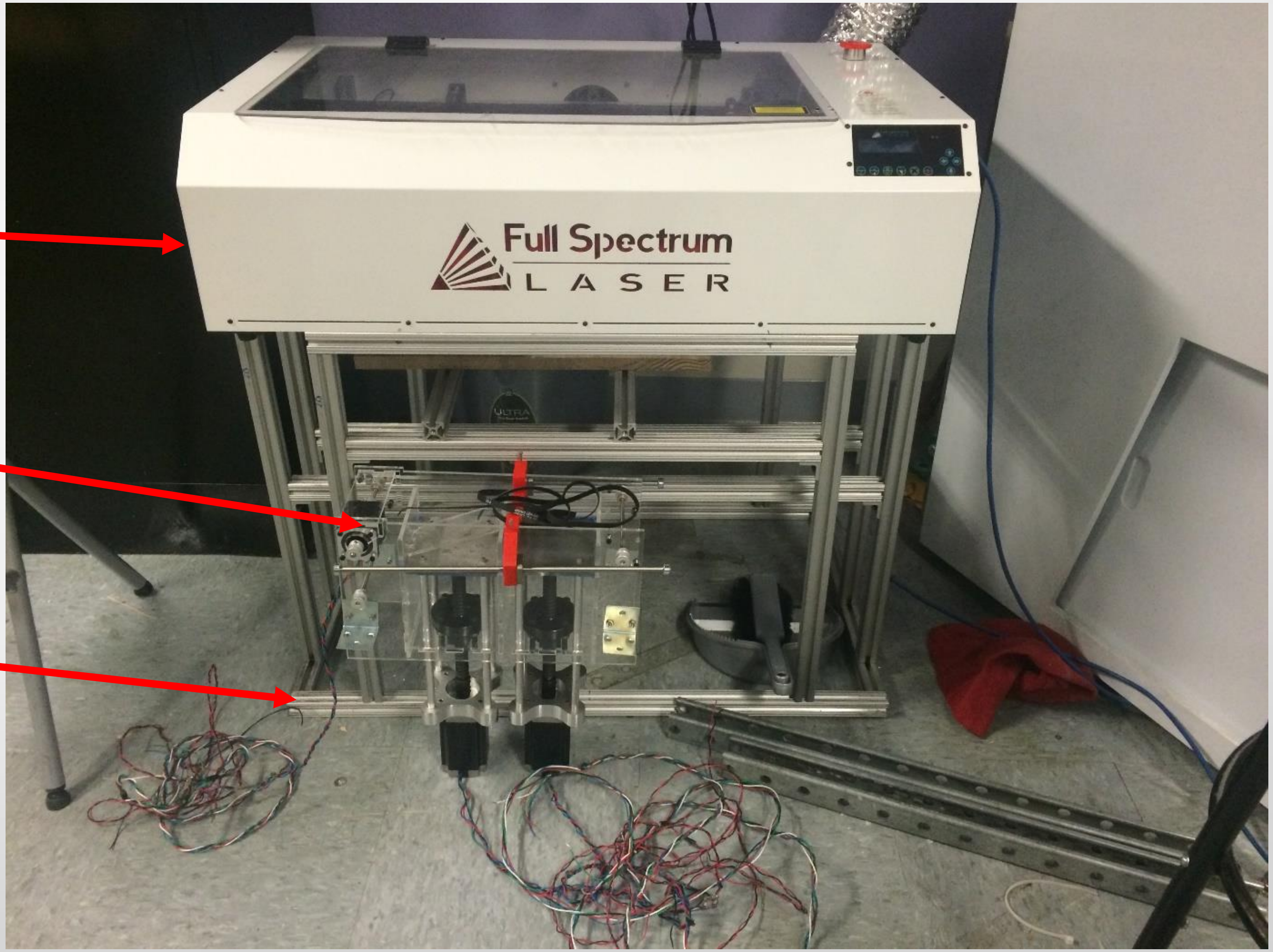
Components and their functions

Components

Laser cutter

Powder bed system

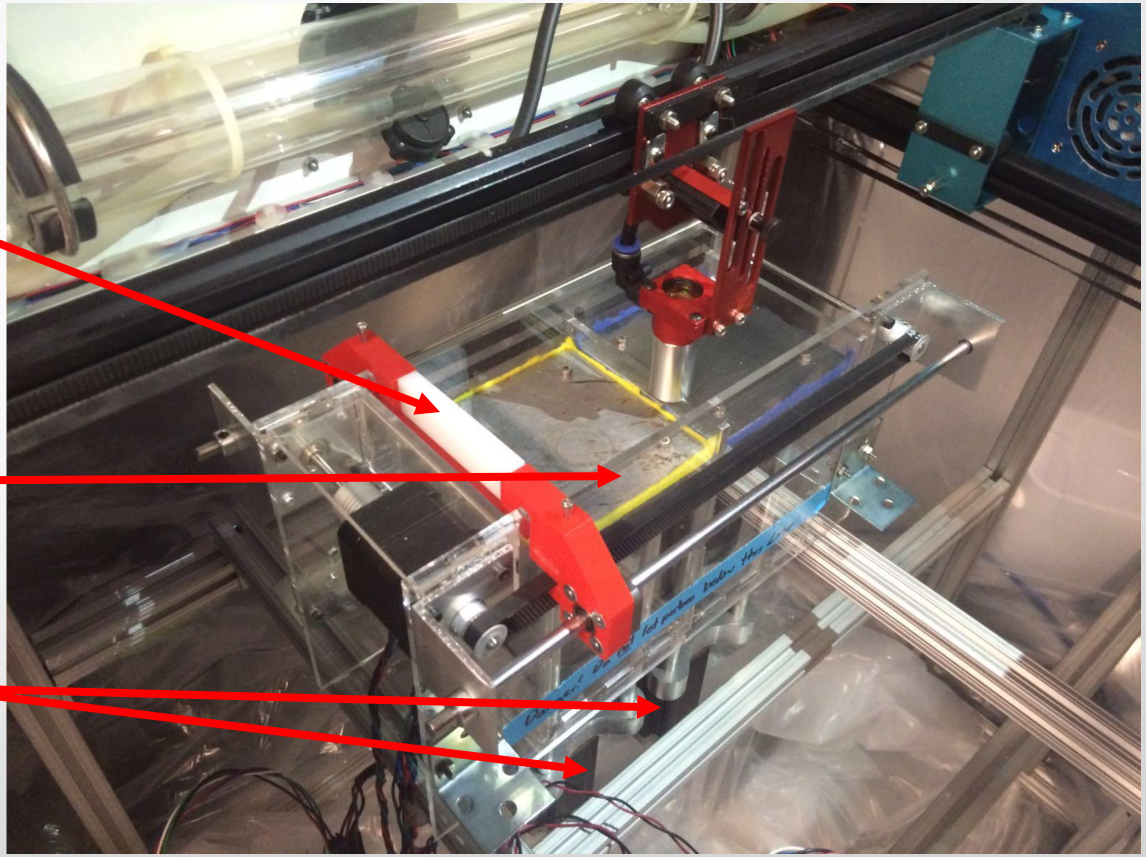
Aluminum frame



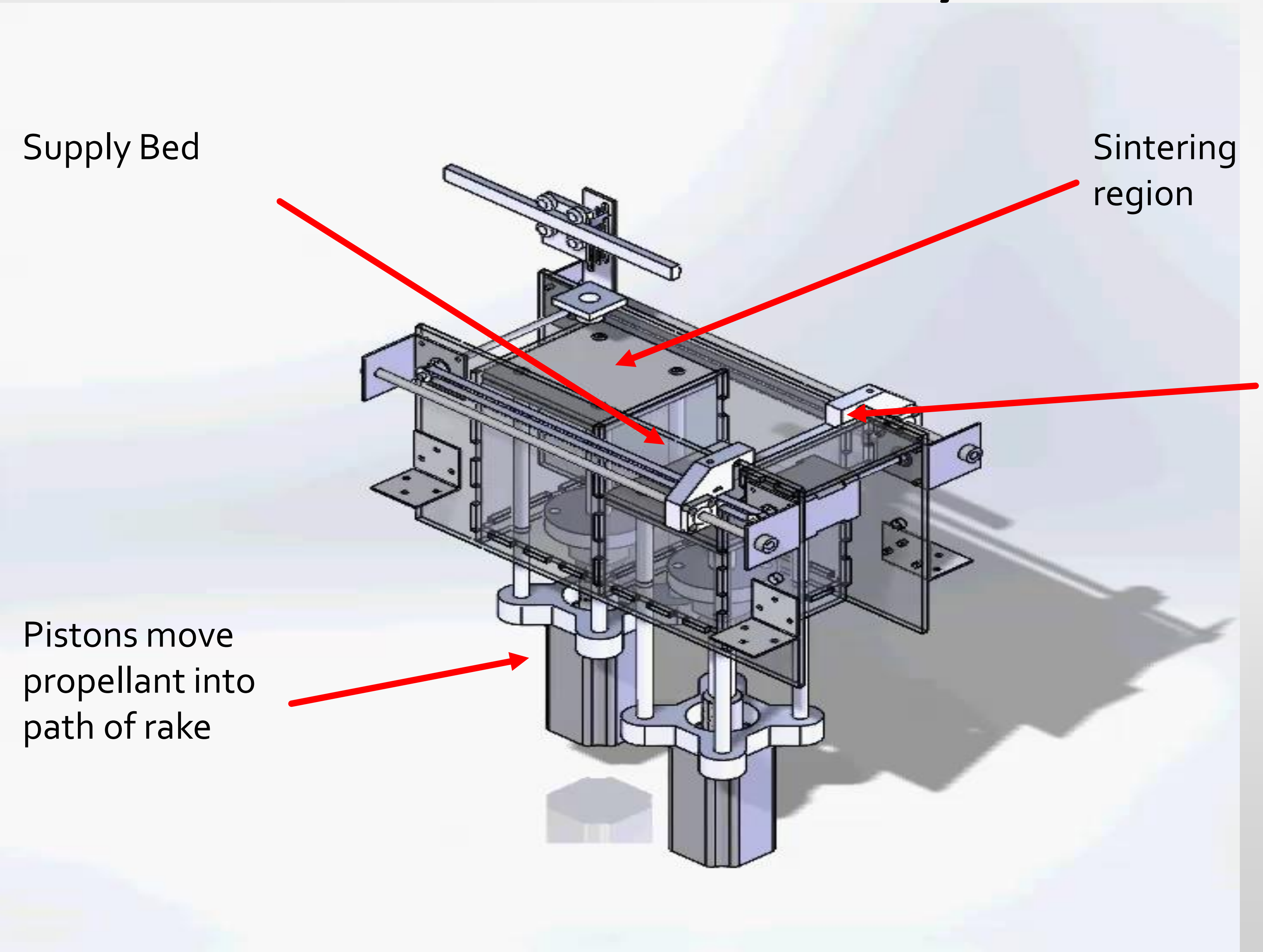
Critical project elements before full integration

Powder Bed Design

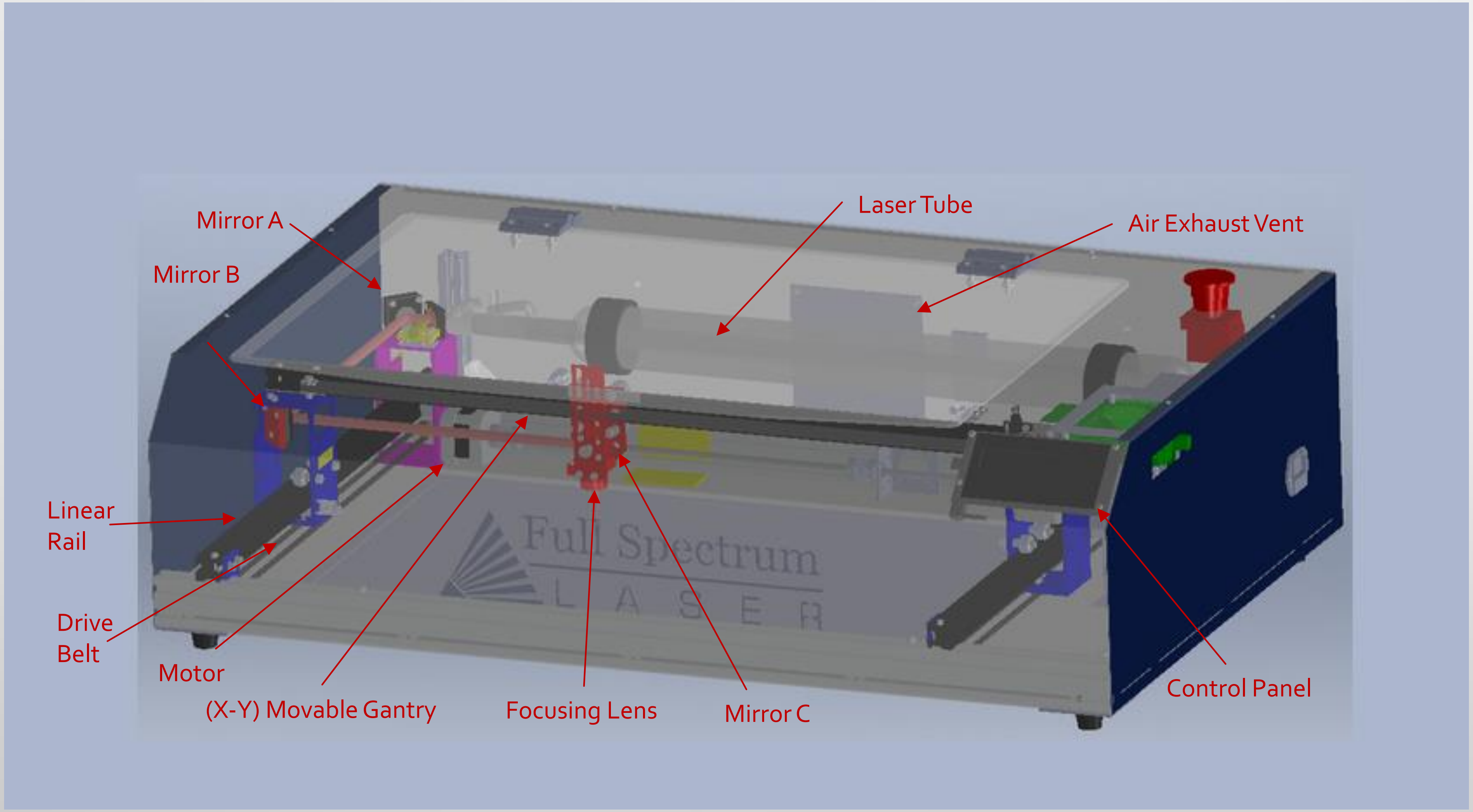
- Acrylic Body
- Rake System
  - Stepper motor and plastic wedge flatten powder and move it to the sintering region
- Gutter System
  - Acrylic body designed to keep water and powder away from the electronics
- Pistons
  - Stepper motors provide vertical motion



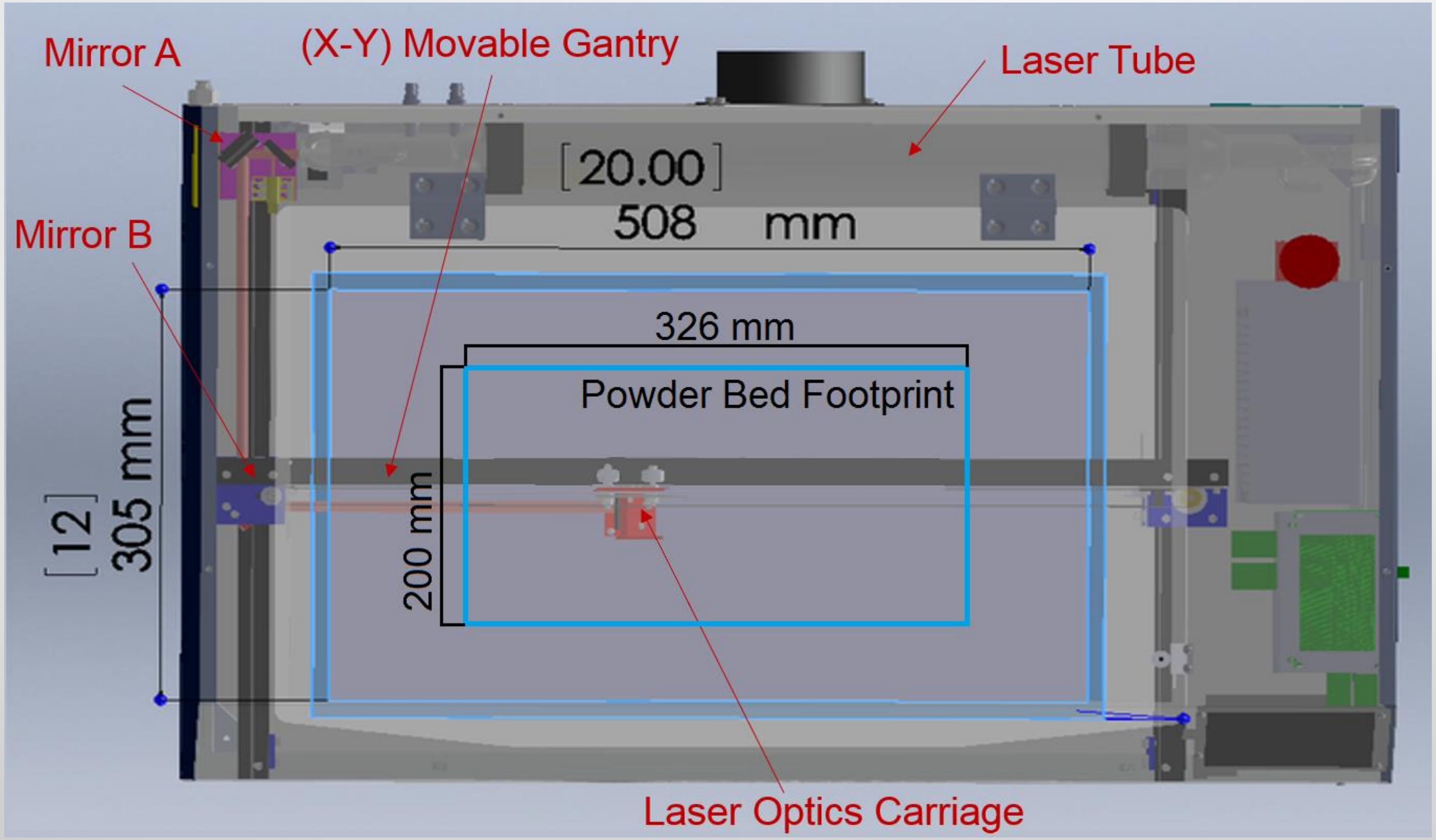
Powder Bed Full Cycle



Laser Cutter

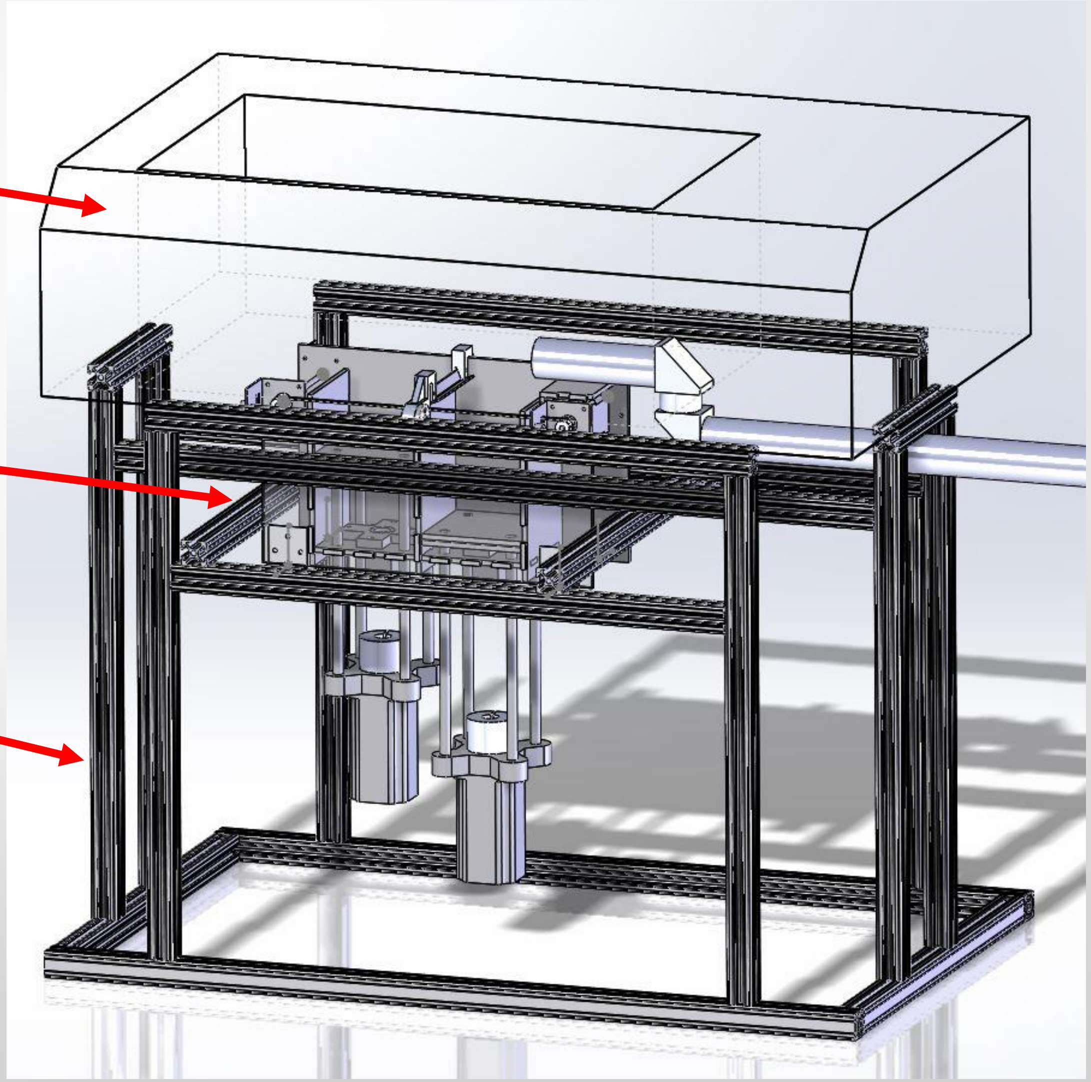


Laser Cutter and Powder Bed Integration



Laser Cutter and Powder Bed Integration

- Laser cutter resting on top of aluminum frame
- Powder bed system resting inside the laser cutter and on the aluminum frame
- Aluminum frame holding up the laser cutter and powder bed



Applying SLS

How to sinter rocket propellant

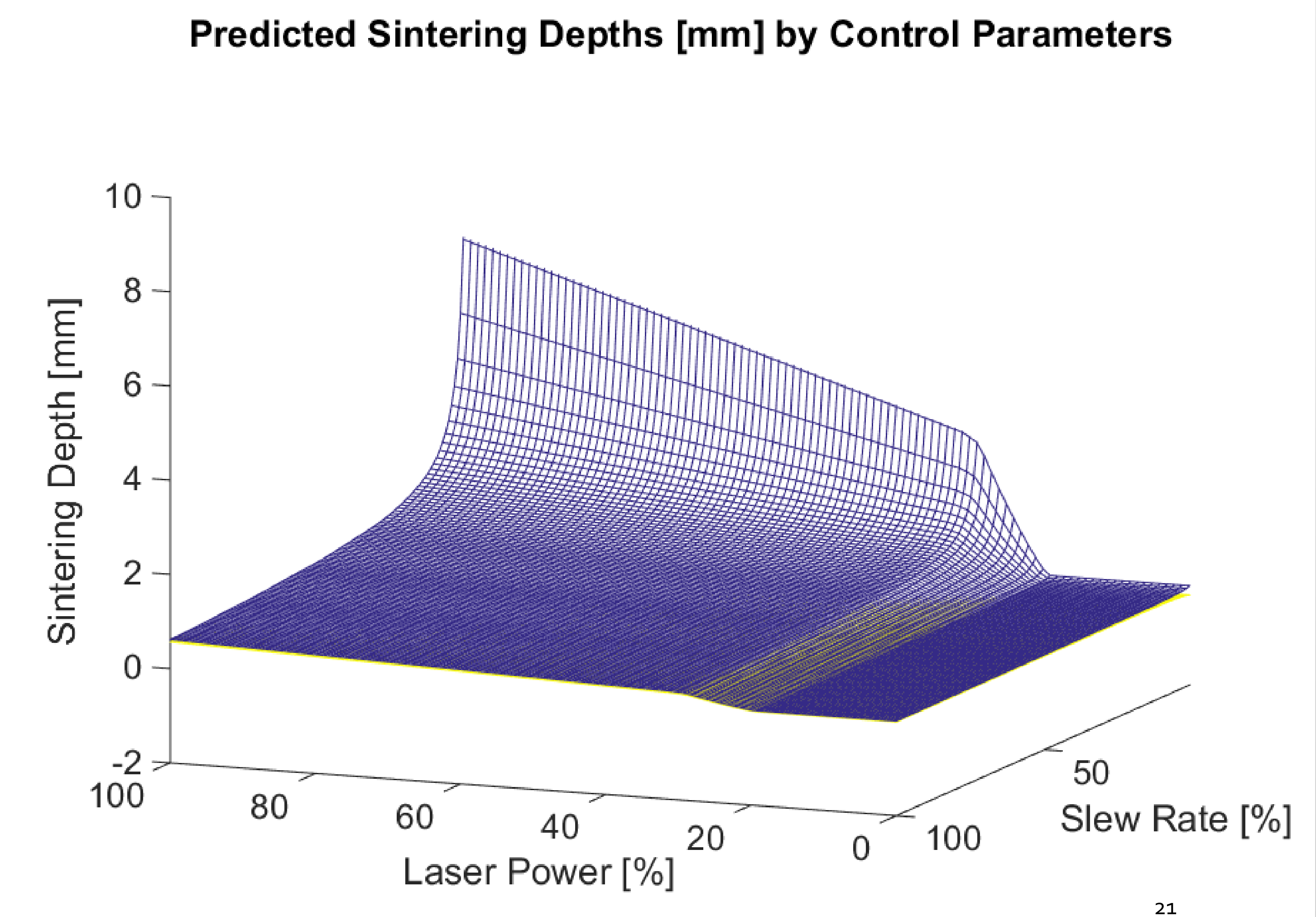
Sugar Sintering: Overview

Initial Sucrose Sintering Model:

- Sucrose only model because absorbs > 90% of the laser heat
- Predicts layer depth (mm) based on laser power (%) and slew rate (%)

Expected Results:

- Sintering depth increases with slower speed and higher power
- Temperatures spike well above auto ignition with higher energy output



Sugar Sintering: Results

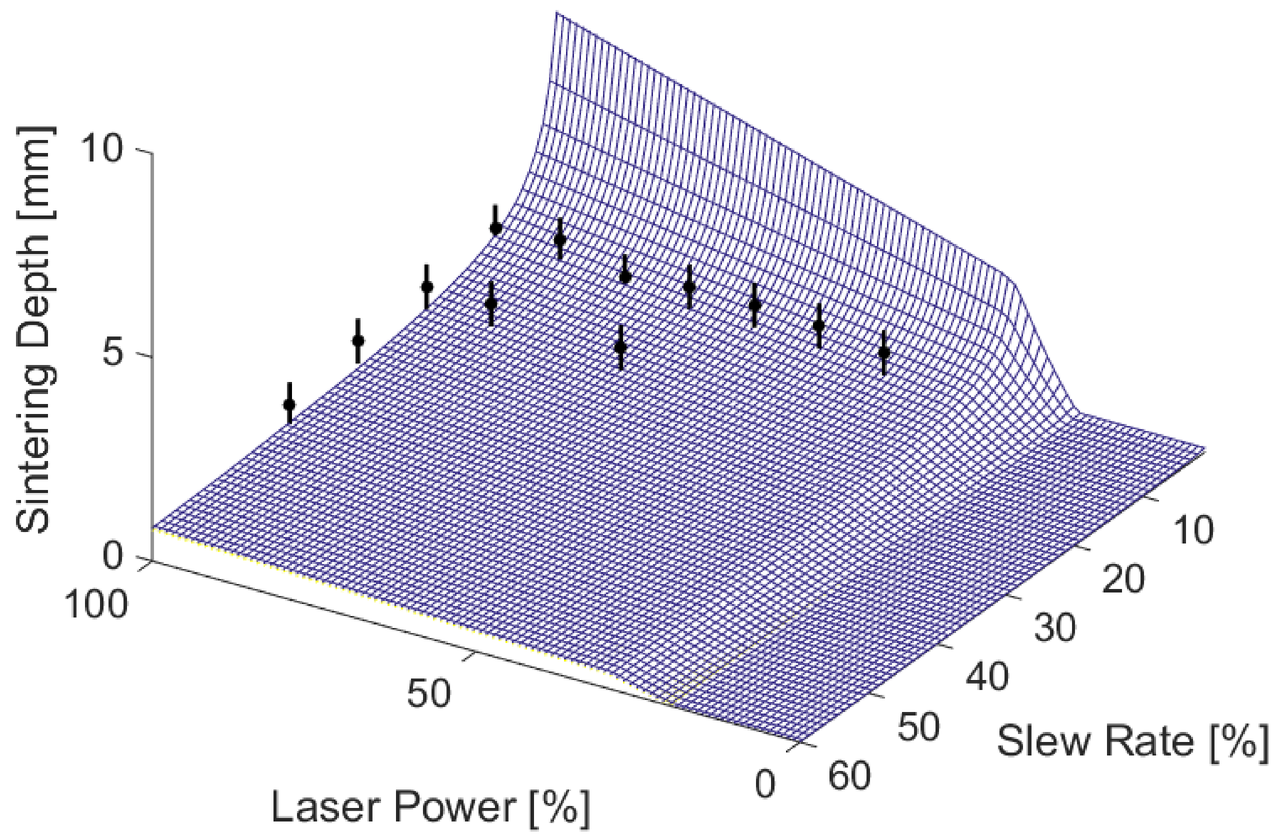
Results:

- Most samples thicker than predicted
  - Likely caused by size of sugar granules
- Minimum Sintering Depth
- Inaccurate (>1 Std) at Power < 5%
  - Caused by heat conduction

Future Analysis:

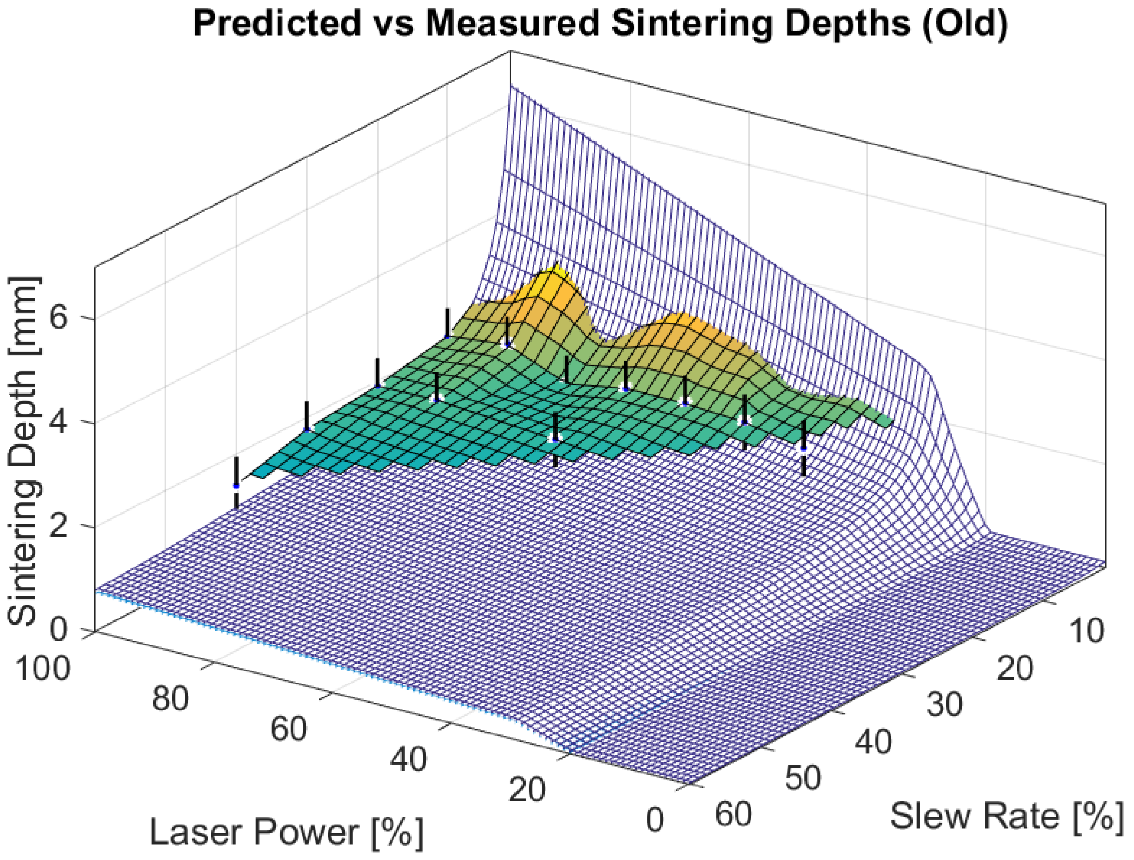
- Test goodness of fit (X^2)
- Update model with minimum thickness
- Calibrate fit

Predicted Vs. Measured Sintering Depths [mm]

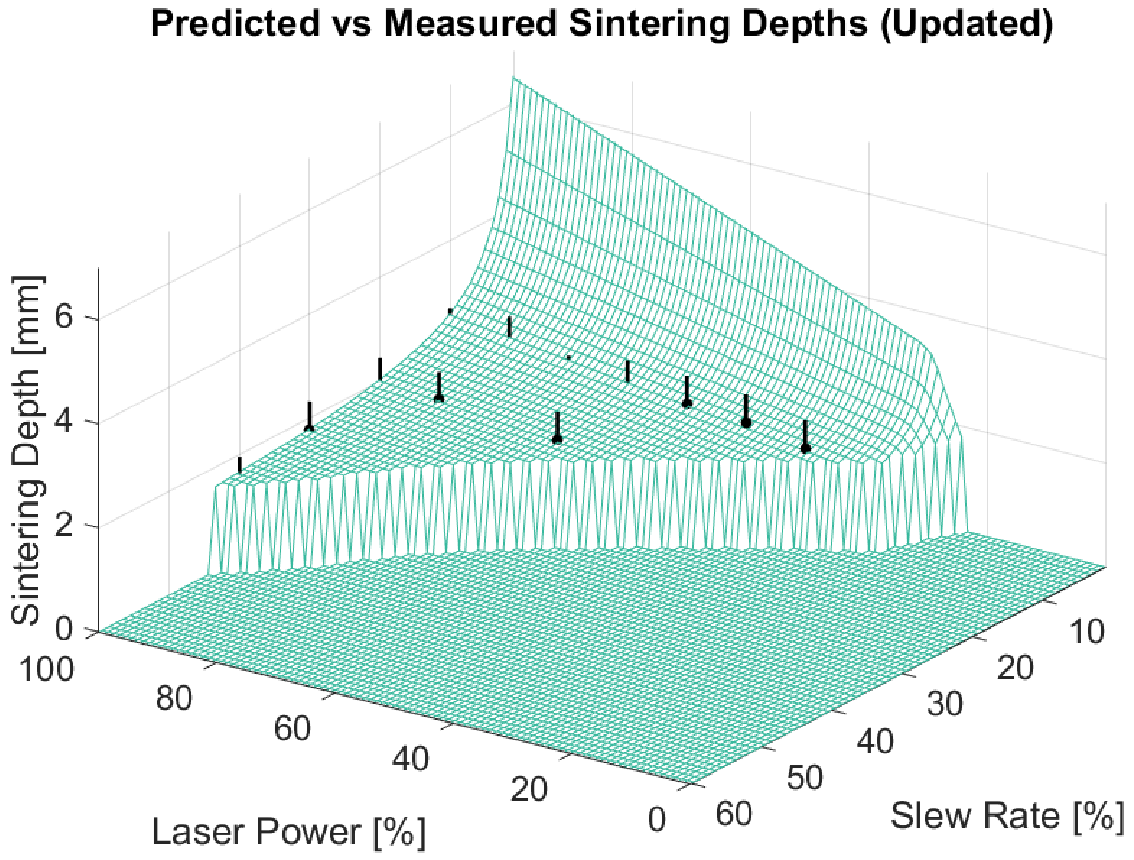


Sugar Sintering: Calibration

Before calibration



After calibration



Propellant Sintering Model

Propellant Thermal Model

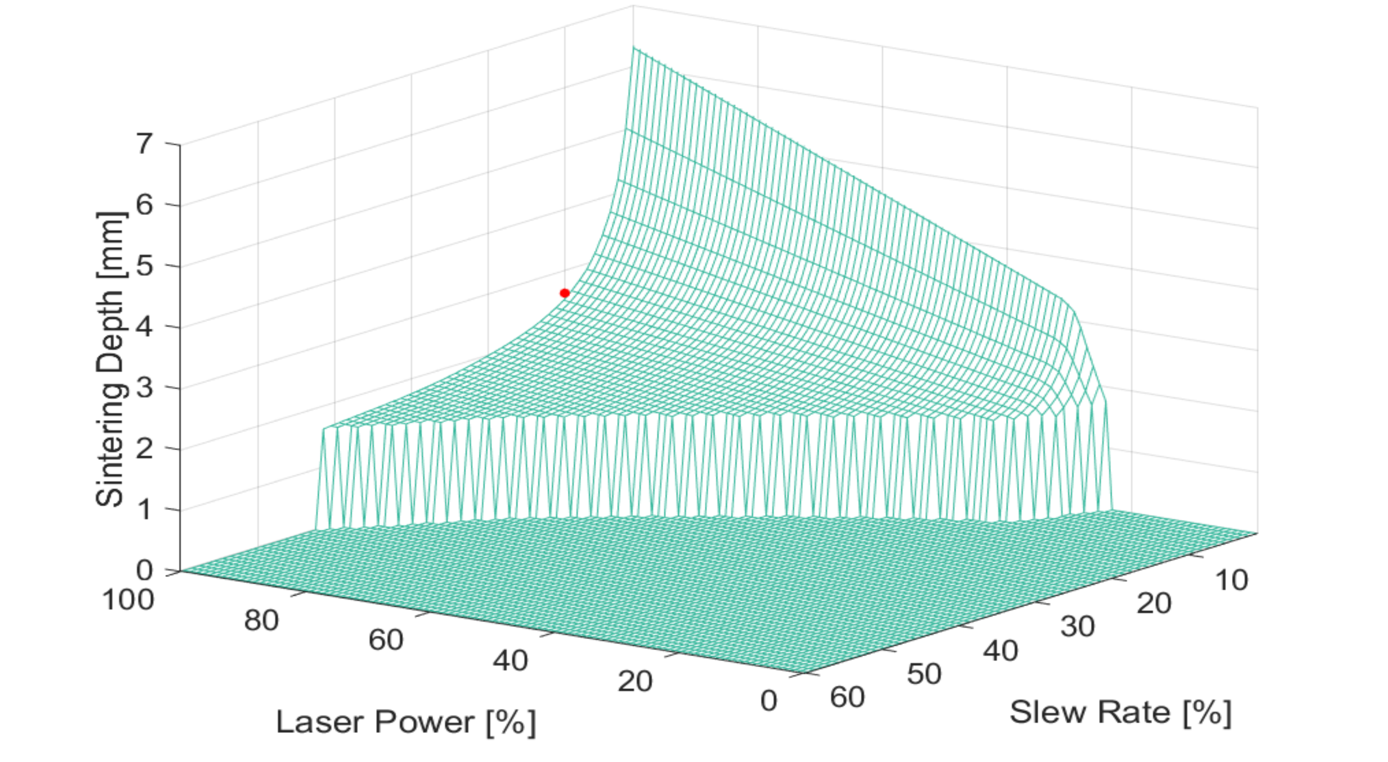
Propellant Thermal Model:

- Matched calibrated model to within 5% error
- Model validated with sintering of sucrose-potassium nitrate

Sintering Results:

- Sintering depths did not change by more than 0.5 mm
- Provided proof of concept for sintering propellant

Predicted Propellant Sintering Depths [mm]



Teal grid shows estimated sintering depths and the red dot marks the tested depth of propellant

Testing and Results

How much have we accomplished?

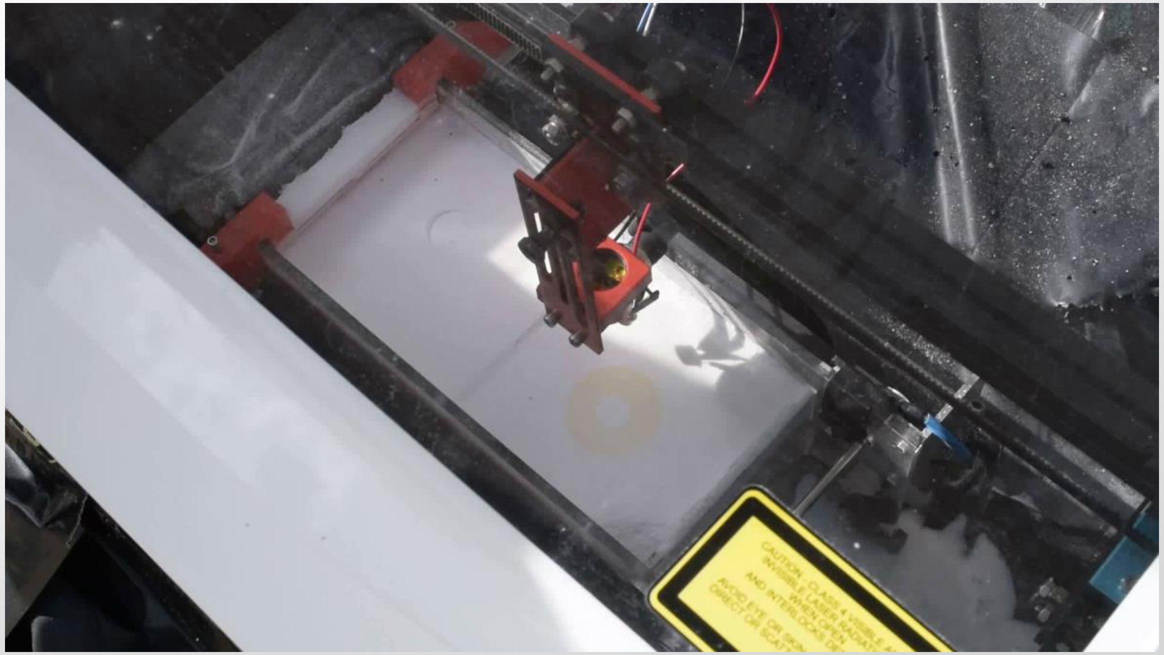
Propellant Sintering Preliminary Results

- Proof of concept
  - **SLS manufacturing of solid propellant is possible**
- We sintered four ~.035" layers of propellant in a cylindrical grain for a total motor length of .130"

First Ever 3D Printed Solid Rocket Motor

Propellant Sintering Preliminary Results

Solid Rocket Motor Printing



Powder Bed Sweeping New Layer of Propellant

Summary

Recap and future work

Future Work

- Dynamic Grains
  - Pseudo-throttling
- Next iteration
  - More robust sensors
  - Non-destructive safety system
  - Larger safety margin before ignition
- Motor performance testing
  - Printed motor will have to withstand substantial vibrational loading before 3D printing can be considered a viable alternative in industry

Acknowledgements

Team SPAM would like to thank everyone who made this project possible:

-Special Aerospace Services
-Dr. Ryan Starkey
-CU Boulder Aerospace PAB
-Ifuzion 3D Printing
-Andreas Bastian (OpenSLS)
-Richard Nakka Rocketry
-Frontier Astronautics

References

- [1]Braeunig, Robert A. "Space Pictures". *Rocket and Space Technology*. Accessed October 2015. Available:
  - http://www.braeunig.us/space/pics/fig1-14.gif
- [2]"Saltpetre". The Ingredient Store.com Accessed October 2015. Available: http://store.theingredientstore.com/saltpetre-food-gradepotassiumnitrate.aspx
- [3]"Sucrose Advanced Inorganics". *India Mart.* Accessed October 2015. Available: http://dir.indiamart.com/impcat/sucrose-powder.html
- [4]Miller, E., "Rapid Prototyping Technology Animations," *PADT, Inc* Available: http://www.padtinc.com/blog/the-rp-resource/rapid-prototyping-technology-animations
- [5]"Selective Laser Sintering (SLS)," *MakeAGif* Available: http://makeagif.com/cpjtel
- [6]Sher, D., "Using SnowWhite to Laser Sinter Sugar," *3D Printing Industry* Available: http://3dprintingindustry.com/2014/09/26/sharebot-used-snowwhite-laser-sinter-sugar-worked-perfectly/.
- [7]"Selective Laser Sugar Snowflakes," *Collected Edition* Available: http://blog.collected-edition.com/post/41556924865/slssnowflakes.
- [8]"EngArc - L - Stress-Strain Diagram," *EngArc - L - Stress-Strain Diagram* Available: http://www.engineeringarchives.com/les_mom_stressstraindiagram.html.
- [9]"Fracture Toughness," *Fracture Toughness* Available: https://www.nde-ed.org/educationresources/communitycollege/materials/mechanical/fracturetoughness.htm.
- [10]"Part 3: How to Build a High Power Rocket - Casting the Fuel into BATES Grains," *YouTube* Available: https://www.youtube.com/watch?v=dfrnimt2bu4
- [11]"HD How to make & cast R-Candy Fuel (BEST RESULTS)," *YouTube* Available: https://www.youtube.com/watch?v=uhm7nrv3bs8

References

- [12]"Sucrose," *National Institute of Standards and Technology* Available: http://webbook.nist.gov/cgi/cbook.cgi?id=c57501&mask=80
- [13]"AC110V 1' Solid Coil Electric Solenoid Valve Gas Water Fuels Air Solid Coil," *Amazon* Available: http://www.amazon.com/ac110v-solid-electric-solenoid-valve/dp/b00lapocie/ref=pd_sim_60_21?ie=utf8&refrid=1wa1qjzcp57mkscsykh7
- [14]Shoberg, R., "Engineering Fundamentals of Threaded Fastener Design and Analysis". PCB Load & Torque, Inc. Accessed Oct. 2015. Available: http://www.hexagon.de/rs/engineering%20fundamentals.pdf
- [15]"Dissecting the Nut Factor". Archetype Joint. Accessed Oct. 2015. Available: http://archetypejoint.com/?page_id=135
- [16]"Joint1.gif". Bolt Science. Accessed Oct. 2015. Available: http://www.boltscience.com/pages/nutorbolttightening.htm
- [17]Herder, G., Weterings, F. P., and de Klerk, W. P. C., "MECHANICAL ANALYSIS ON ROCKET PROPELLANTS," *Journal of Thermal Analysis and Calorimetry*, vol. 72, 2003, pp. 921–929. [18]"Stereolighography," *Wikipedia* Available: https://en.wikipedia.org/wiki/stereolithography. [19]"Testing – Testing?," *IMPRESS Education: Mechanical Properties, Testing* Available: http://www.spaceflight.esa.int/impress/text/education/mechanical properties/testing.html. [20]Tussiwand, G. S., Saouma, V., Terzenbach, R., and Luca, L. D., "Fracture Mechanics of Composite Solid Rocket Propellant Grains: Material Testing," *Journal of Propulsion and Power*, pp. 60–73. [21]Bastian, Andreas. "R2 Final Assembly". *RepRap Wiki.* Open Source CAD Files. Modified 7 December 2013. Accessed October 2015. Available: http://reprap.org/wiki/File:R2_final_assembly.png
- [22]Kodikara, J., "*Tensile strength of clay soils*," *Tensile strength of clay soils* Available: http://eng.monash.edu.au/civil/research/centres/geomechanics/cracking/tensile-clay.html
- [23]"*What is a Creep Test?*," *What is a Creep Test?* Available: http://www.wmtr.com/en.whatisacreeptest.html .
- [24]Jacobsson, L., and Flansbjer, M., "*Uniaxial compression tests*," *Uniaxial compression tests* Available: http://www.sp.se/en/index/services/rockmechanicaltesting/uniaxial/sidor/default.aspx .
- [25]Full Spectrum Laser, "Hardware Setup and Operation," *FSL 40w Hobby Laser Manual*
- [26] Laser Institute of America, "American National Standard for Safe Use of Lasers," *ANSI Z136.1*, published 2007
- [27] Occupational Safety & Health Administration, "Laser Hazards," *OSHA Technical Manual, Section III: Chapter 6*
- [28] CU Boulder Environmental Health and Safety, "Hazardous Materials & Waste Management," http://ehs.colorado.edu/about/hazardous-materials-and-waste-management/ [retrieved 15 November 2015]
- [29] National Fire Protection Agency, "NFPA 704: Standard System for the Identification of the Hazards of Materials for Emergency Response," http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=704 [retrieved 20 November 2015]

Questions?