Solid Propellant Additive Manufacturing

Critical Design Review

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Special Aerospace Services (SAS)

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Agenda

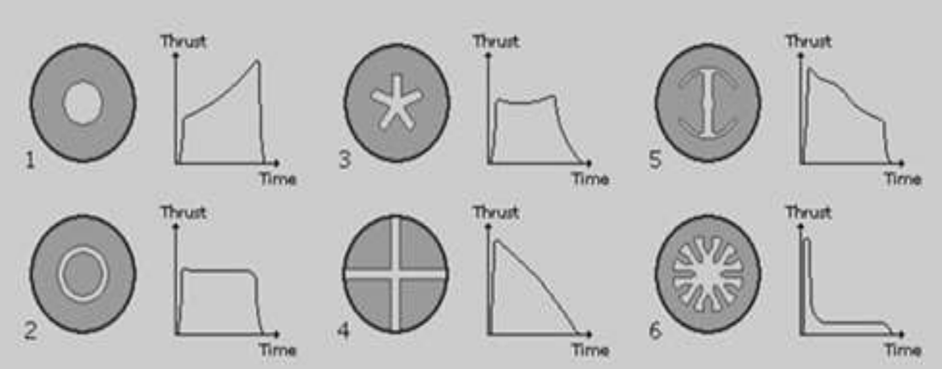
- Project motivation and background
- Design Requirements Fulfillment
  - Thermal
  - Safety System
  - Powder Bed System
  - Software Integration
  - Electronics Integration
- Risk Mitigation
- Verification and Validation
- Project Planning

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.

Project Background

- Traditional Casting Limitations:
  - Limited number of grain shapes
  - Air Bubbles in cast
  - Nonuniform setting

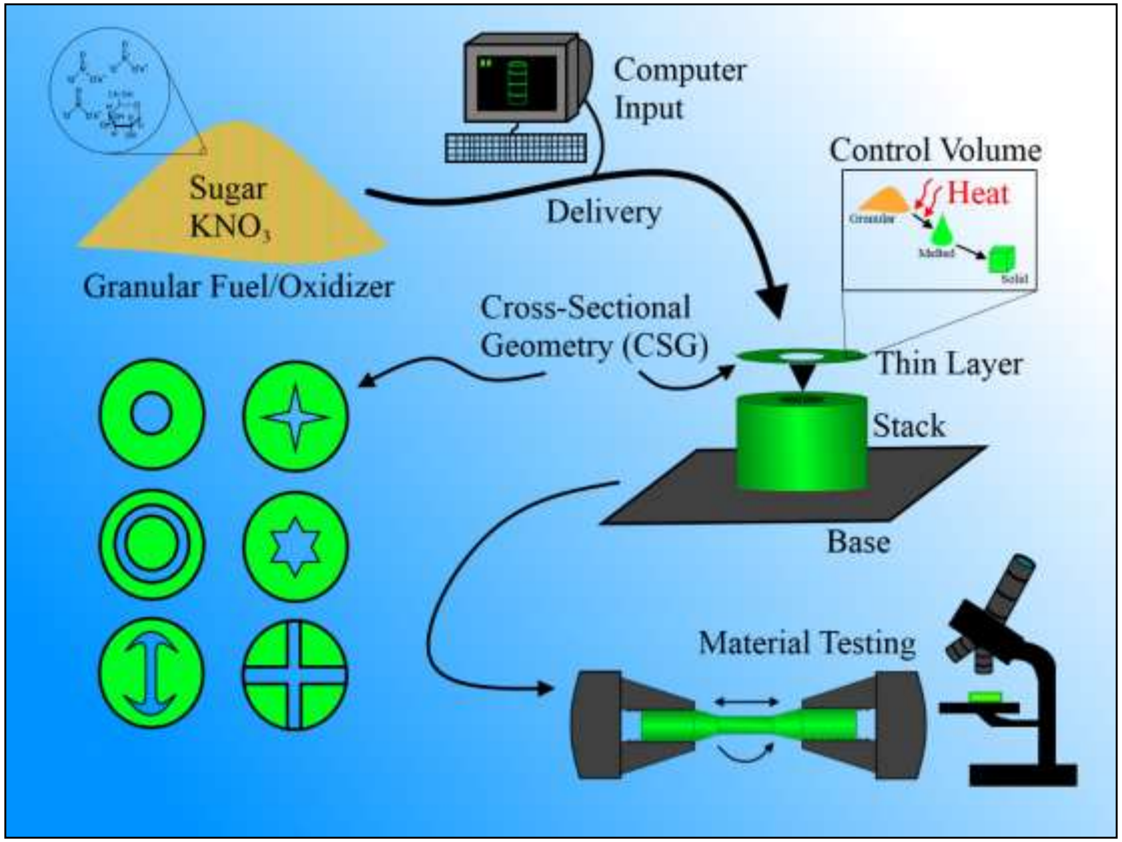


- Example Grain Shapes and Thrust Profiles[1]

- 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

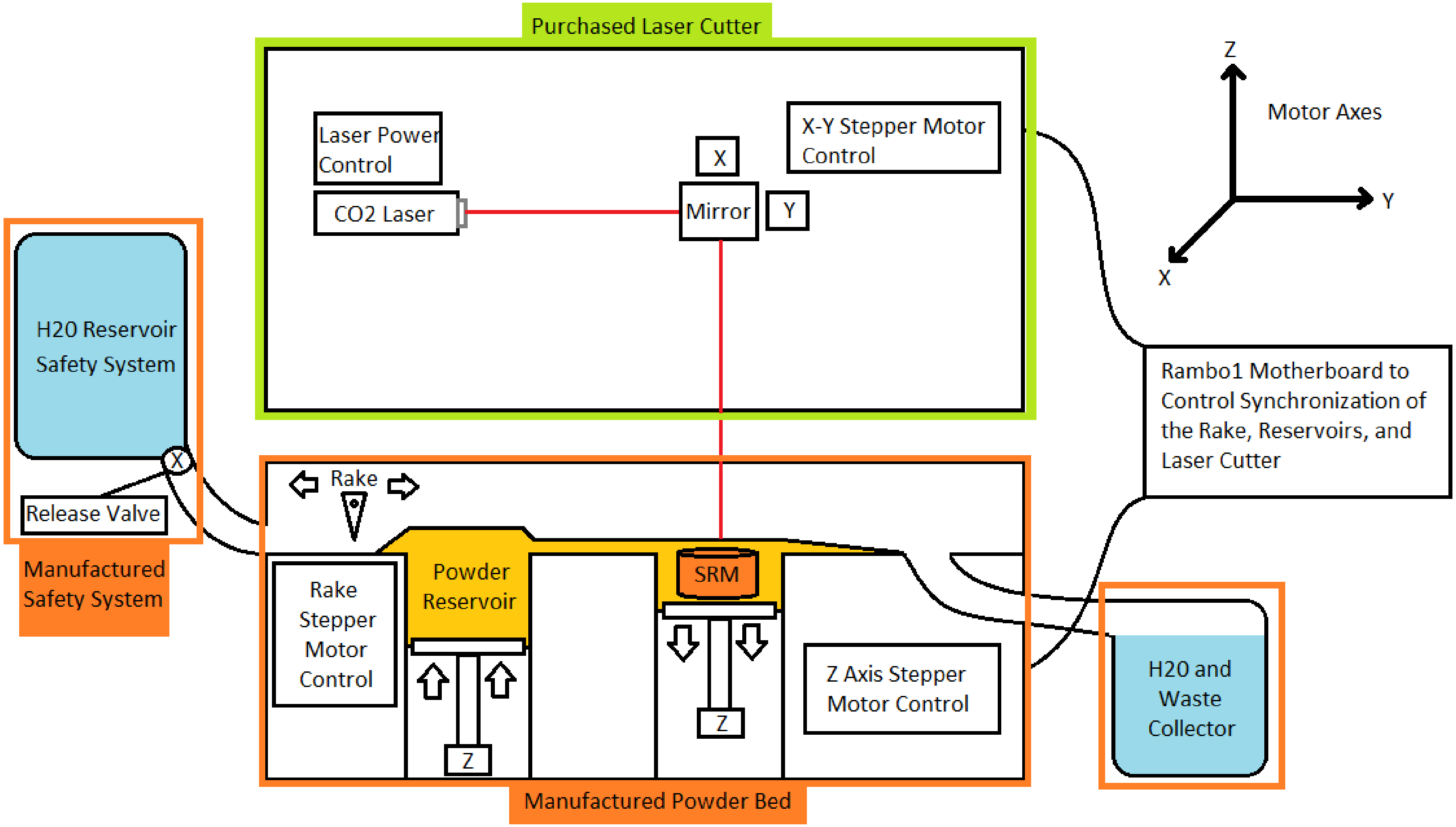
Full Project Concept of Operations

1) Mix KNO3 and sucrose for printing
2) Upload CAD file of desired grain shape to printer
3) Print desired cross section layer by layer
4) Remove finished motor from printer bed and conduct material testing



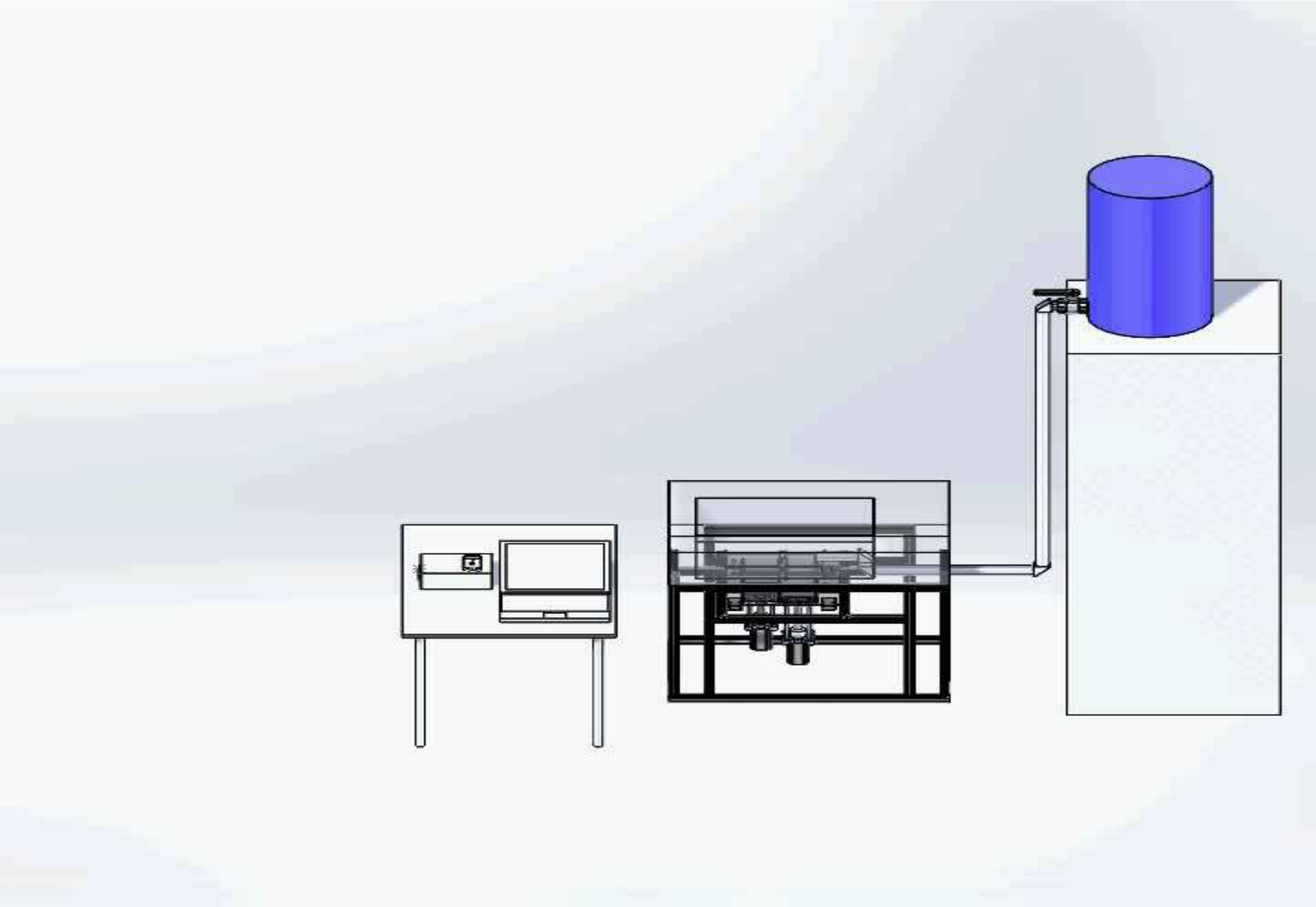
Project CONOPs Diagram

Printer Concept of Operations



Baseline Design Overview

Baseline Design

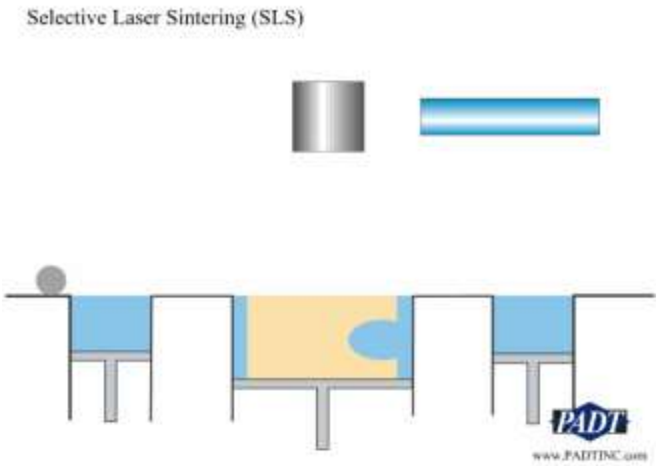


How Does the Design Work?

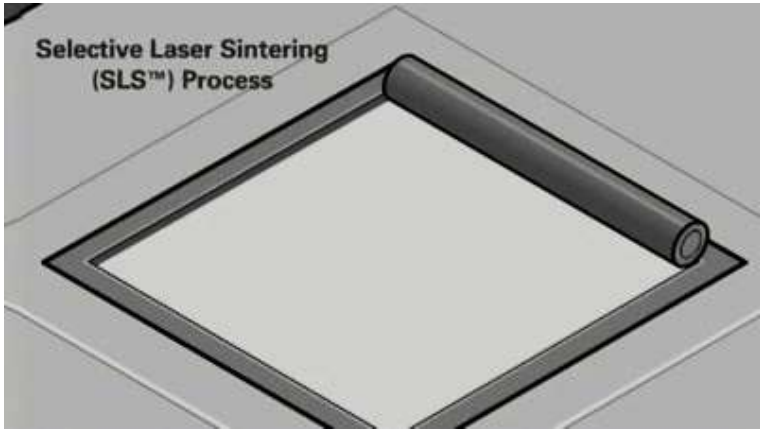
- Selective Laser Sintering (SLS) is a type of Additive Manufacturing which sinters/melts a powder with a laser

<u>SLS Operation:</u>

1. A CAD file is uploaded to the printer
2. The printer uses a CO_2 laser to heat a specified cross-sectional area of the powdered material
3. The heated material binds together forming a solid
4. The powder bed is then lowered by one layer thickness
5. A new layer of powder material is then swept on top of the previously fused layer



SLS Process (Profile View)[4]



SLS Process (Top View)[5]

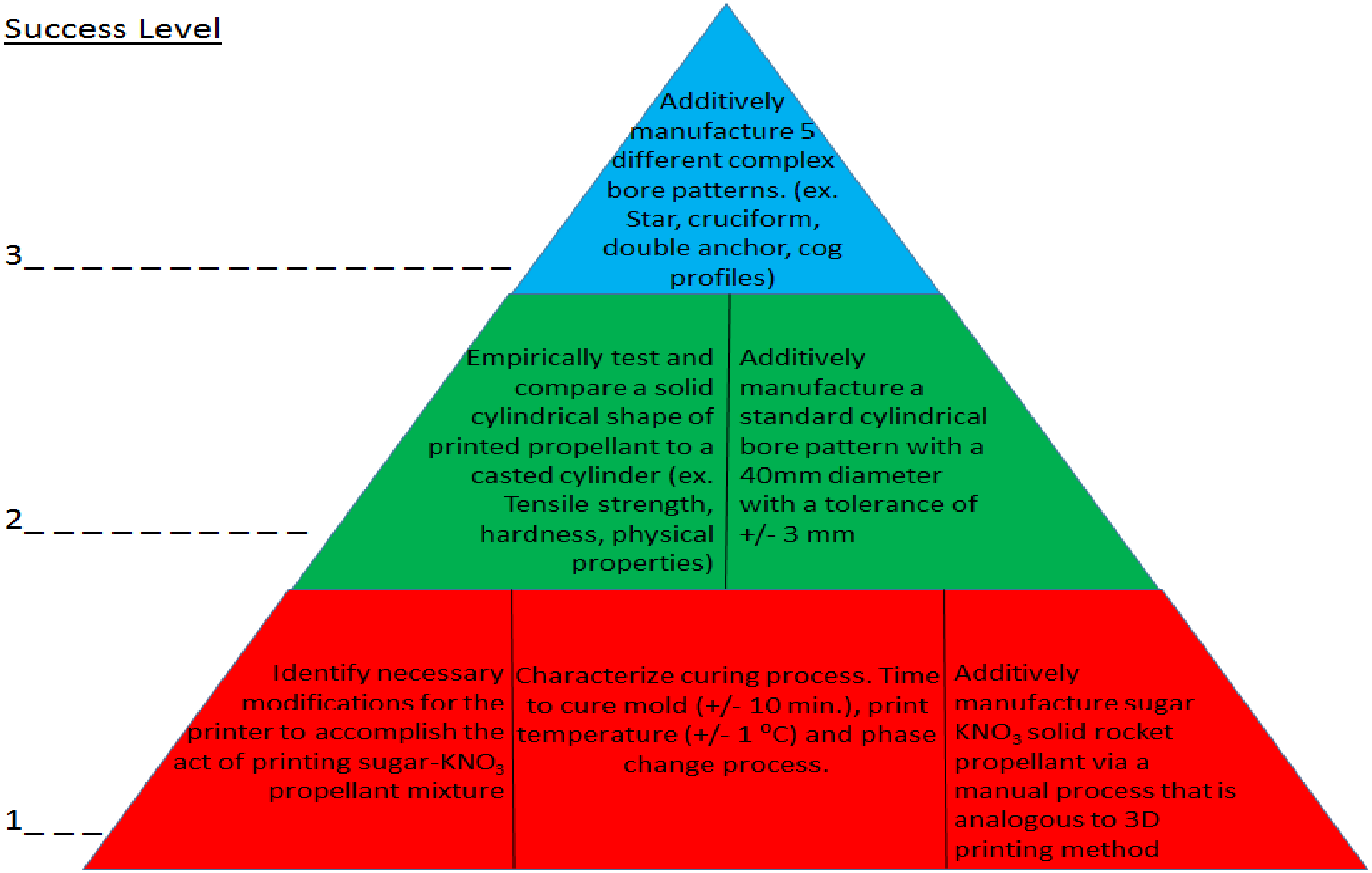
Functional Requirements

Designation	Requirement Description
FR 1	The project shall produce a printer capable of automated 3D additive manufacturing.
FR 2	The rocket propellant shall be a solid composite propellant consisting of oxidizer and fuel.
FR 3	The printer shall have a mechanism to transport the mixed fuel and oxidizer to the manufacturing area.
FR 4	The printed propellant properties shall be compared to traditionally cast propellant material properties.
FR 5	Safety shall be the primary concern in every aspect of the project.

Critical Project Elements

Critical Project Element (CPE)	**Description**
CPE #1: Thermal Model	• Safety • Laser requirements
CPE #2: Safety Design	• Fire risk • Prevention
CPE #3: Powder Bed	• Layer thickness • Motor control
CPE #4: Software and Electronics Integration	• Electronics system design • Software integration
CPE #5: Material Testing	• Necessary tests • Machinery

Levels of Success



Success Level

3

Additively manufacture 5 different complex bore patterns. (ex. Star, cruciform, double anchor, cog profiles)

2

Empirically test and compare a solid cylindrical shape of printed propellant to a casted cylinder (ex. Tensile strength, hardness, physical properties)

Additively manufacture a standard cylindrical bore pattern with a 40mm diameter with a tolerance of +/- 3 mm

1

Identify necessary modifications for the printer to accomplish the act of printing sugar-KNO_3 propellant mixture

Characterize curing process. Time to cure mold (+/- 10 min.), print temperature (+/- 1 ^{o}C) and phase change process.

Additively manufacture sugar KNO_3 solid rocket propellant via a manual process that is analogous to 3D printing method

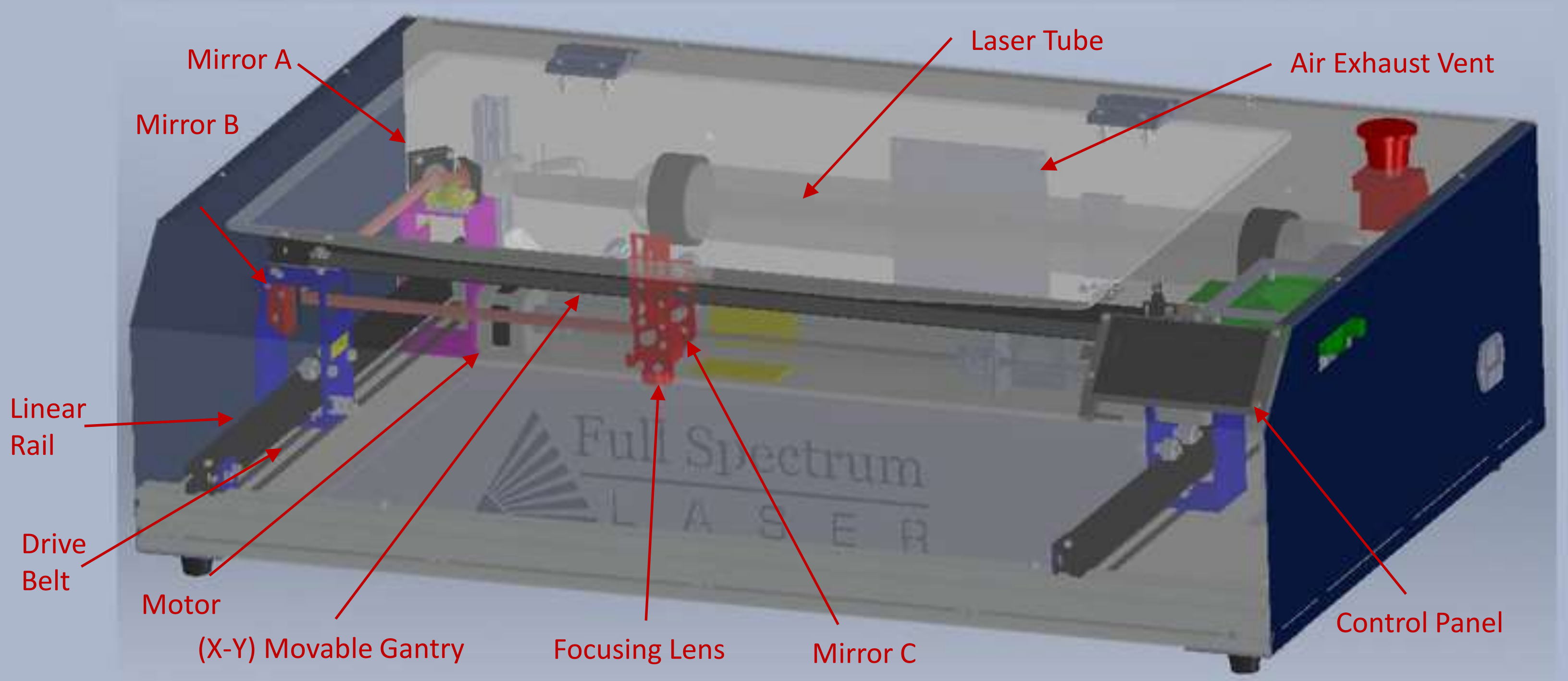
Laser System

Laser Cutter Selection

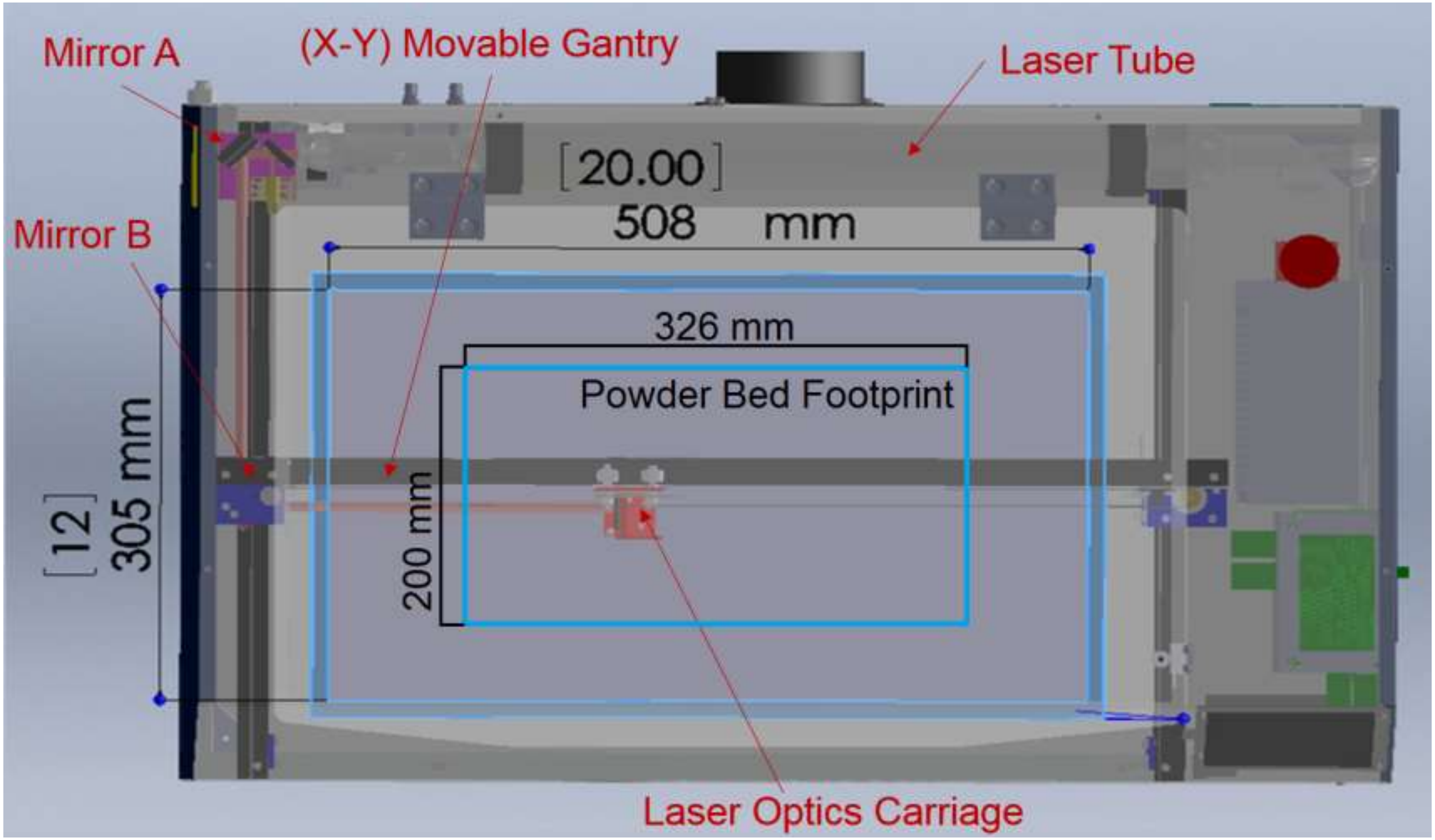
Req.	Criteria	Laser Cutter Specification
1.1.1	Positioning in 2-D: (X - Y) Accuracy: +/- 1 mm	(X-Y) Movable Gantry Motor Accuracy: 1000 DPI → 0.025 mm Laser Spot Diameter: 0.178 mm
3	Work Area Dimensions: Greater than 326 x 200 x 200 mm (L x W x H)	Cutting Area: 508 x 304 mm (L x W) Bottom of Laser Cutter is removable
1.4	Controllable Laser Power	Pulse Width Modulation Slew Rate Laser De-Focusing Current Limitation
2.3	Laser Power is absorbed by Propellant	Laser Wavelength: 10.6 microns (CO2) Sucrose has 95% Absorption

Laser Cutter Selection

Full Spectrum H-Series 5G Laser Cutter



Laser Cutter Selection – Top View

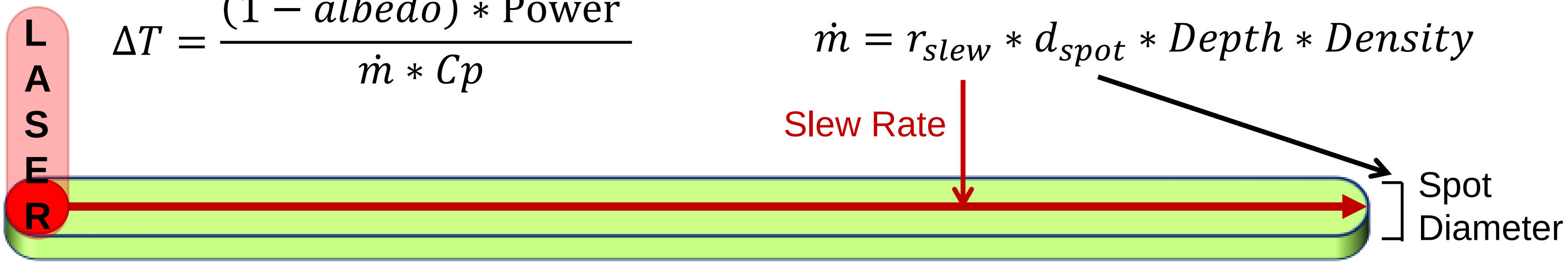


Sintering Model - Assumptions

- Laser sweeps out a rectangle of area as it moves
- Layer depth is 1 mm
- All laser energy is deposited uniformly into the layer
- No heat loss to surroundings

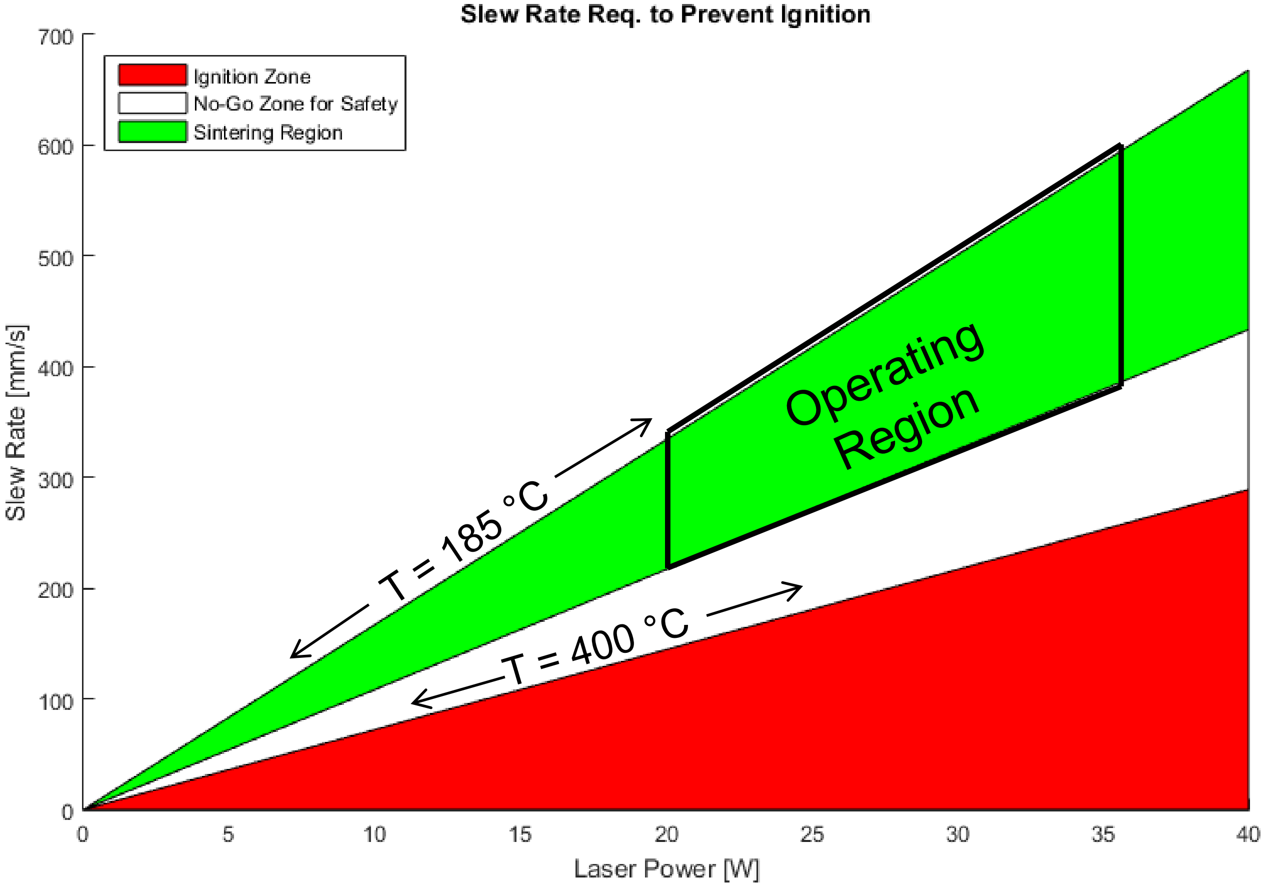
$$\Delta T = \frac{(1 - albedo) * \text{Power}}{\dot{m} * Cp}$$

$$\dot{m} = r_{slew} * d_{spot} * Depth * Density$$



Propellant Layer that receives Laser energy

Sintering Model - Results



- Maximum Slew Rate is adjustable in software
- Maximum Capability: 800 mm/s*
- Operating Range:
  - 20 – 35 W
  - 200 – 600 mm/s

*According to Comparable Models

Safety

Safety Requirements Compliance

ID	Description	Solution
5.1	Shall calculate combustion energy potential in powder bed	1231 KJ/kg of propellant
5.2	Shall identify reactants and products of combustion	CO_2, CO, H_2O, H_2, N_2, K_2CO_3, KOH
5.3	Shall implement extinguishing safety system	Water extinguishing system
5.5	State of Health system shall detect fire & alert the operator	• Infrared thermometer (-70°C to 382°C) • Carbon Monoxide sensors, buzzer and LED
5.6	Laser safety shall be in compliance with all ANSI and OSHA laser safety standards	Compliance with ANSI Z134 laser safety standards, compliance with OSHA laser safety standards

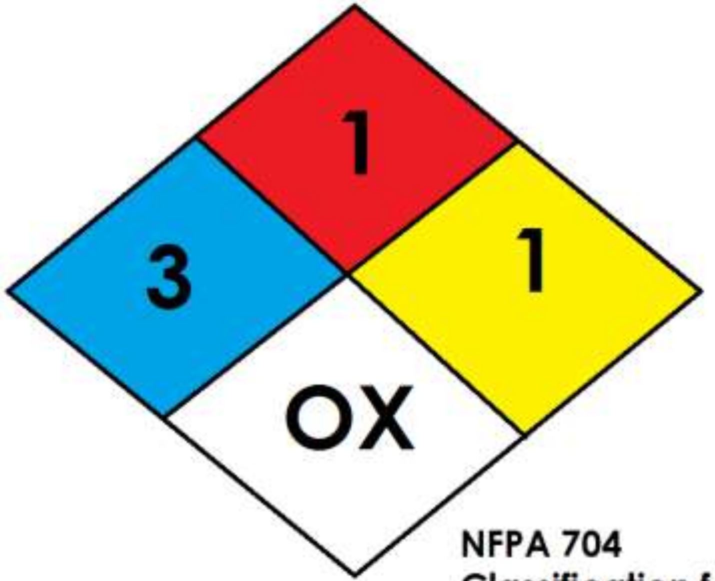
Safety Standards & Compliance

Safety Standard	Compliance
US FDA	FSL Laser Cutter complies with 21 CFR 1040.10 and 1040.11 Federal Performance Standards for Light-Emitting Products
ANSI Z136 Laser Classification (Class 3A Laser)	FSL Laser Cutter has a magnetic safety interlock switch that deactivates the laser OFF if the door is opened during operation
OSHA Workplace Safety	Laser Safety Goggles providing appropriate attenuation of laser intensity
Environmental Health and Safety	1. SPAM will complete Laser Registration 2. Laser will operate in BAC lab 3. Safety goggles worn at all times 4. Hazardous Waste Disposal Procedure compliance

Safety Standards & Compliance

Health:

Short exposure could cause serious, temporary, or moderate residual injury (CO)



NFPA 704 Classification for KNSU propellant

Flammability:

Materials that require considerable preheating, under all ambient temperature conditions, before ignition and combustion can occur. Flash point at or above 93°C

Instability/reactivity (yellow)

Normally stable, but can become unstable at elevated temperatures and pressures

Special Notice (White)

OX: Oxidizer, allows chemicals to burn without an air supply

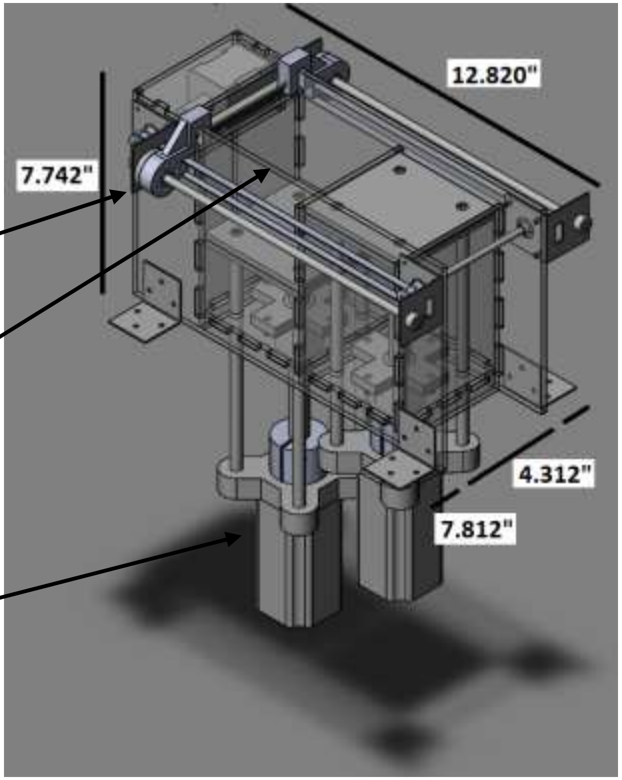
Powder Bed System

Powder Bed Subsystem

Req.	Criteria	Powder Bed Specifications
3.1	Printed layer depth shall be 0.7-1.0mm	Ball Screw/Nut pitch: 13/64” (5.159mm) Piston motor single step accuracy: 1.8° Vertical accuracy: 0.001” (0.025mm)
3.2.1	Piston motors can move a maximum of 2.5kg of propellant in addition to their own weight	Torque to spin ball nut/screw: 0.05Nm Motor holding torque: 2.4Nm
3.4	Print piston shall allow 2.85” (7.24cm) of vertical motion	Maximum piston stroke: 4.9” (12.4cm)
3.2.2	Reservoir piston shall deliver 1.5 times the powder required by the print piston each layer	Print piston vertical motion: 2.85” (7.24cm) Required Reservoir vertical motion: 4.275” (10.86cm)

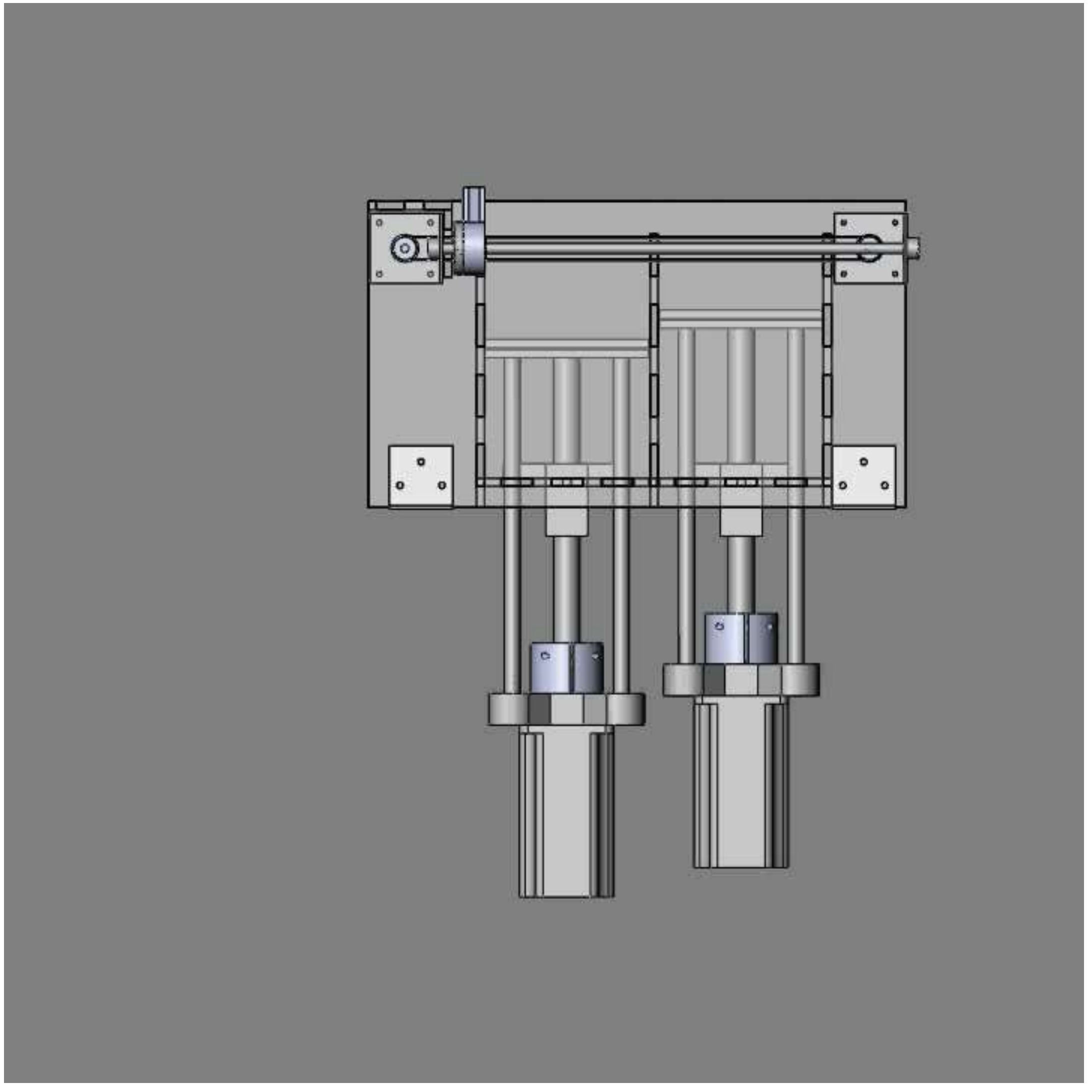
Overview

- Acrylic Body
  - Holds components together in a cheap and easy to manufacture shell
- Rake System
  - Stepper motor and aluminum wedge flatten powder to be printed
- Gutter System
  - Acrylic body designed to keep water and powder away from electronics
- Pistons
  - Stepper motors provide vertical motion

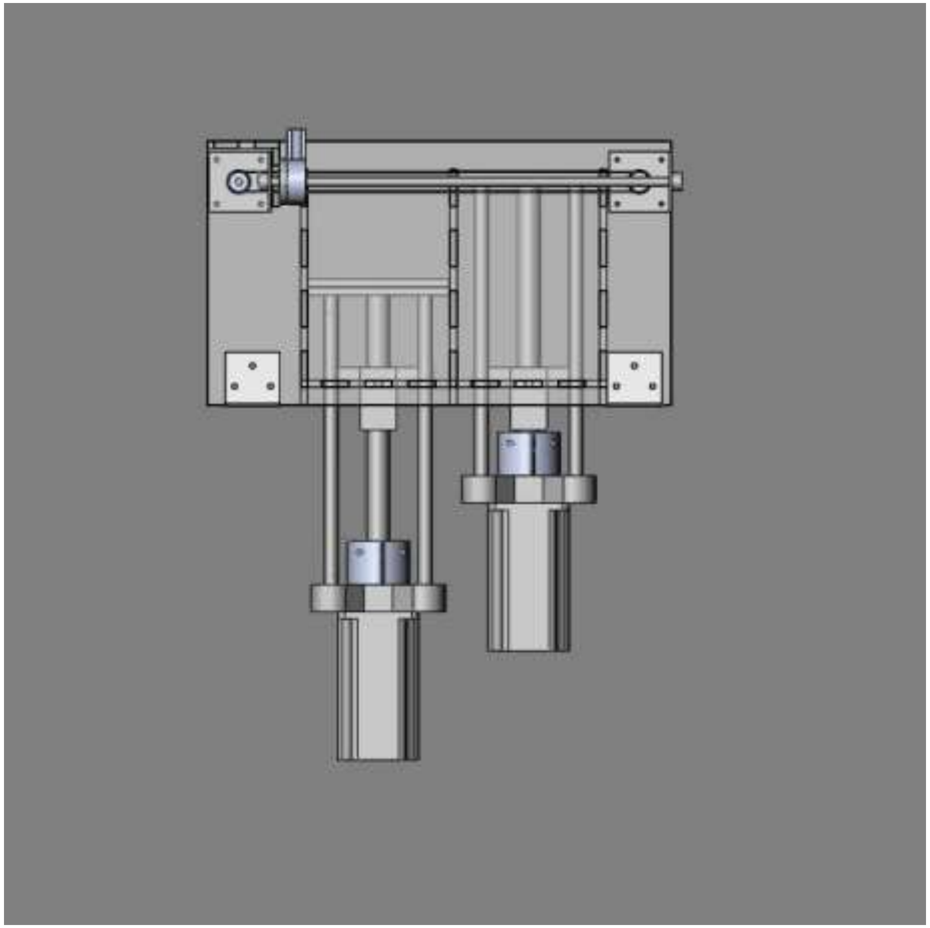


3D View

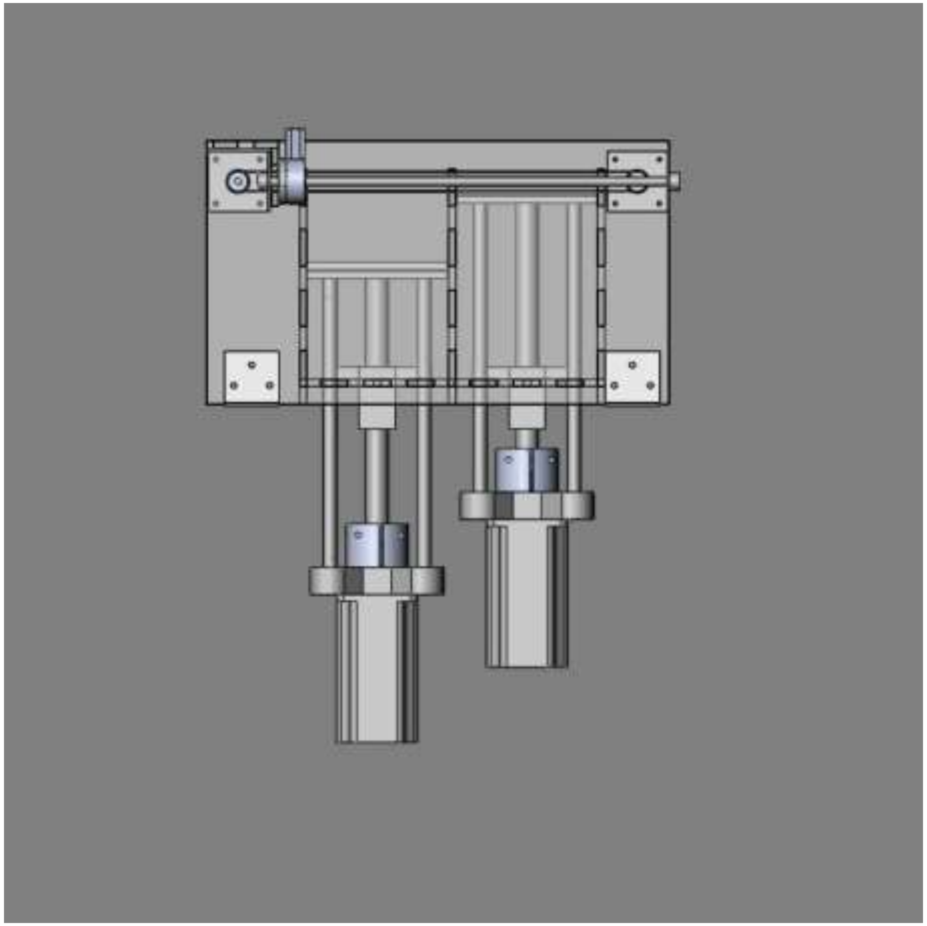
- Based off of previous open source projects
- Baseline design proven to work by hobbyists
- All components can be bought or manufactured in-house
- Projected cost: $450



Step 1: Pistons

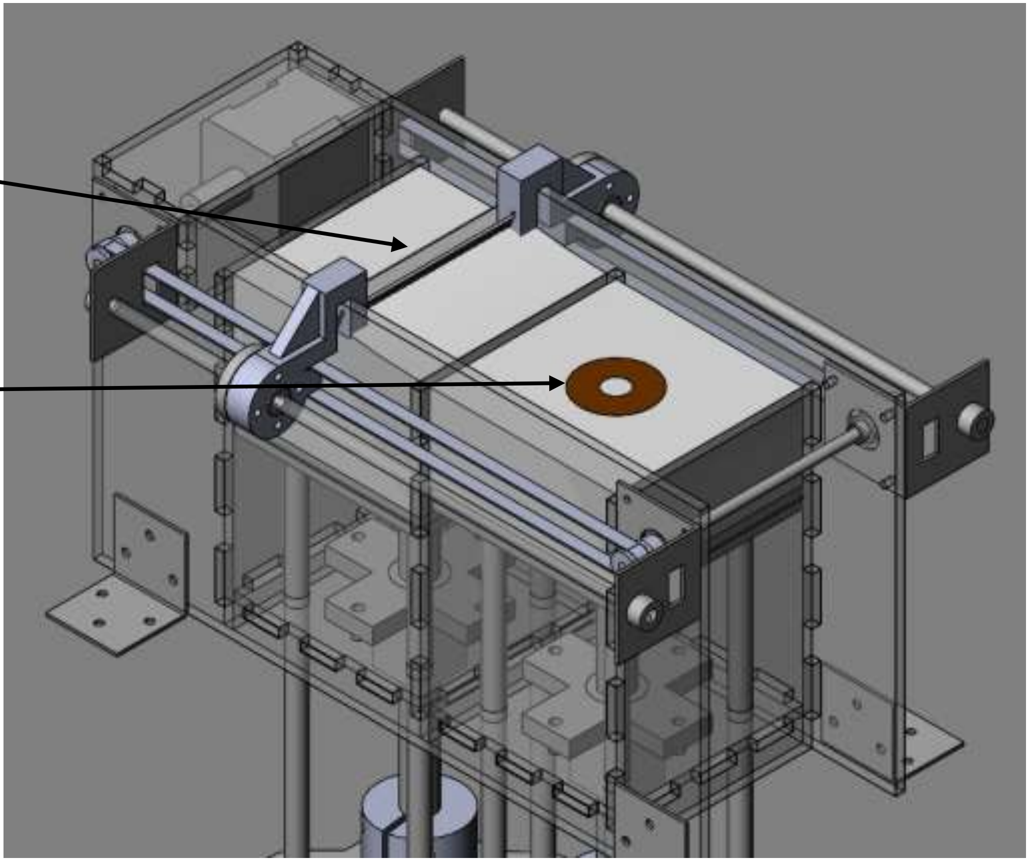


Step 2: Rake



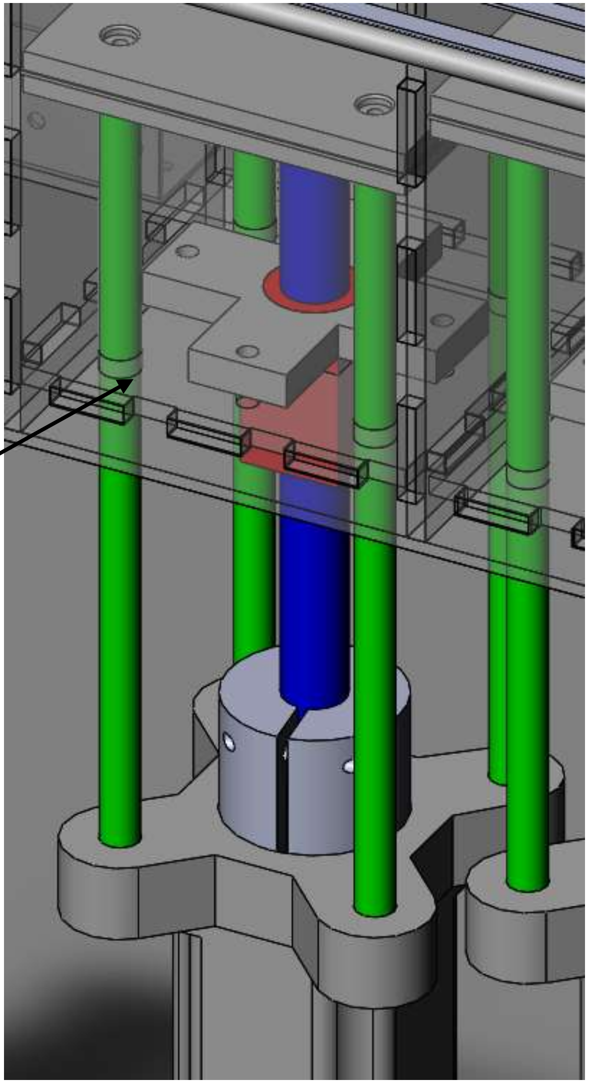
Snapshot During Operation

- ➢Powder lifted by Reservoir Piston being pushed/flattened by the rake
- ➢Print area (with previous layers of sintered material) waiting for next layer
- ➢Not shown: Laser head



Piston Subassembly

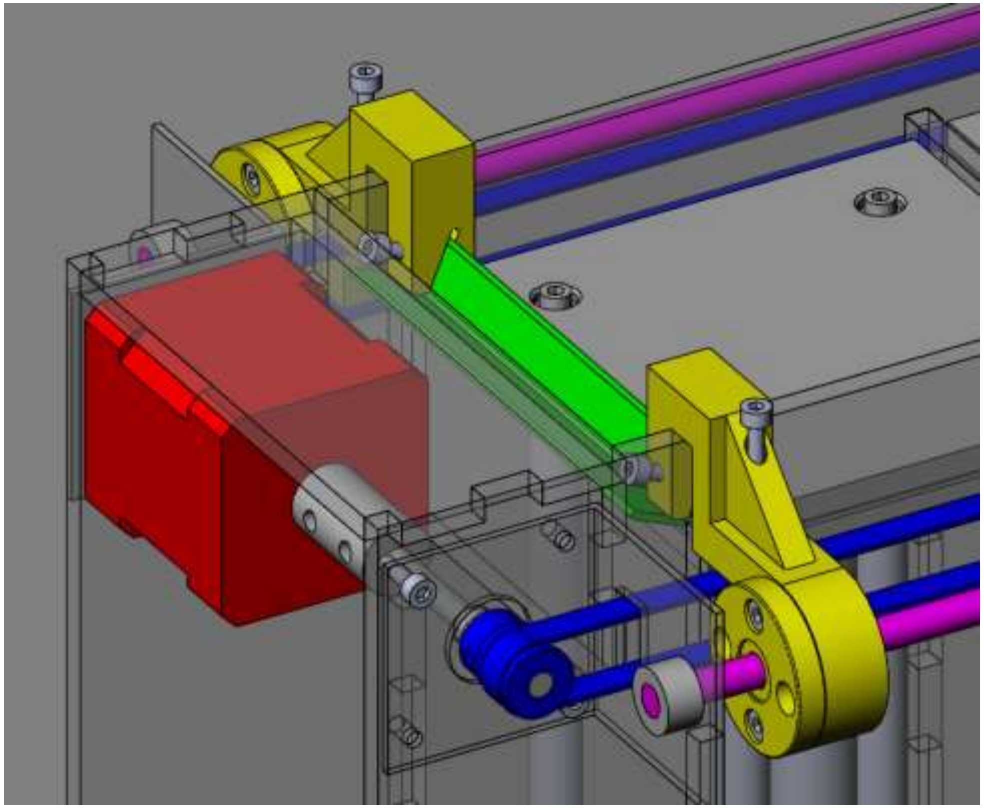
- Ball Nut/Screw Assembly (Red/Blue)
  - Turns rotation from motor into vertical motion
- Holder Rods (Green)
  - Provide counter-torque and keep piston head level
- Motor (Bottom)
  - NEMA23 provides torque to lift piston
- Holder Bearings (Not shown)
  - Reduce friction from holder rods to negligible amounts



Rake Subassembly

- ➢Motor (Red) turns MLX Pulleys and Belt (Blue)
- ➢Rake Holders (Yellow) pinch onto the belt and move with it
- ➢Rake (Green) clamped into Holders and flattens powder
- ➢Holders ride along guide rails (Magenta) to stay level

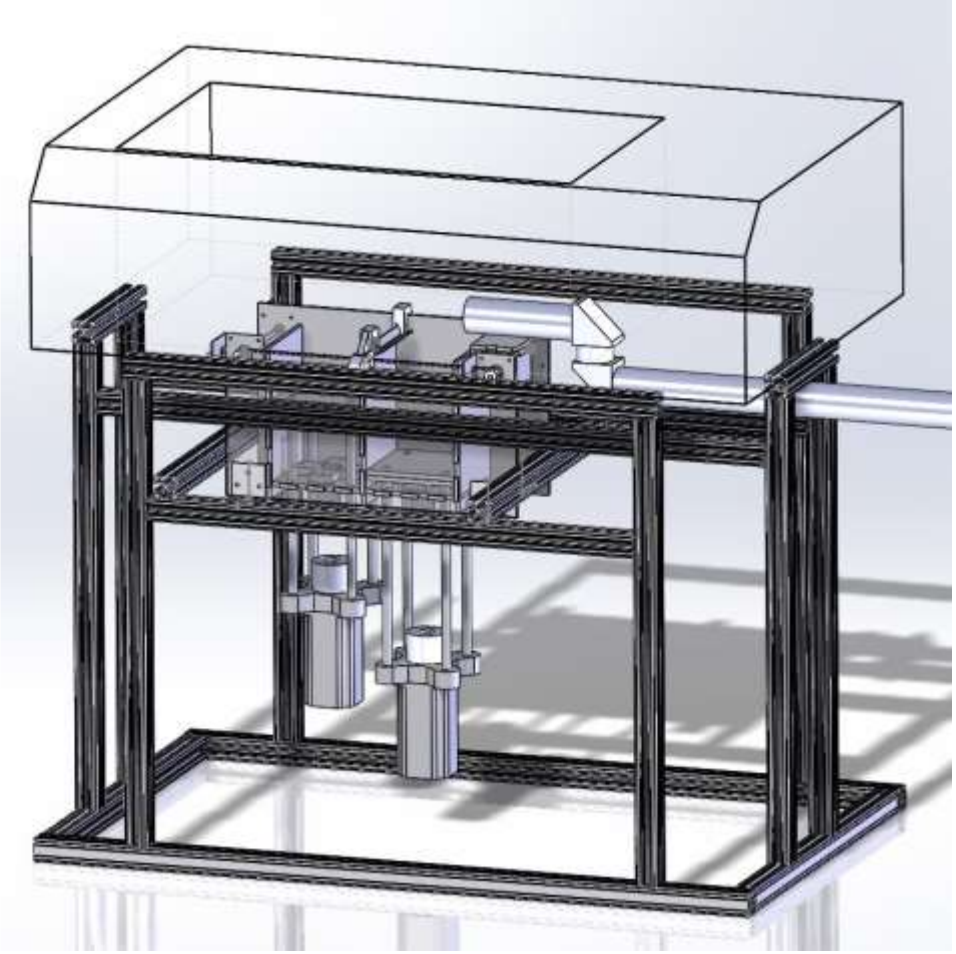
- ➢Note: Rake is low enough that it can travel under the laser

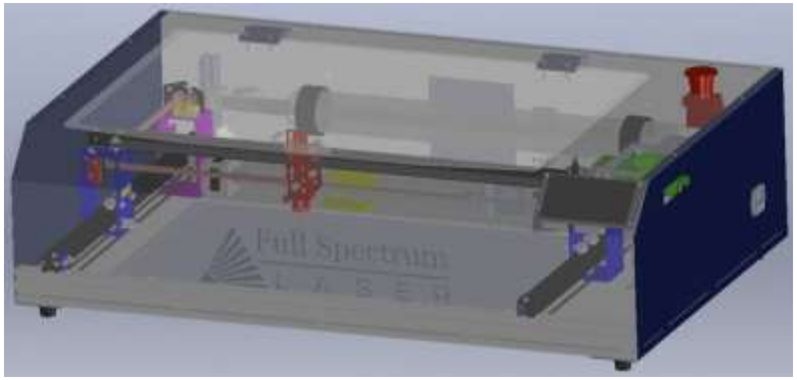


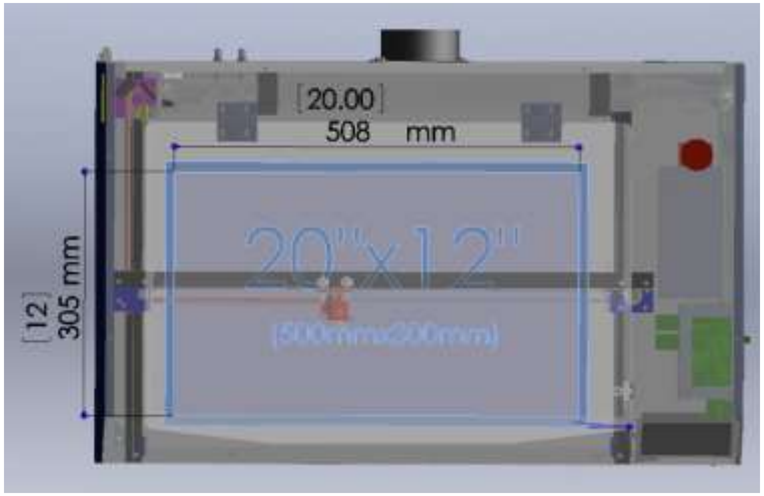
Integration

Overall System View

Laser Cutter Frame Overview

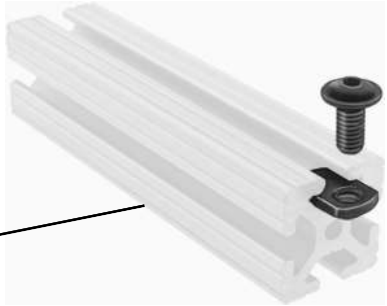


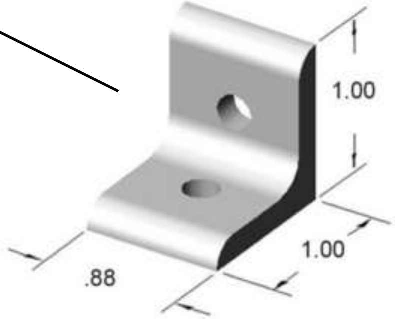




Specifications: Frame Hardware

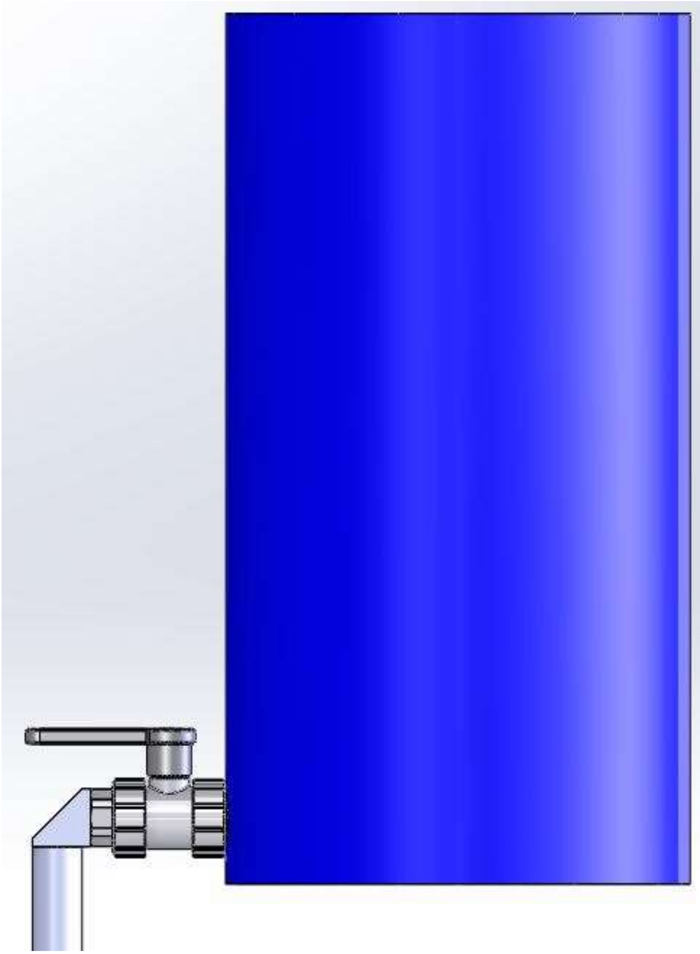
- T-Slot 10 Series 6105-T5 aluminum (462in needed)
  - Sold in 20ft lengths, 40ft will be purchased
- ¼”-20 T-Slotted Fasteners (12 needed)
- ¼” Concealed connectors (24 needed)
- 1” x 1” corner brackets (12 needed)
- ¼”-20 x ½” BHSCS (24 needed)
- ¼”-20 T-nut (24 needed)





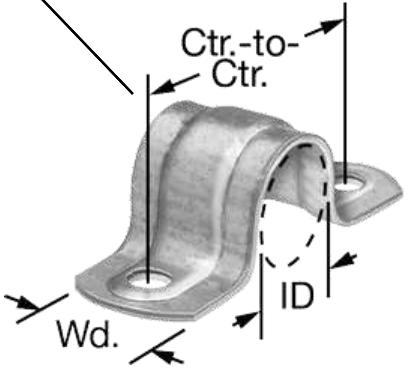
Water Safety Subsystem

- Maximum rate of energy release by propellant during ignition (spherical burn regression model)
  - 278 J/s
- If water temperature is raised 1°C
  - Required volumetric flow rate to powder bed is ~1 gal/min
- For chosen tubing, water level must be higher than ~3 ft above powder bed

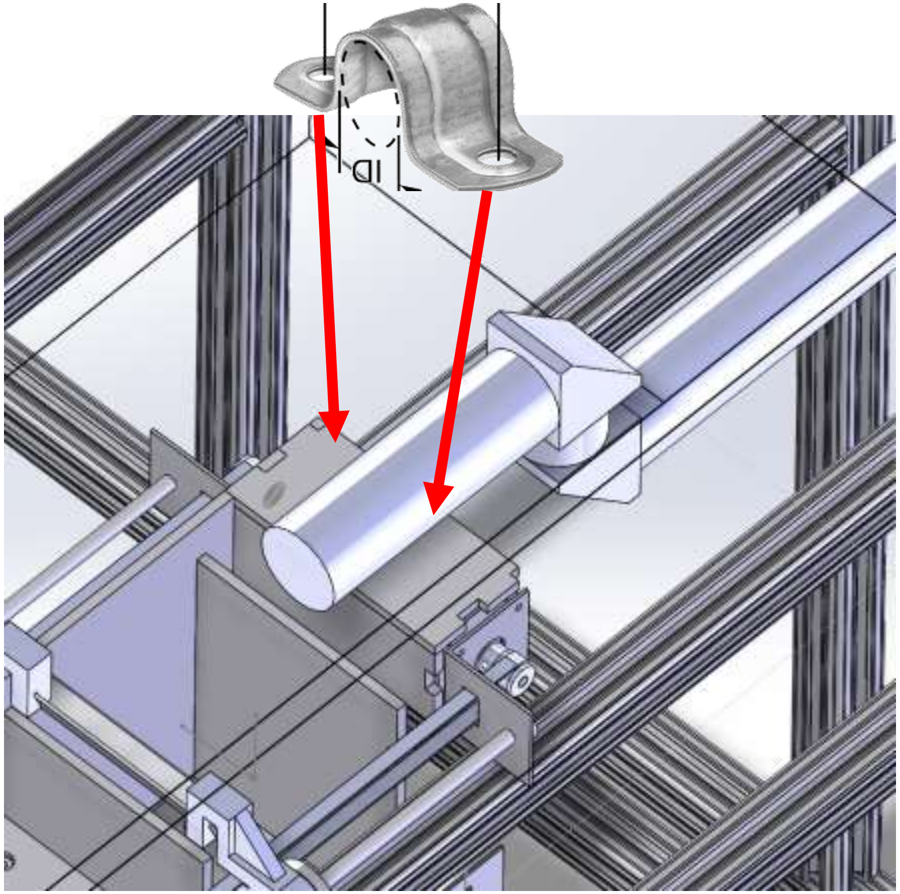


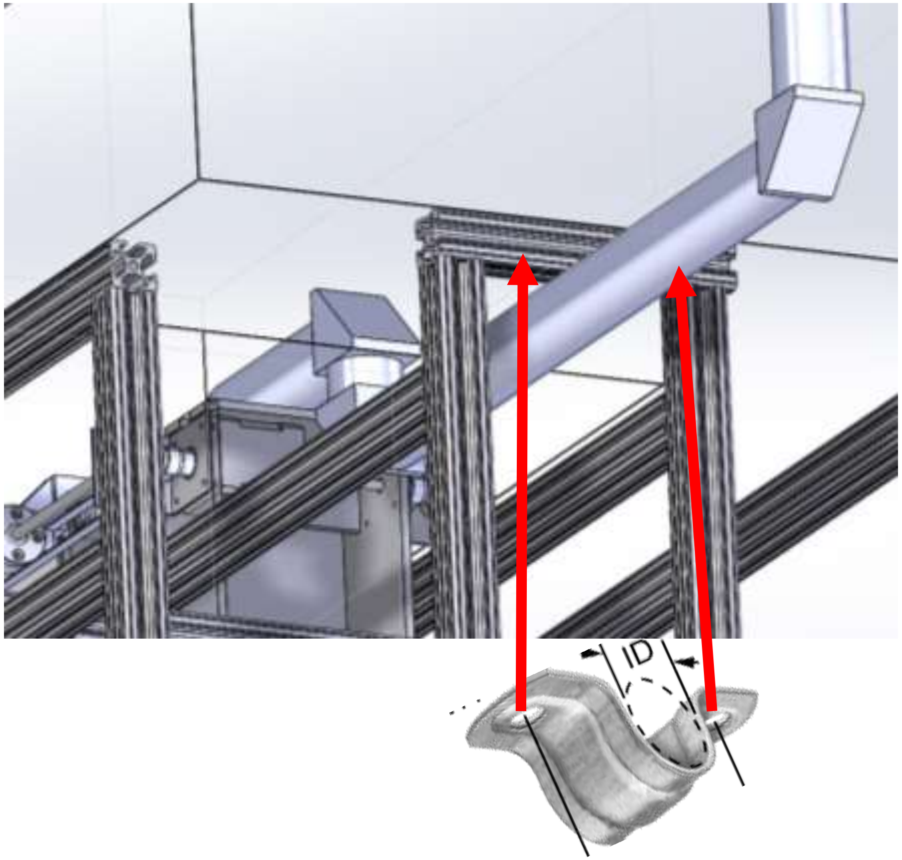
Specifications: Safety Subsystem

- 15 gallon water container (1 needed)
- 1” ball valve (1 needed)
- 1”ID 1.5” OD PVC tubing (69in needed)
- 1”ID 1.5” OD PVC corner tubing (4 needed)
- 1.5” ID Steel Clamp (¼”mounting hole’s)
- ¼”-20 x ½” Pan head screw (4 needed)
- ¼”-20 T-nut (2 needed)

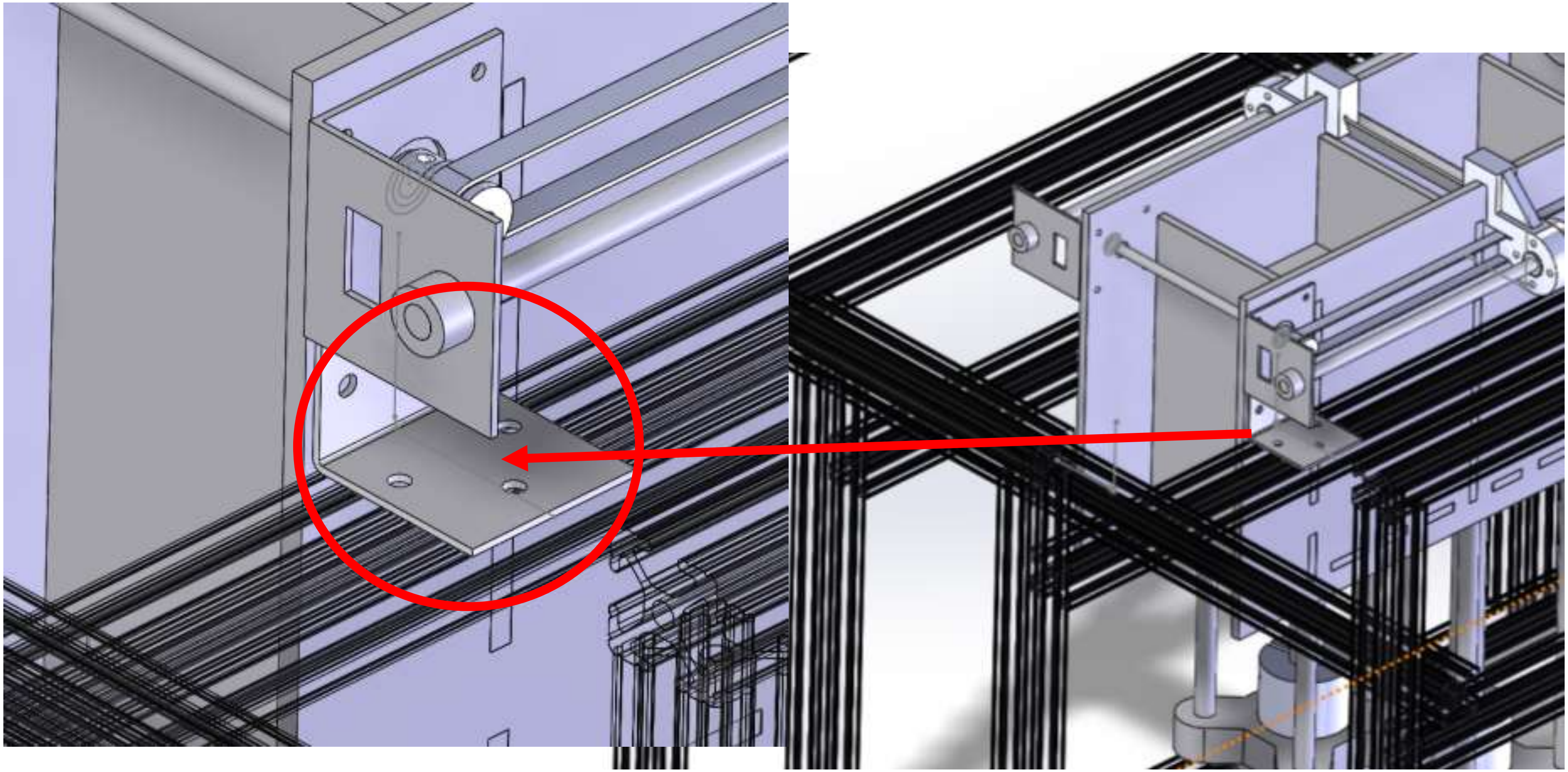


Clamp Positioning





Powder Bed Integration

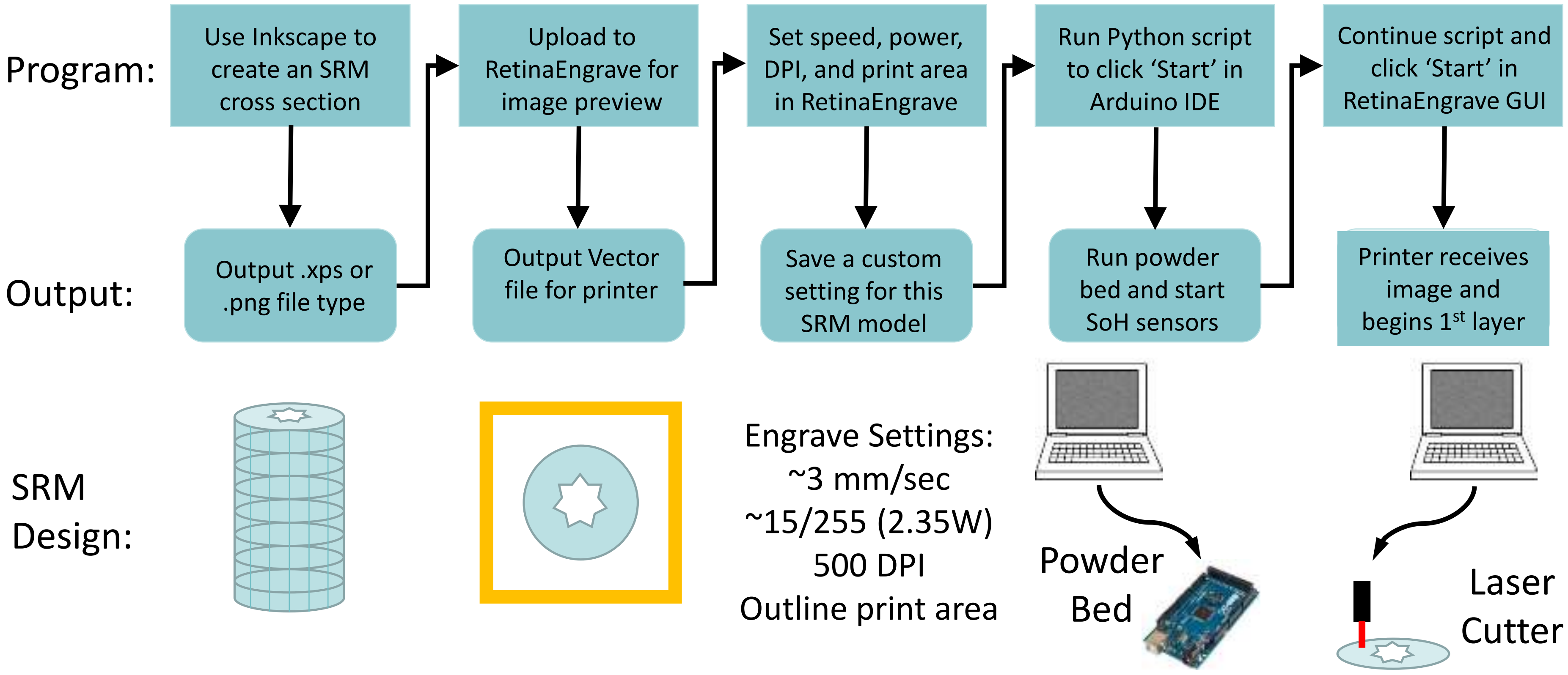


Software Integration

Software Requirements

ID	Description	Solution
1.1	Positioning system	Define the ‘Print Area’ and use ‘Move Relative’ in RetinaEngrave
1.2	Can use standard file types	RetinaEngrave can import standard image files (.png, .jpeg, .bmp) as well as .xps vector files
1.5	Autonomous printing	Sikuli-Python loops for necessary number of layers and automatically detects and clicks on GUI buttons
3.1	Powder bed raises 1mm +/- .3mm	Arduino script handling the motor drivers can implement .0256mm increments before micro stepping
5.5	State of Health System	Able to detect a fire through thermal and CO sensors checked on a continuous loop during sintering

Flow Chart for a Single Print Job



Program:

Use Inkscape to create an SRM cross section

Upload to RetinaEngrave for image preview

Set speed, power, DPI, and print area in RetinaEngrave

Run Python script to click ‘Start’ in Arduino IDE

Continue script and click ‘Start’ in RetinaEngrave GUI

Output:

Output .xps or .png file type

Output Vector file for printer

Save a custom setting for this SRM model

Run powder bed and start SoH sensors

Printer receives image and begins 1st layer

SRM Design:

Engrave Settings:
~3 mm/sec
~15/255 (2.35W)
500 DPI
Outline print area

Steps for Full Automation

- Sikuli script uses image recognition to find and interact with GUI

1) Sikuli-Python script clicks ‘Start’ in Arduino IDE then pauses
    a. Powder bed pistons activated
    b. SoH sensors activated after pistons finish

2) Sikuli-Python script continues by clicking ‘Start’ in RetinaEngrave
    a. Laser cutter prints a full layer
    b. SoH sensors still running

3) Pause for sintering then stop the Arduino sketch
    a. One layer finished and Arduino reset

4) Repeat steps 1-3 for as many layers needed for the SRM

Electronics

Electrical System Requirements

ID	Description	Solution
1.1.2	Positioning accuracy of powder bed shall be 1mm +/- .3mm	Stepper motors are capable of rotating $1.8^0 \pm 0.09^0$. This correlates to 0.0257 mm ± 0.0013 mm
3.4	Microcontroller must control powder bed system	Drivers operate at 0-5V, 10mA logic
5.5	SOH system shall detect fire	Infrared, CO sensors
5.5.1	Shall detect CO levels of 1000ppm	CO sensor detects 200-5000 ppm
5.5.2	Shall detect temperature 150°C to 300°C +/- 5°C	Infrared sensor detects -70 ^{0}C to 380 ^{0}C with a an error of ±5^{0}C
5.5.3	Shall alert operator of harmful system operating conditions	9000 mCd LED and a 103 Db buzzer

Electrical System Overview

- 2 DC Power Supplies
- 1 Microcontroller
  - Arduino Mega 2560
- 3 Stepper motors and drivers
  - Move rake and powder bed pistons
- 3 Rotary Encoders
  - Record angular position of motors
- 4 snap switches
  - Stop motors if they have moved to far
- 1 LED and Buzzer warning system
  - Alerts printer user of an impending fire
- 2 SOH Sensors
  - Infrared Thermometer
  - Carbon Monoxide Sensor

Driver

Motor

Encoder

Snap Switch

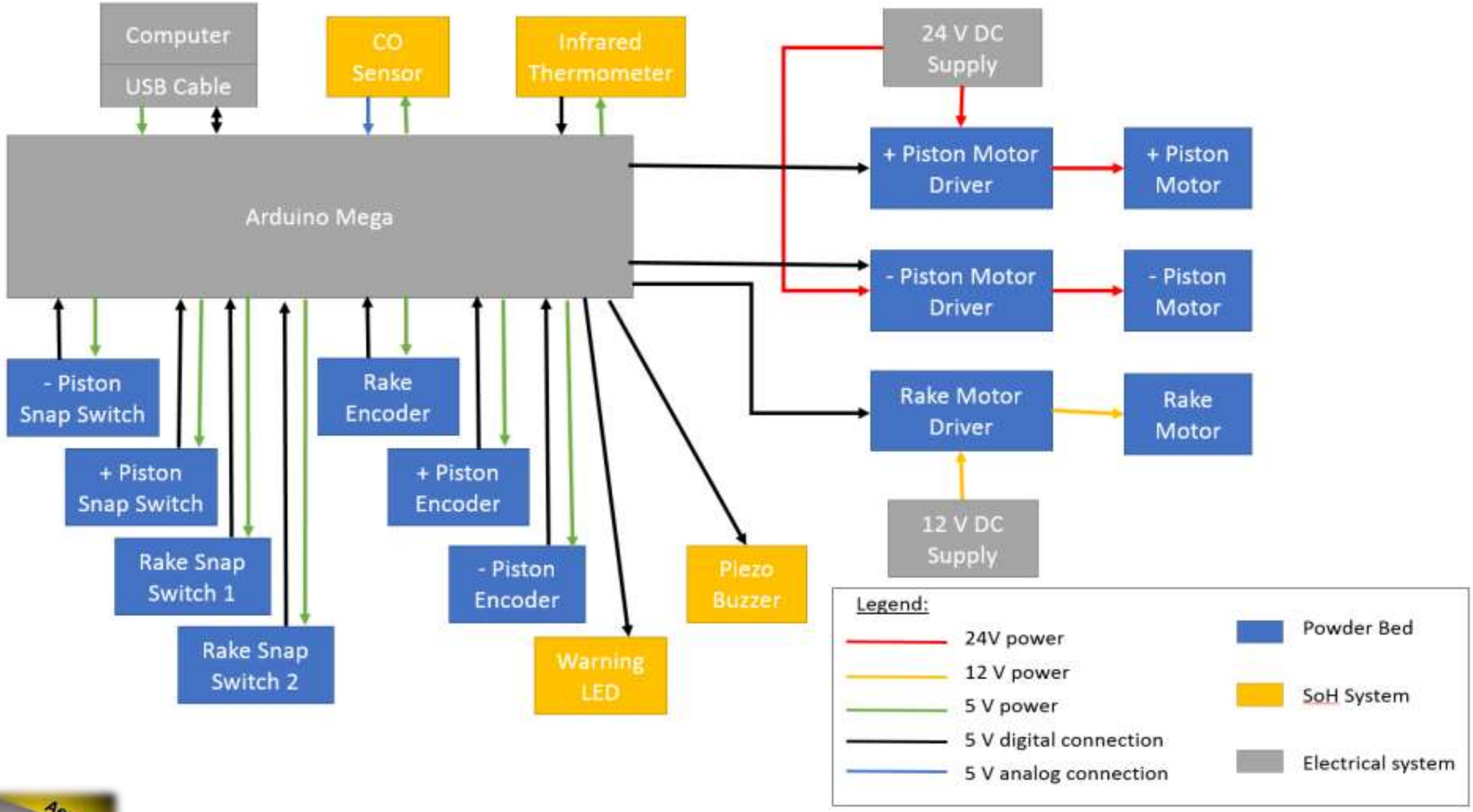
LED

Buzzer

Infrared Thermometer

Carbon Monoxide Sensor

Electrical System FBD



Computer

USB Cable

CO Sensor

Infrared Thermometer

24 V DC Supply

Arduino Mega

+ Piston Motor Driver

+ Piston Motor

- Piston Motor Driver

- Piston Motor

Rake Motor Driver

Rake Motor

12 V DC Supply

- Piston Snap Switch

+ Piston Snap Switch

Rake Snap Switch 1

Rake Snap Switch 2

Rake Encoder

+ Piston Encoder

- Piston Encoder

Warning LED

Piezo Buzzer

Legend:

- 🟥 24V power
- 🟨 12 V power
- 🟩 5 V power
- ⬛ 5 V digital connection
- 🟦 5 V analog connection

- 🟦 Powder Bed
- 🟨 SoH System
- ▨ Electrical system

External Power Supply Budget

12 V External Power Supply

Component	Part Number	Operating Voltage [V]	Operating Current [A]	Operating Power [W]
Rake Motor	17HS19-1684D	12	1.68	20.16
Total	N/A	12	1.68	20.16
12 V Power Supply	PSS12-035	12	3	35

24 V External Power Supply

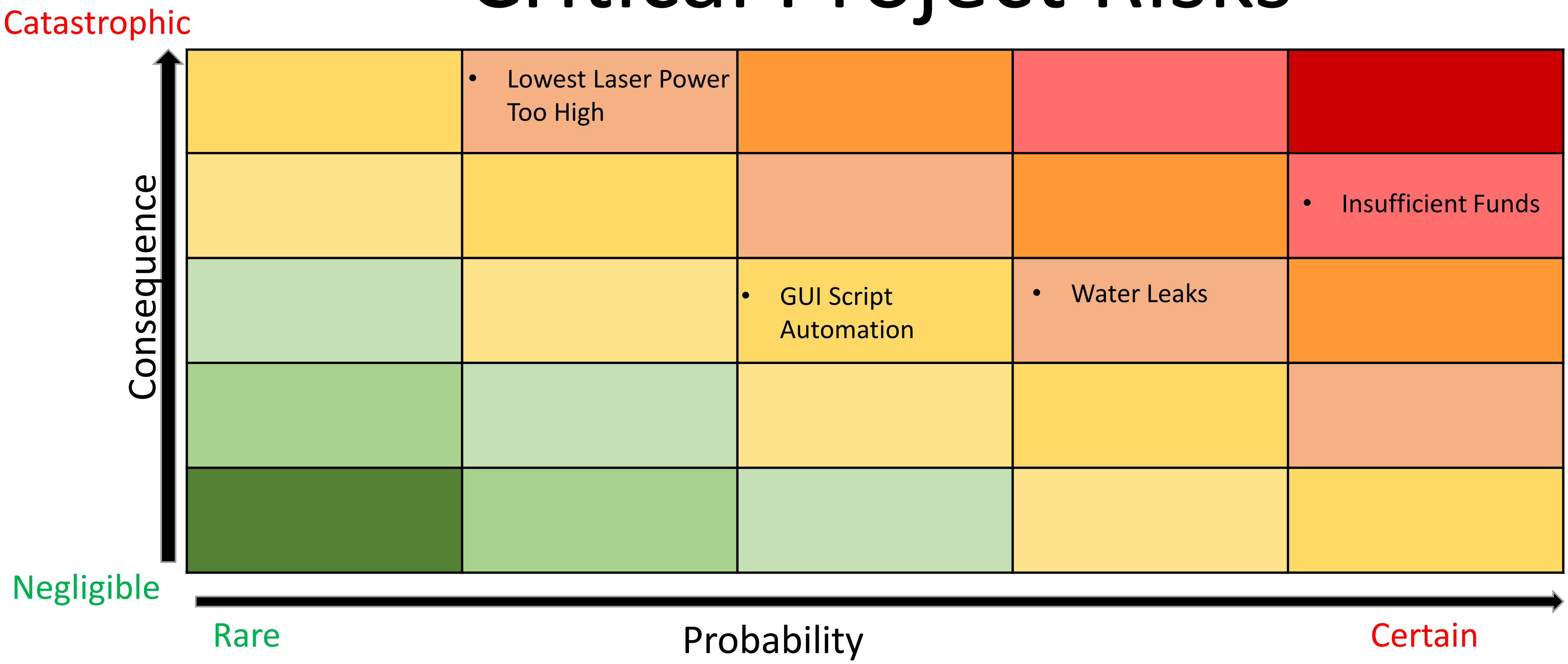
Component	Part Number	Operating Voltage [V]	Operating Current [A]	Operating Power [W]
+ Piston Motor	23HS41-1804S	24	1.8	43.2
- Piston Motor	23HS41-1804S	24	1.8	43.2
Total	N/A	24	3.6	86.4
24 V Power Supply	PSS24-100	24	4.17	100

Arduino Power Budget

Component	Part Number	Operating Voltage [V]	Operating Current [A]	Operating Power [W]
Infrared Thermometer	MLX90614	5	0.001	0.005
Carbon Monoxide Sensor	MQ-7	5	0.180	0.9
Rake Encoder	AMT102-V	5	0.006	0.03
+ Piston Encoder	AMT102-V	5	0.006	0.03
- Piston Encoder	AMT102-V	5	0.006	0.03
Rake Snap Switch 1	TS0101F020P	5	0.01	0.05
Rake Snap Switch 2	TS0101F020P	5	0.01	0.05
+ Piston Snap Switch	TS0101F020P	5	0.01	0.05
- Piston Snap Switch	TS0101F020P	5	0.01	0.05
Total	N/A	5	0.239	1.195
Arduino 5V pin	N/A	5	0.5	2.5

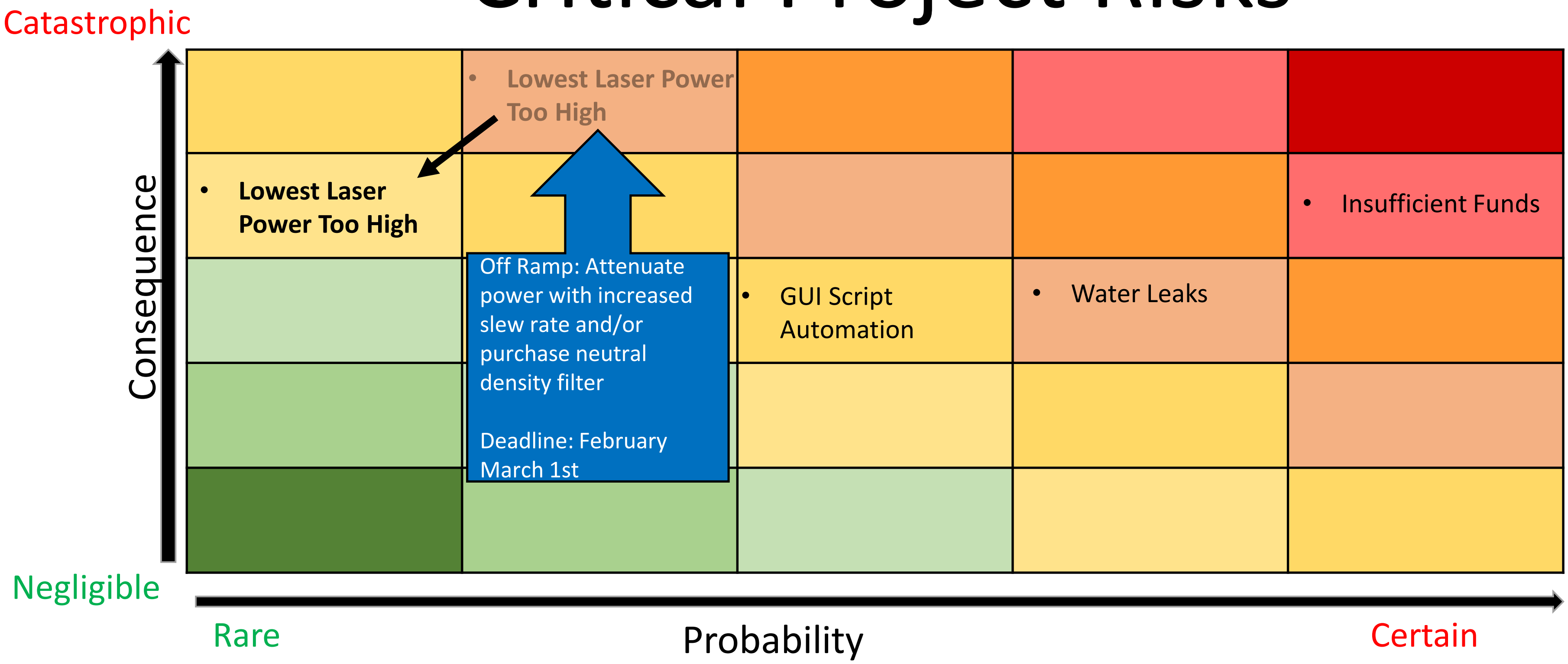
Risk Mitigation

Critical Project Risks



	• Lowest Laser Power Too High			
				• Insufficient Funds
		• GUI Script Automation	• Water Leaks	

Critical Project Risks



Catastrophic

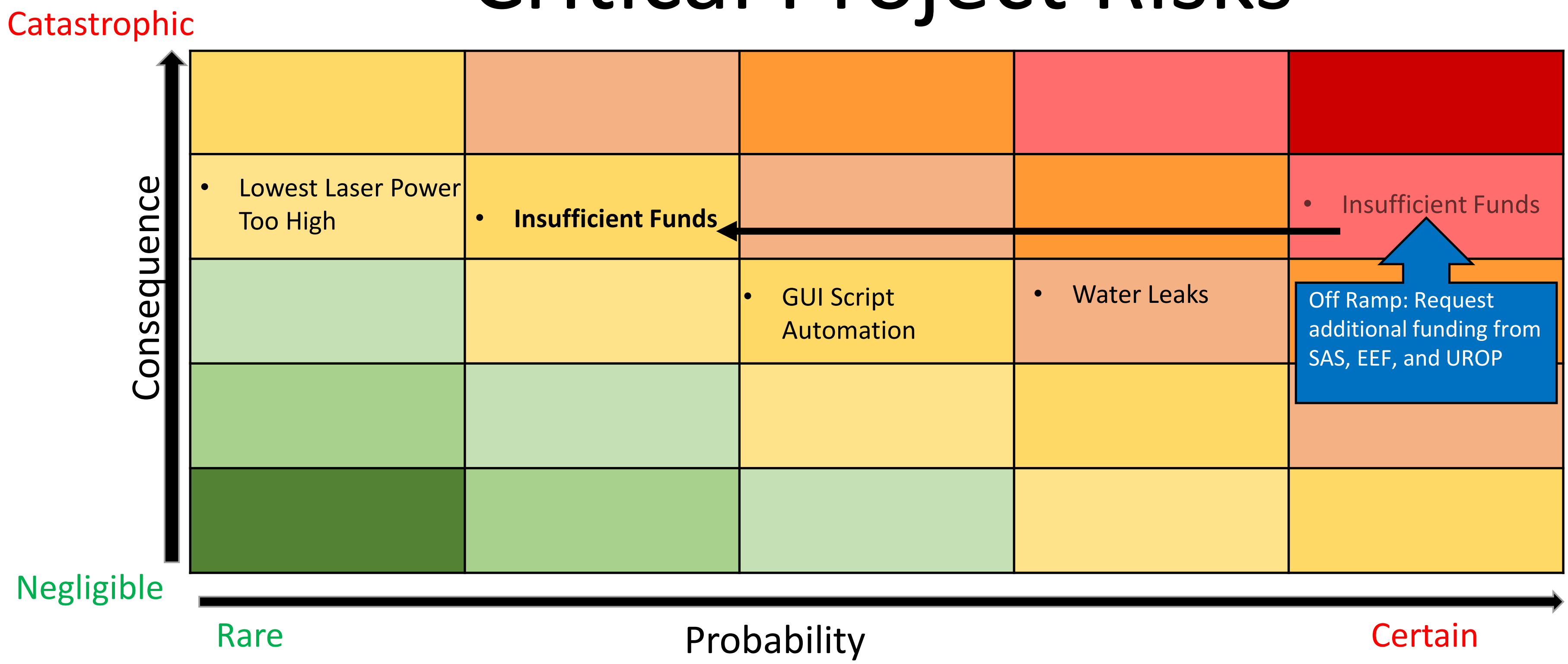
	- Lowest Laser Power Too High			
- **Lowest Laser Power Too High**				- Insufficient Funds
		- GUI Script Automation	- Water Leaks	

Negligible

Off Ramp: Attenuate power with increased slew rate and/or purchase neutral density filter

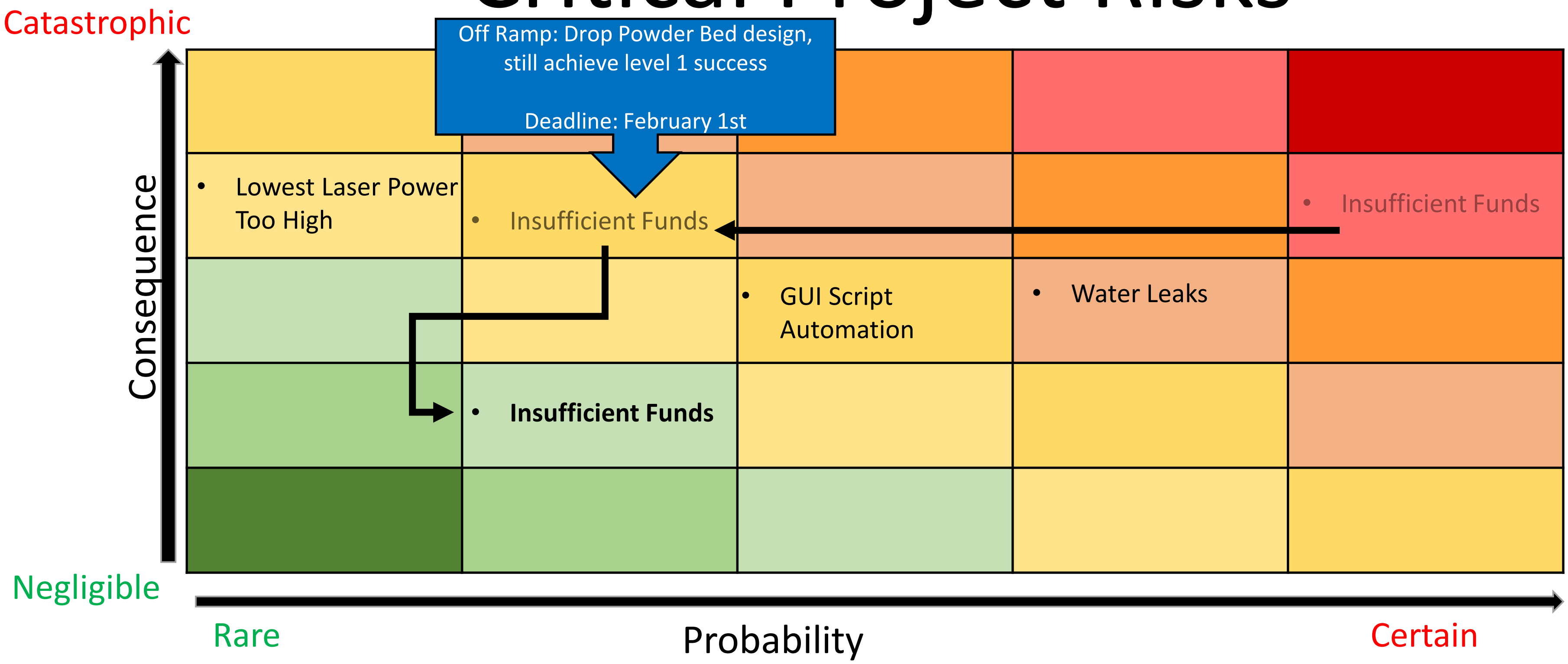
Deadline: February March 1st

Critical Project Risks



Lowest Laser Power Too High	**Insufficient Funds**			Insufficient Funds
		GUI Script Automation	Water Leaks	Off Ramp: Request additional funding from SAS, EEF, and UROP

Critical Project Risks



Catastrophic

Off Ramp: Drop Powder Bed design, still achieve level 1 success

Deadline: February 1st

- Lowest Laser Power Too High
- Insufficient Funds
- Insufficient Funds
- GUI Script Automation
- Water Leaks
- **Insufficient Funds**

Consequence

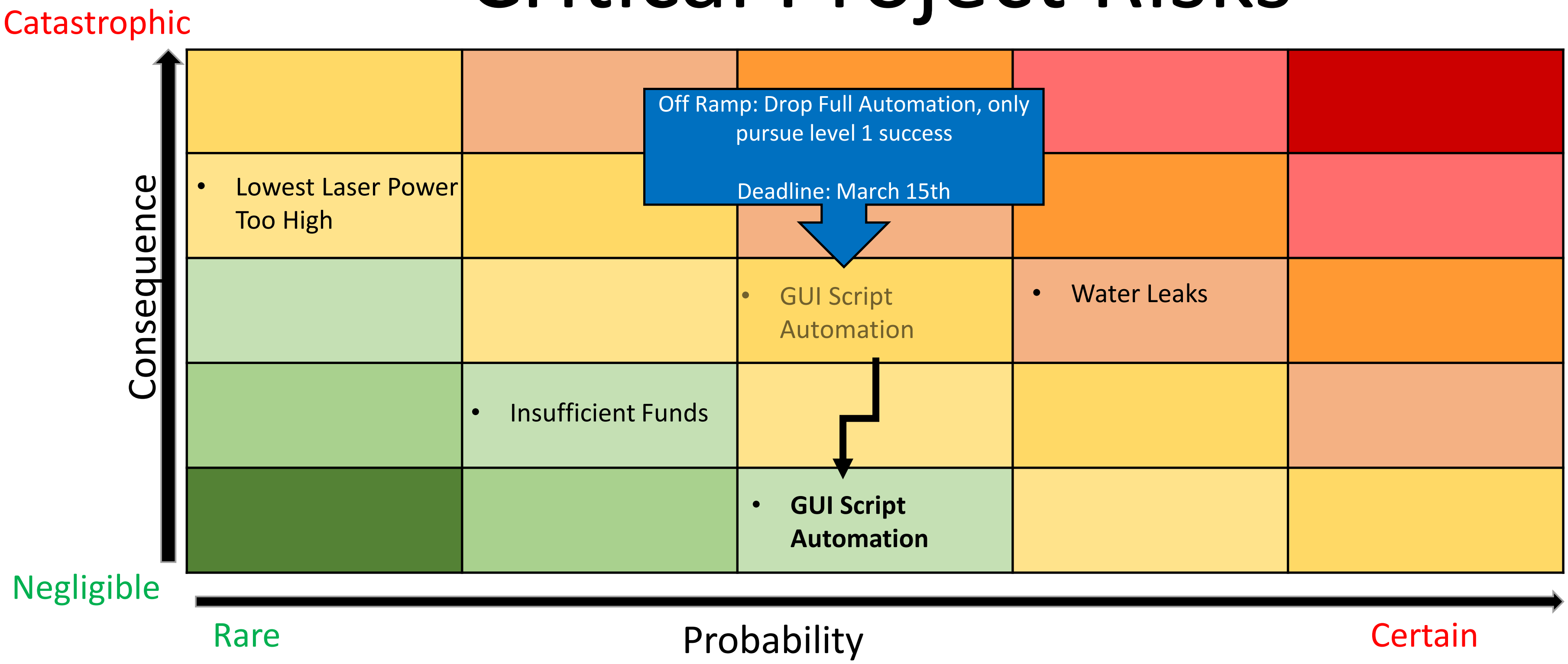
Negligible

Rare

Probability

Certain

Critical Project Risks

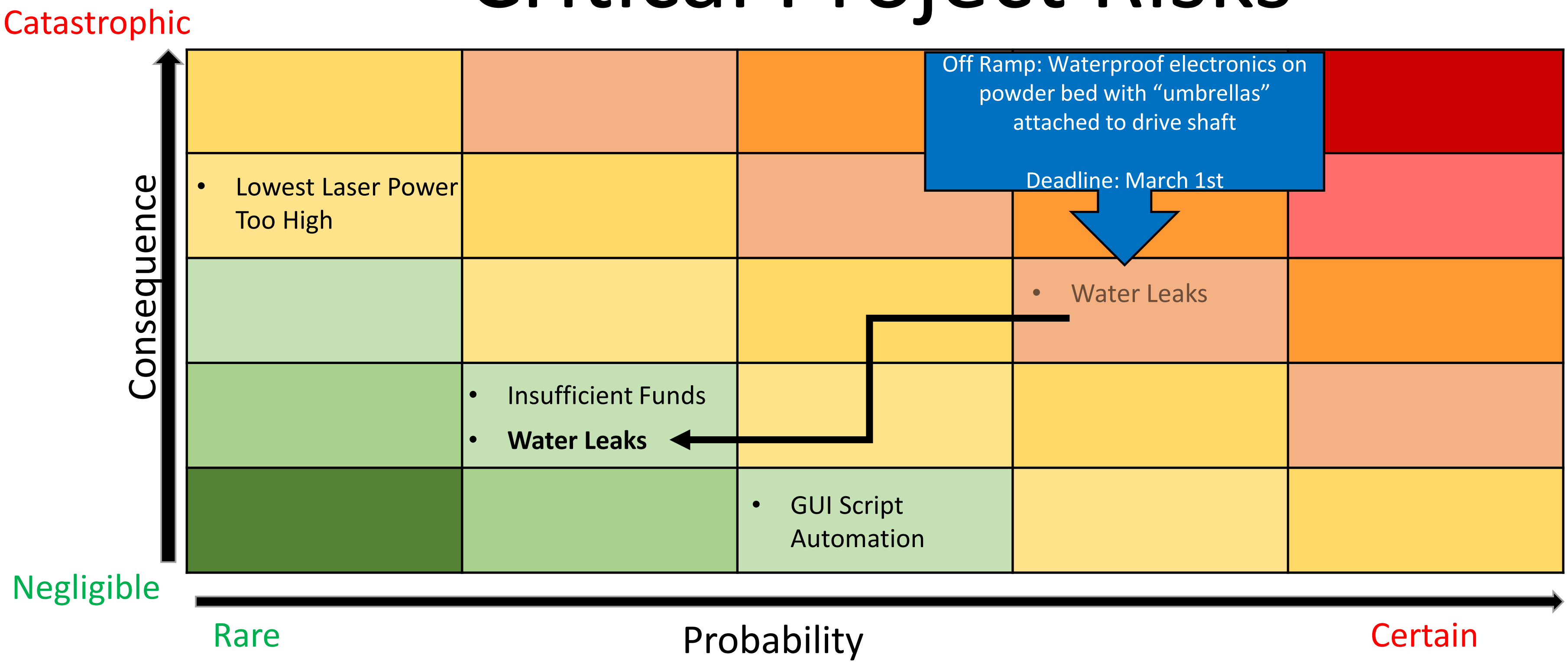


• Lowest Laser Power Too High				
		• GUI Script Automation	• Water Leaks	
	• Insufficient Funds			
		• **GUI Script Automation**		

Off Ramp: Drop Full Automation, only pursue level 1 success

Deadline: March 15th

Critical Project Risks

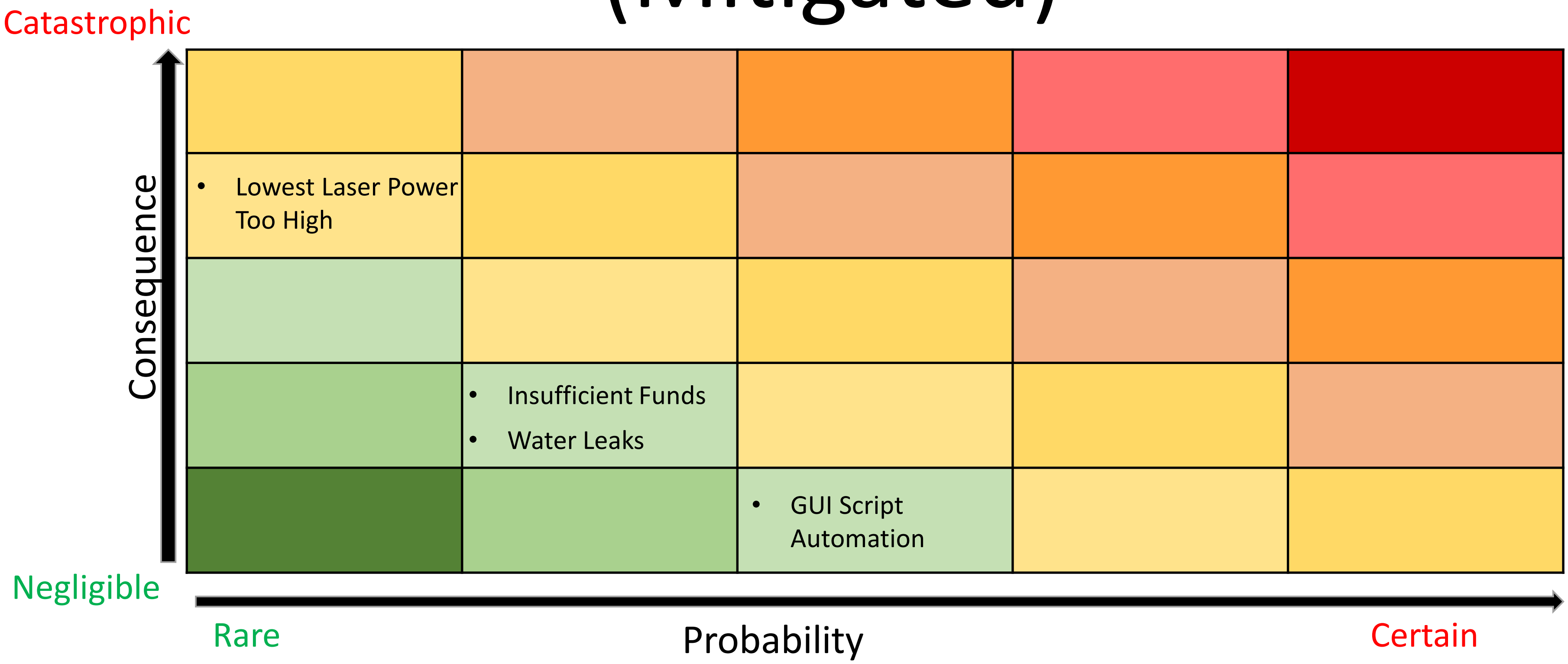


- Lowest Laser Power Too High				
			- Water Leaks	
	- Insufficient Funds - **Water Leaks**			
		- GUI Script Automation		

Off Ramp: Waterproof electronics on powder bed with "umbrellas" attached to drive shaft

Deadline: March 1st

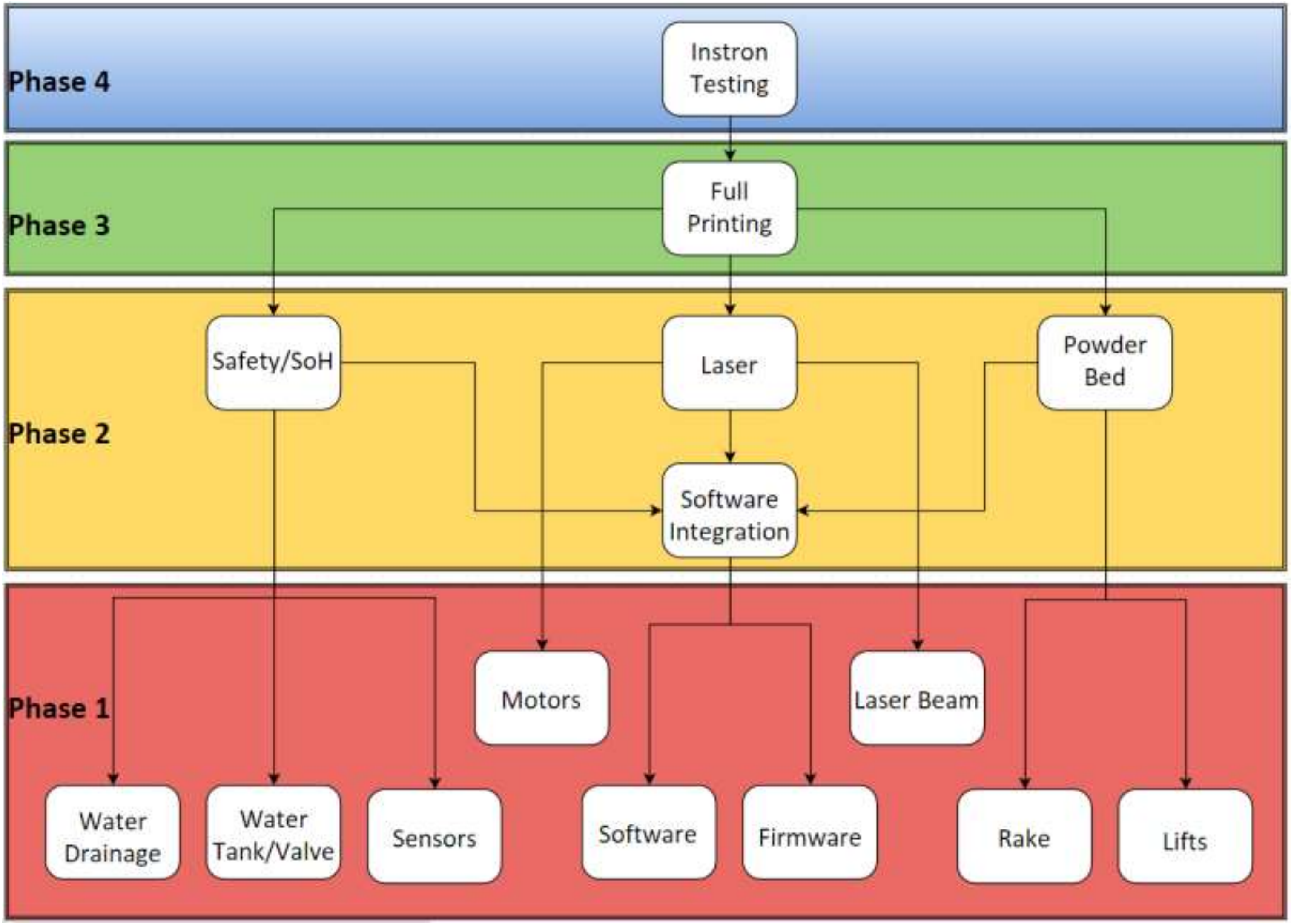
Critical Project Risks (Mitigated)



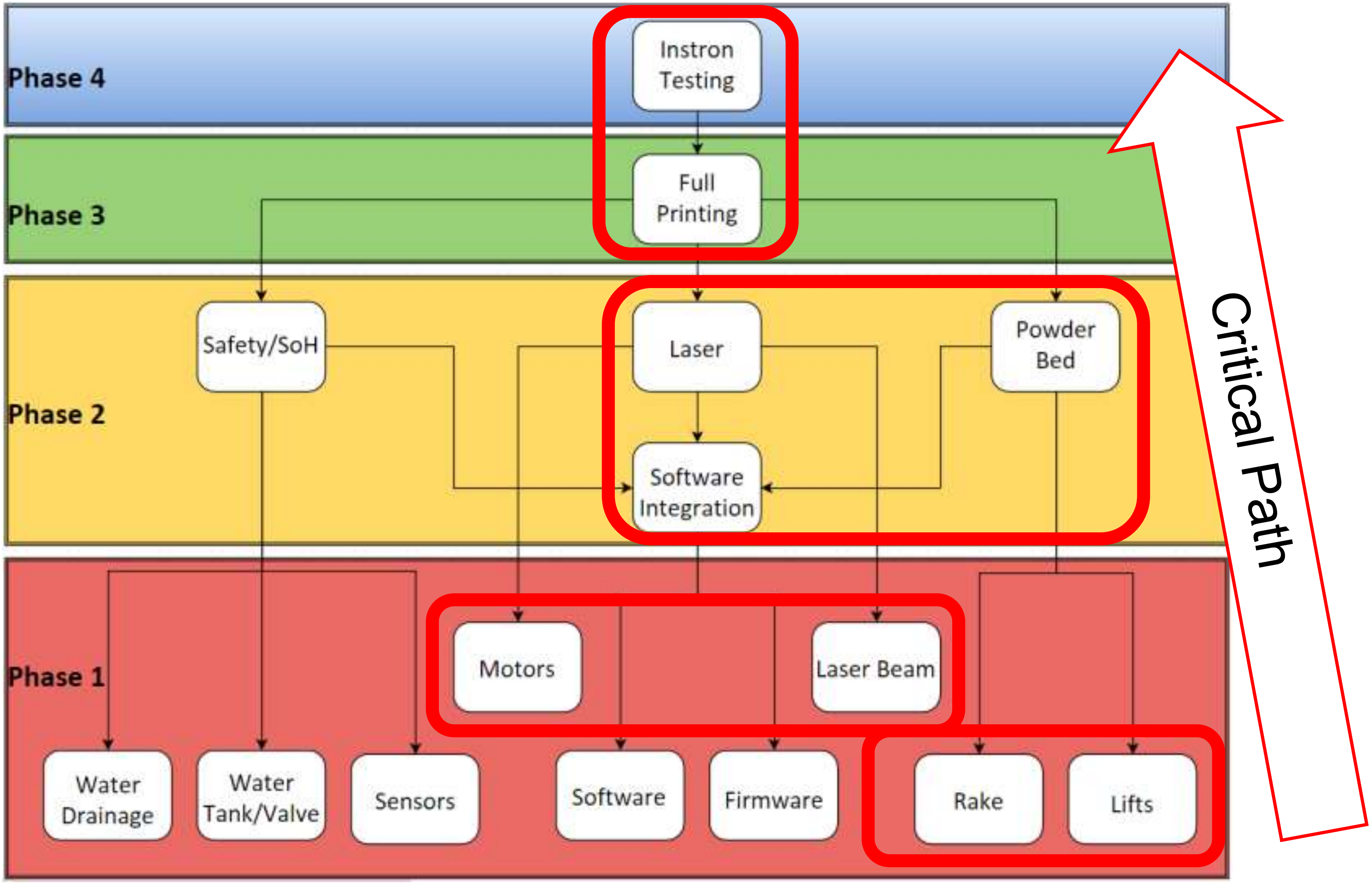
• Lowest Laser Power Too High				
	• Insufficient Funds • Water Leaks			
		• GUI Script Automation		

Verification and Validation

Validation and Verification Plan

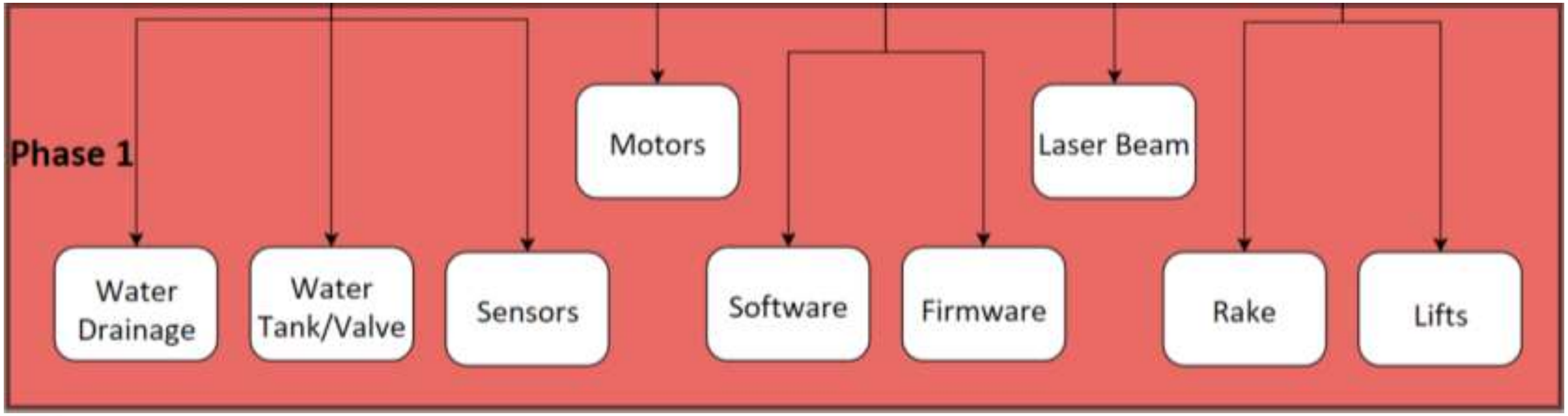


Validation and Verification Plan (Critical Path)



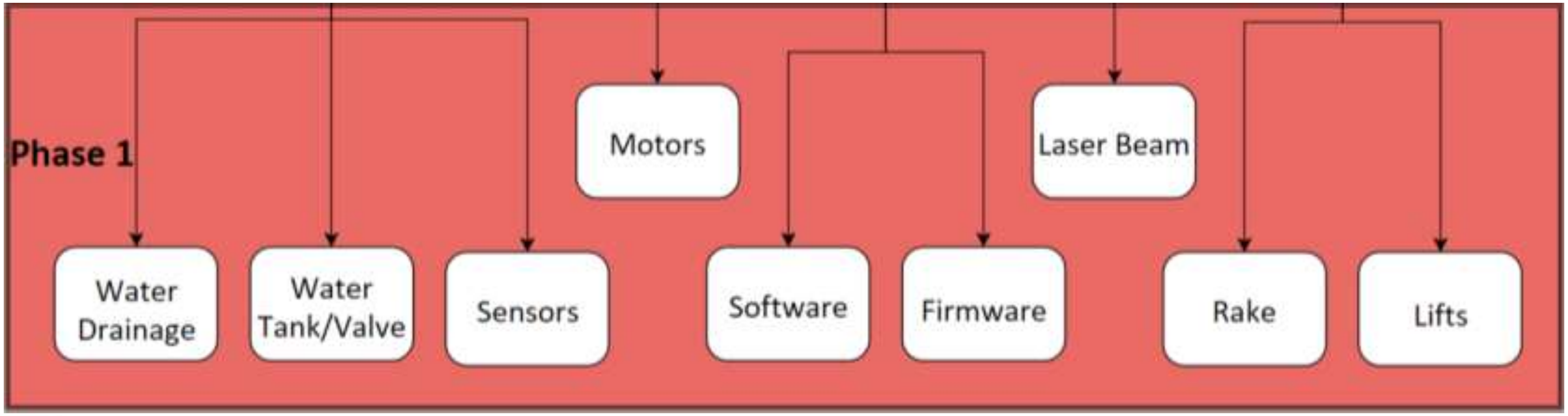
Validation and Verification: Phase 1

Requirement Designation	Description
DR 1.1	3D positioning system
FR 3	Powder transportation subsystem
DR 3.1	Layer depth of 1 mm
DR 3.2	Pistons move required mass of powder
DR 5.4	Model/predict heat transfer to powder



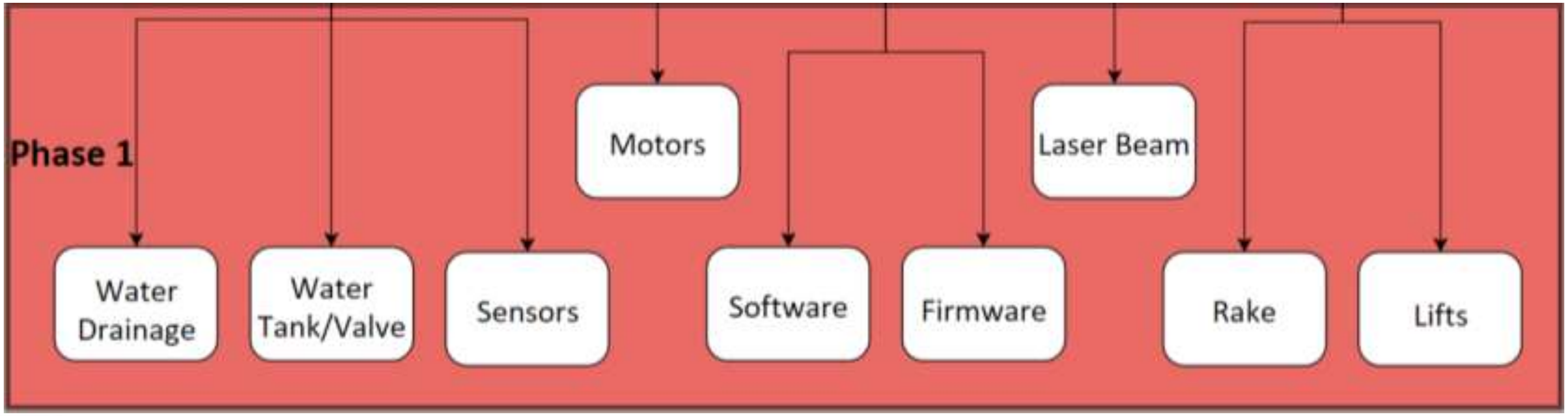
Validation and Verification: Phase 1

- 3D positioning; laser power/thermal model
  - COTS test laser cutting job
  - Does the laser hardware work?
  - Laser power measurement
    - Black body power sensor

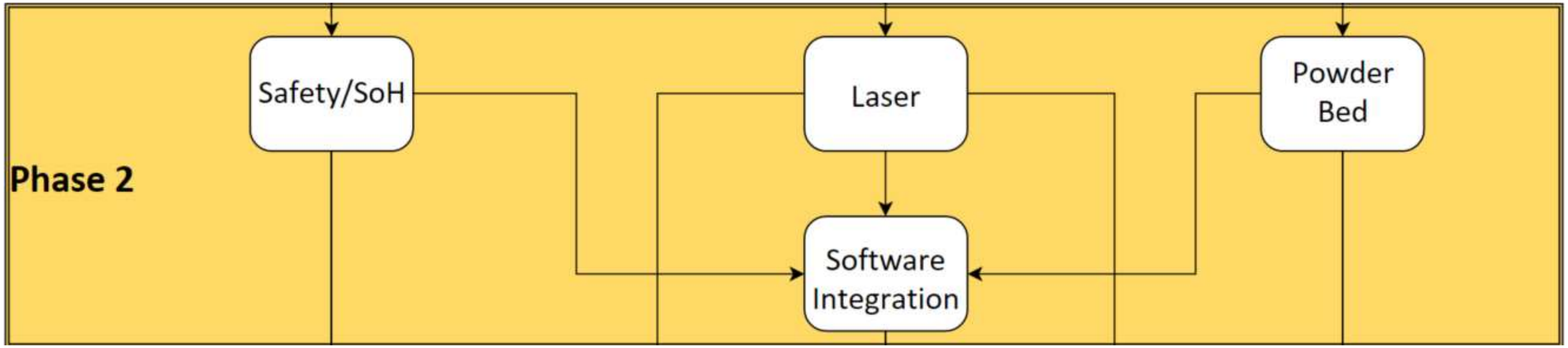


Validation and Verification: Phase 1

- Transportation system; 1mm layer depth
  - Rake sweep test with static pistons
  - Does the rake deposit a level layer of powder in the print area?
- Propellant transportation system; 1mm layer depth; pistons supply powder
  - Lift test with sugar
  - Do they move opposite directions? Does the gasket hold the powder?

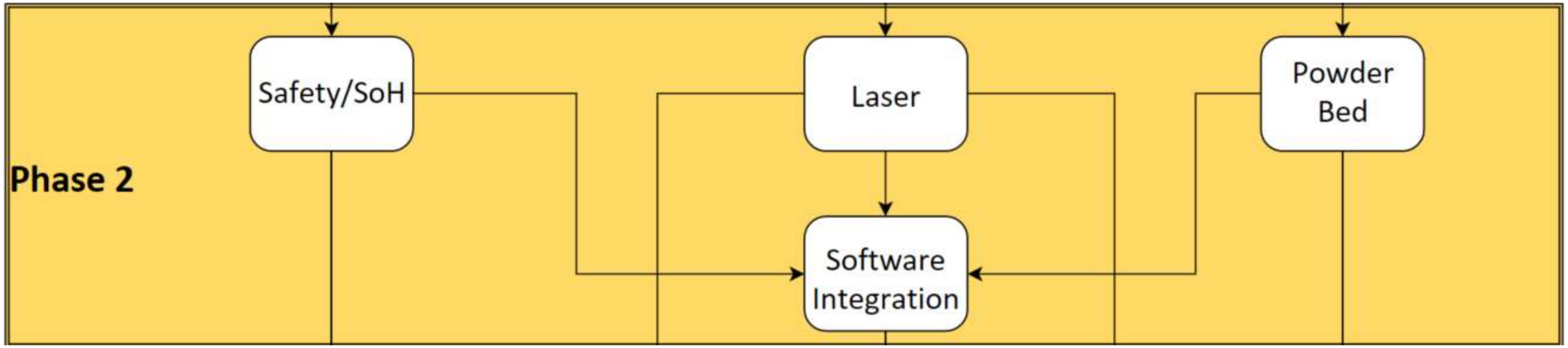


Validation and Verification: Phase 2



Requirement Designation	Description
FR 1	Functional automated 3D printer
FR 3	Powder transportation subsystem
FR 5	Safety system
DR 5.3	Implement fire extinguishing system
DR 5.4	Model/predict heat transfer to powder
DR 5.5	State of Health sensors

Validation and Verification: Phase 2



- Software integration and component integration
  - Safety system can detect and react to fire
  - Laser can deliver power needed to sinter which matches model
  - Powder bed can create layers of powder less than 1mm

Validation and Verification: Phase 3/4


Phase 4

Instron Testing

Requirement Designation	Description
DR 4.1	Printed vs. cast propellant comparison


Phase 3

Full Printing

Requirement Designation	Description
FR 1	Automated 3D printer
FR 2	Propellant composition
FR 3	Powder transportation subsystem

Validation and Verification: Phase 3/4

Phase 4

Instron Testing

- Level 3 success
    - Compare physical properties of printed vs. cast propellant
    - Does one fracture while the other holds?
    - Is 3D printing a viable replacement manufacturing technique for SRMs?

Phase 3

Full Printing

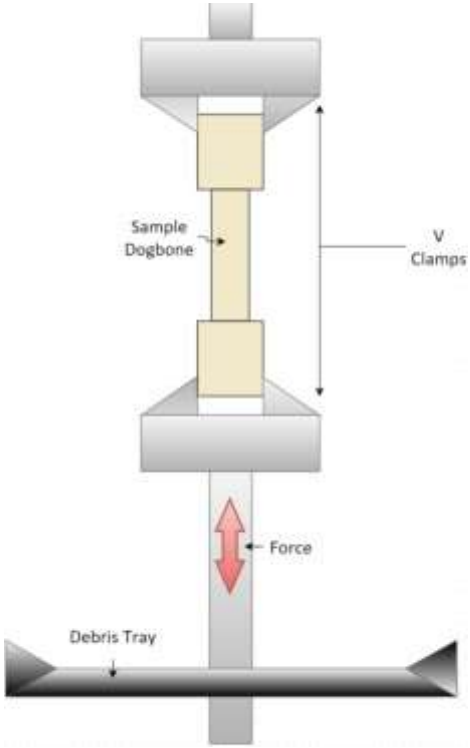
- Level 2 Success
    - Demonstrates additive manufacturing of solid rocket propellant
    - Satisfies all functional requirements
- Level 3 Success
    - Print 5 complex bore patterns

Test Plan: Full Printing

- Prerequisites
  - TRR green light
  - Sugar sinter test
- Location: Busemann Advanced Concepts Lab
- Personnel: 2
- Equipment: assembled printer, laser safety goggles, fire extinguisher, propellant powder, computer
- Print duration ~3 hours; constant supervision
- Predicted March 28 – April 4

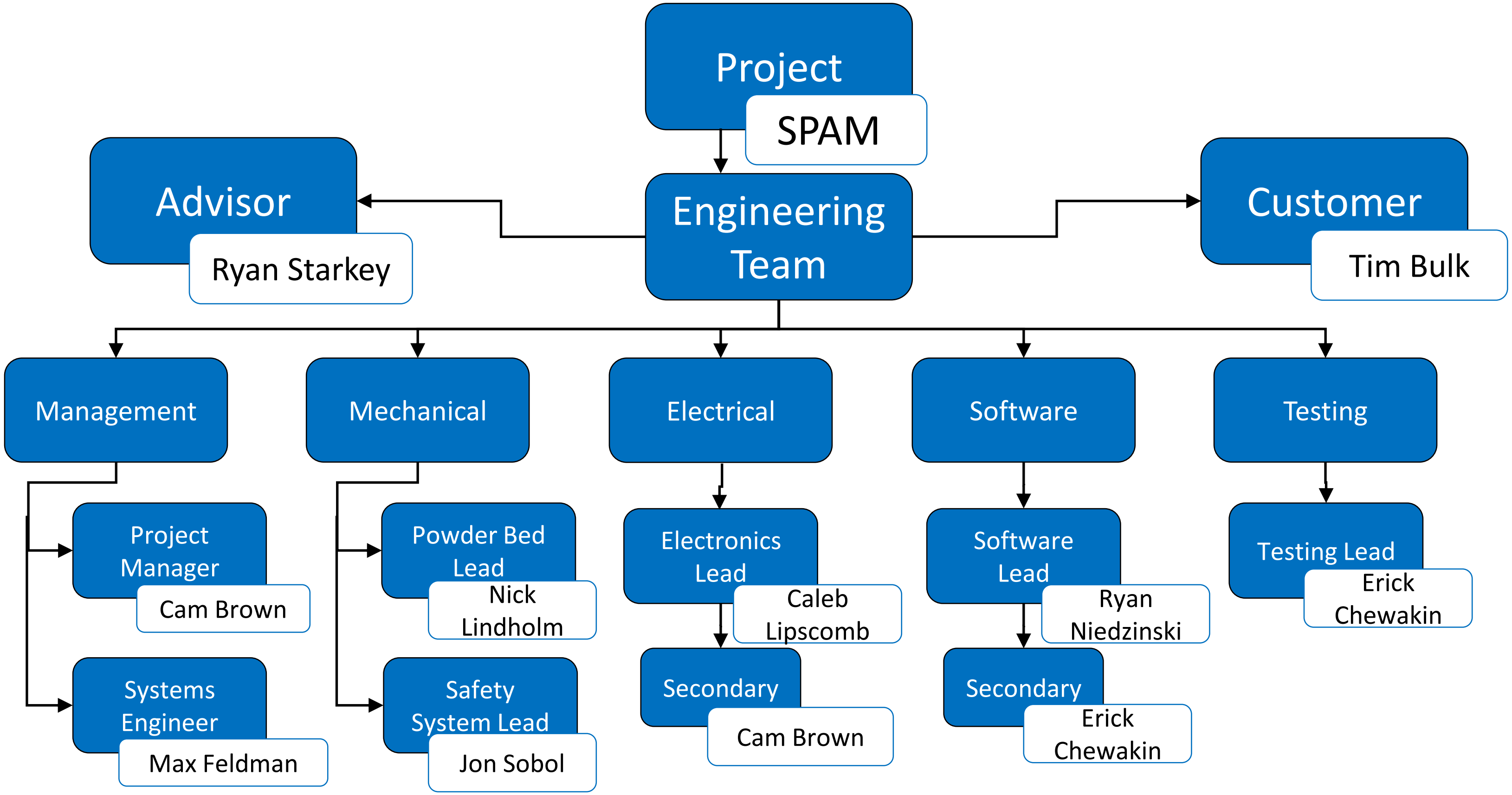
Test Plan: ITLL Instron Testing

- Tensile strength, crush strength
- Differences between printed and cast propellant? Is printing viable?
- Deformation measured via camera
- Max stress of 24 Mpa
    - Ignition from thermoelastic effects at 72 MPa
    - 271 lbf for our sample for Safety factor of 2.4
- Potential for propellant debris



Project Planning

Project Organization



Project

SPAM

Engineering Team

Advisor

Ryan Starkey

Customer

Tim Bulk

Management

- Project Manager: Cam Brown
- Systems Engineer: Max Feldman

Mechanical

- Powder Bed Lead: Nick Lindholm
- Safety System Lead: Jon Sobol

Electrical

- Electronics Lead: Caleb Lipscomb
- Secondary: Cam Brown

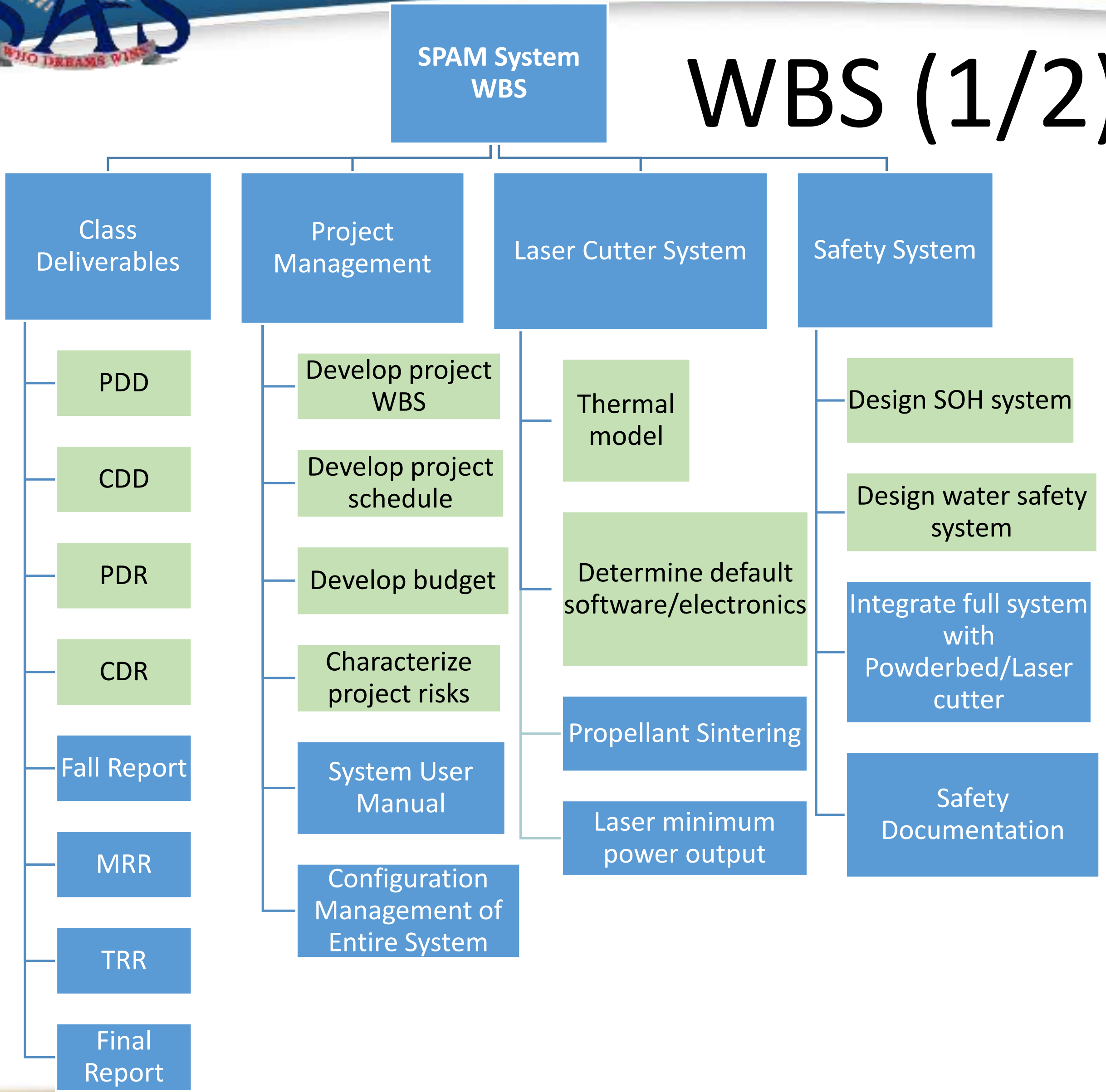
Software

- Software Lead: Ryan Niedzinski
- Secondary: Erick Chewakin

Testing

- Testing Lead: Erick Chewakin

WBS (1/2)



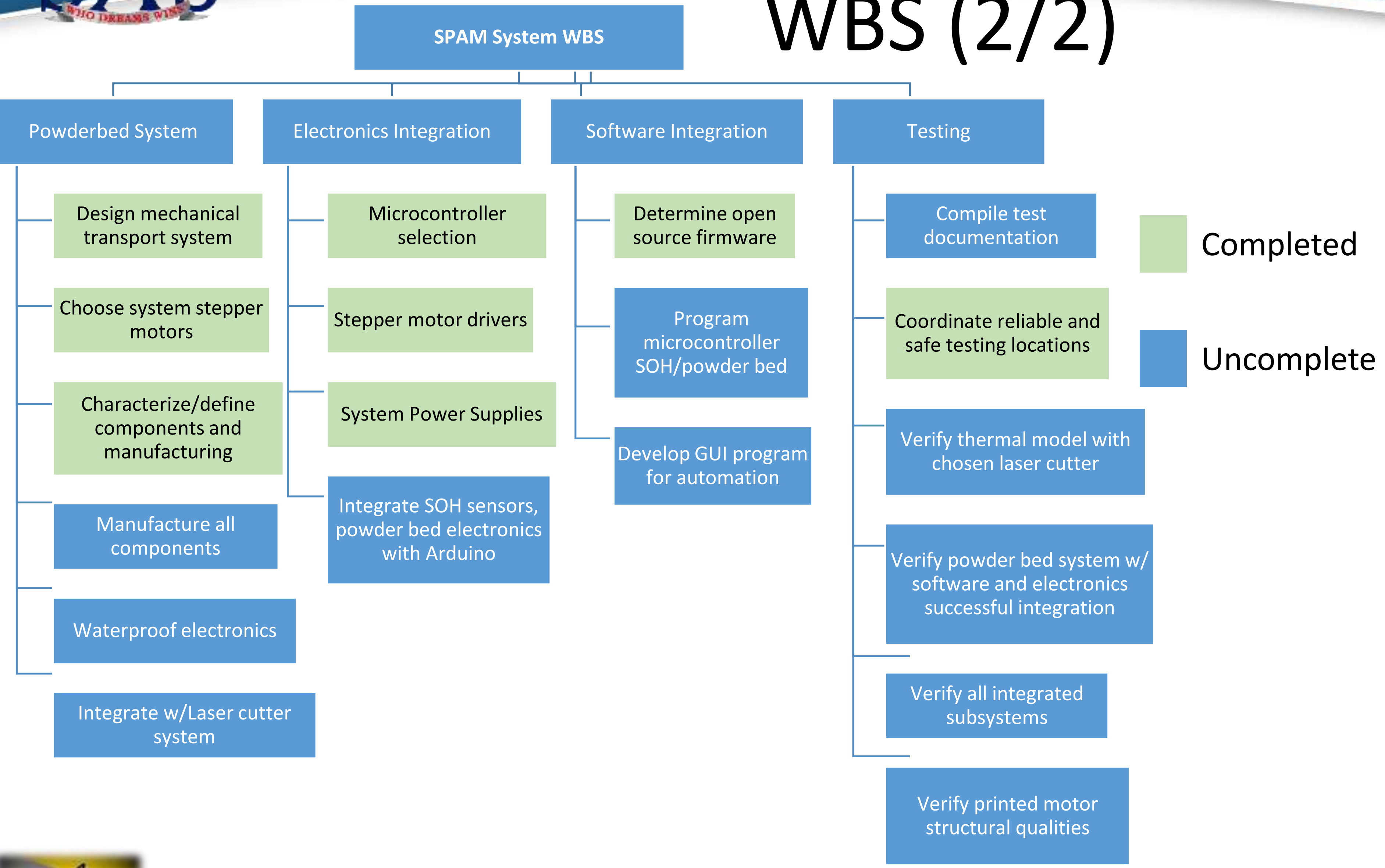
SPAM System WBS

- Class Deliverables
  - PDD
  - CDD
  - PDR
  - CDR
  - Fall Report
  - MRR
  - TRR
  - Final Report
- Project Management
  - Develop project WBS
  - Develop project schedule
  - Develop budget
  - Characterize project risks
  - System User Manual
  - Configuration Management of Entire System
- Laser Cutter System
  - Thermal model
  - Determine default software/electronics
  - Propellant Sintering
  - Laser minimum power output
- Safety System
  - Design SOH system
  - Design water safety system
  - Integrate full system with Powderbed/Laser cutter
  - Safety Documentation

🟩 Completed

🟦 Uncomplete

WBS (2/2)



SPAM System WBS

- Powderbed System
  - 🟩 Design mechanical transport system
  - 🟩 Choose system stepper motors
  - 🟩 Characterize/define components and manufacturing
  - 🟦 Manufacture all components
  - 🟦 Waterproof electronics
  - 🟦 Integrate w/Laser cutter system
- Electronics Integration
  - 🟩 Microcontroller selection
  - 🟩 Stepper motor drivers
  - 🟩 System Power Supplies
  - 🟦 Integrate SOH sensors, powder bed electronics with Arduino
- Software Integration
  - 🟩 Determine open source firmware
  - 🟦 Program microcontroller SOH/powder bed
  - 🟦 Develop GUI program for automation
- Testing
  - 🟦 Compile test documentation
  - 🟩 Coordinate reliable and safe testing locations
  - 🟦 Verify thermal model with chosen laser cutter
  - 🟦 Verify powder bed system w/ software and electronics successful integration
  - 🟦 Verify all integrated subsystems
  - 🟦 Verify printed motor structural qualities

🟩 Completed

🟦 Uncomplete

Spring Schedule

🟦 Financial

🟥 Software

🟩 Manufacturing

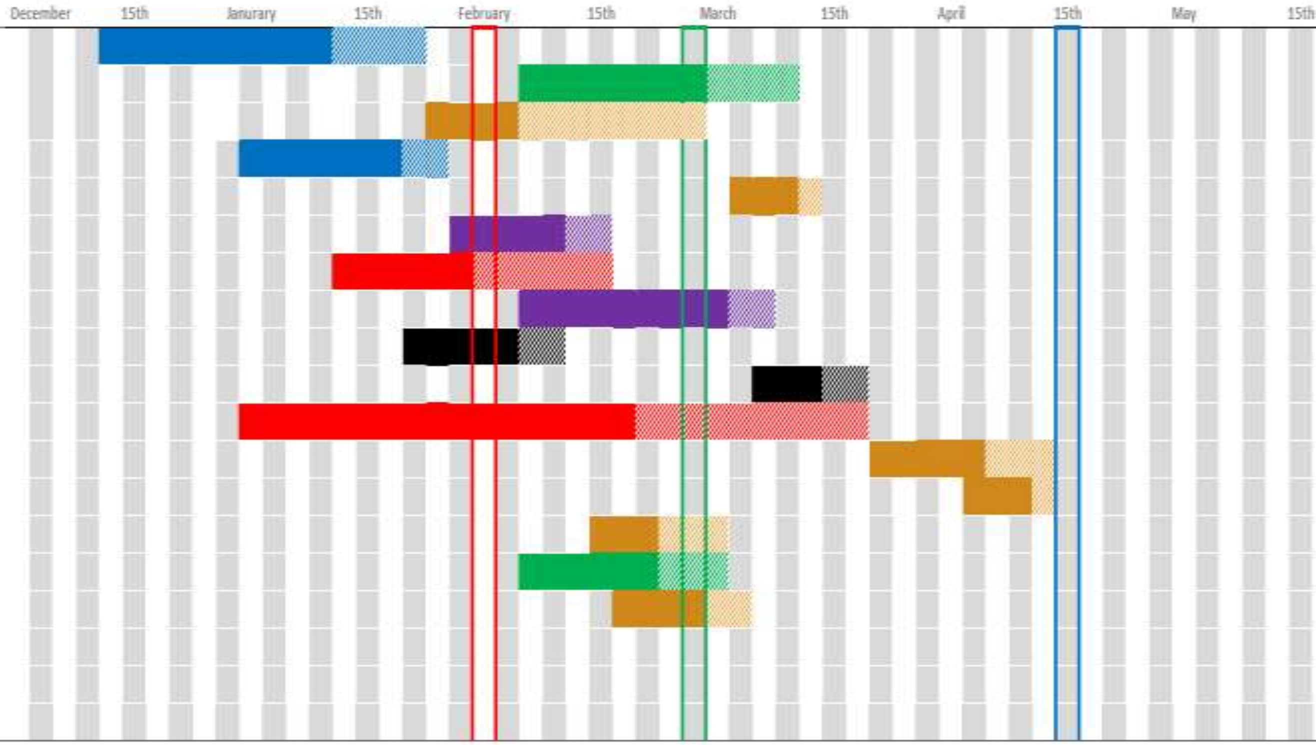
🟪 Electronics

⬛ Integration

🟨 Testing

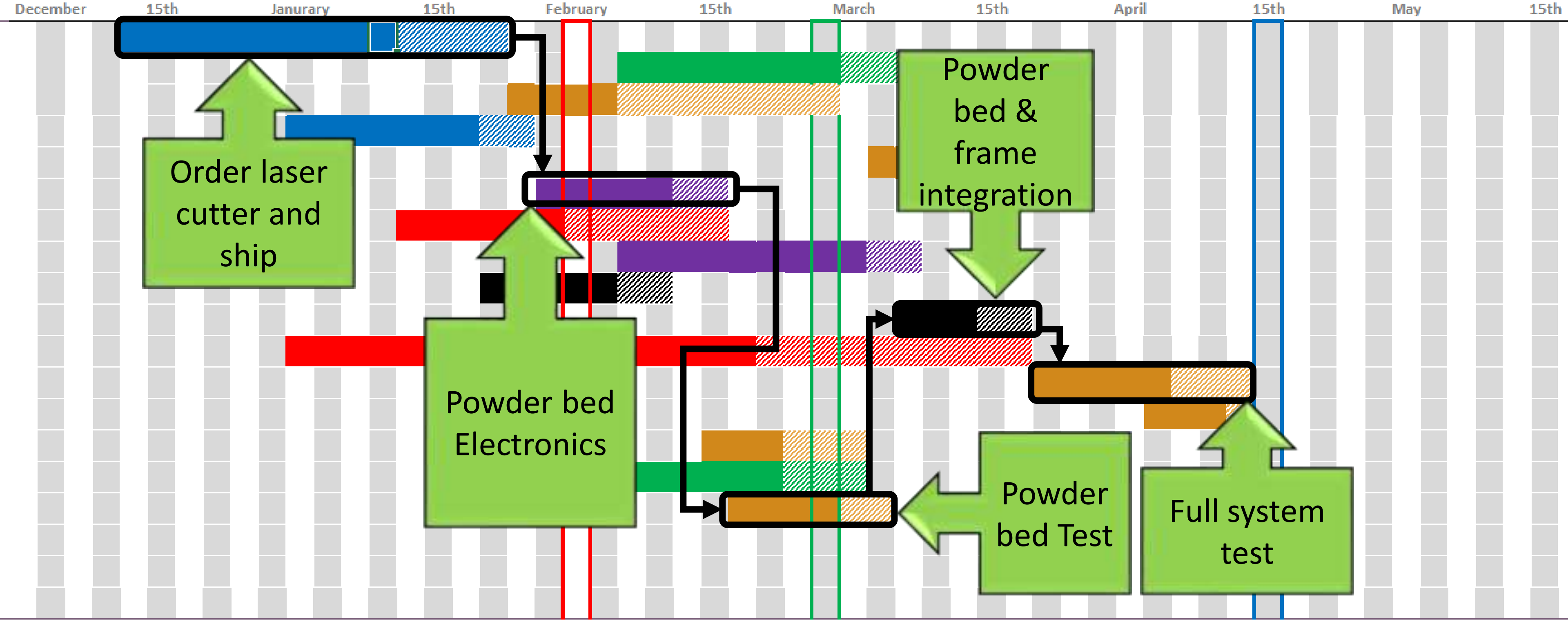
SPAM Schedule

ACTIVITY	START	End
Order laser cutter and ship	10-Dec	11-Jan
Manufacture powder bed	8-Feb	Feb-29
Test lower bound laser power	25-Jan	Feb-15
Purchase all materials	1-Jan	22-Jan
Test propellant sintering at varying slew rates	4-Mar	12-Mar
Integrate powder bed electronics	28-Jan	14-Feb
Develop powder bed software	12-Jan	1-Feb
Integrate SOH sensors with laser cutter	7-Feb	4-Mar
Integrate water system with laser cutter	22-Jan	7-Feb
Integrate powder bed with laser cutter/frame	7-Mar	15-Mar
Develop laser cutter GUI software	1-Jan	22-Feb
Full system test	22-Mar	8-Apr
Structural Testing	5-Apr	11-Apr
Water system test	15-Feb	24-Feb
Manufacture system frame	7-Feb	24-Feb
Full powderbed test	18-Feb	28-Feb
MRR	2-Feb	2-Feb
TRR	Feb-29	Feb-29
AES Symposium	15-Apr	15-Apr



Spring Schedule (Critical Path)

🟦	Financial	🟪	Electronics
🟥	Software	⬛	Integration
🟩	Manufacturing	🟧	Testing



Order laser cutter and ship

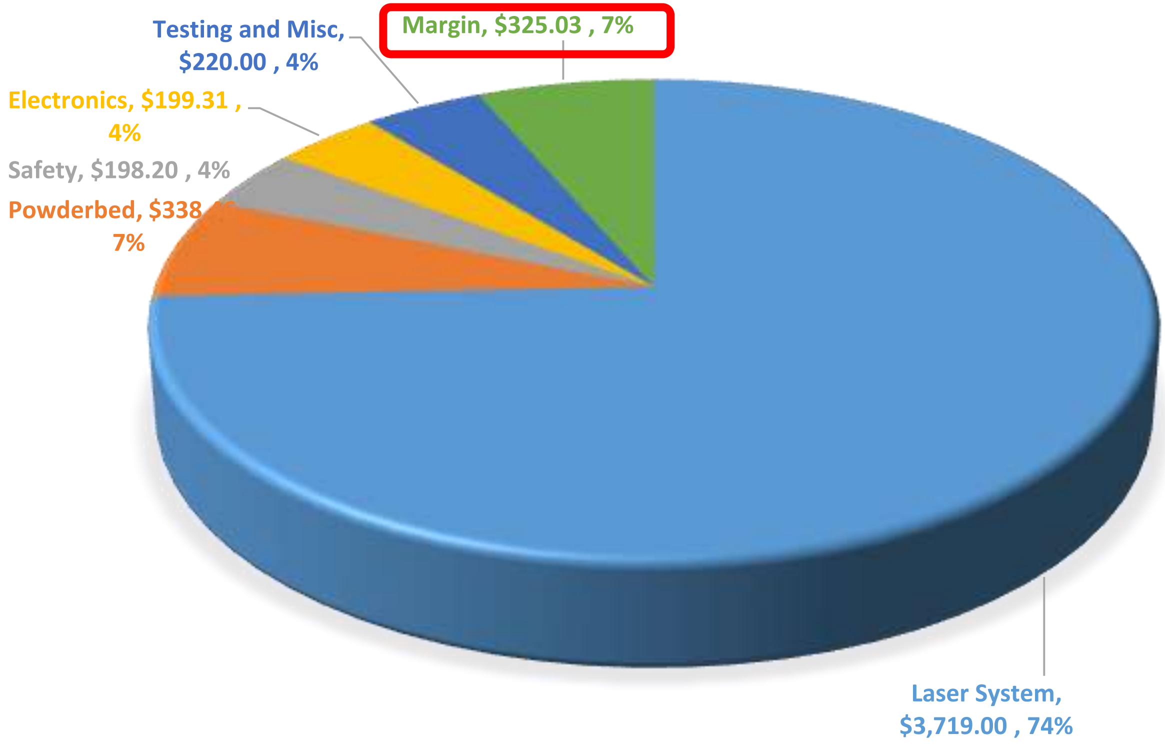
Powder bed Electronics

Powder bed & frame integration

Powder bed Test

Full system test

Budget



Laser System	- FSL H-Series
Powder Bed	- Nema 23 motors - Material cost (Al, Acrylic)
Safety	- Safety goggles - SOH sensors - Hardware
Electronics	- Arduino - Power supply - Encoders
Testing and Misc.	- Propellant - Test equipment

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Backup Slides

Slide Key (Main)

- Baseline Design
- Functional Requirements
- Laser System
- Safety
- Powder Bed
- Integration
- Software
- Electronics
- Risk Mitigation
- V&V
- Project Planning

Slide Key (Backup)

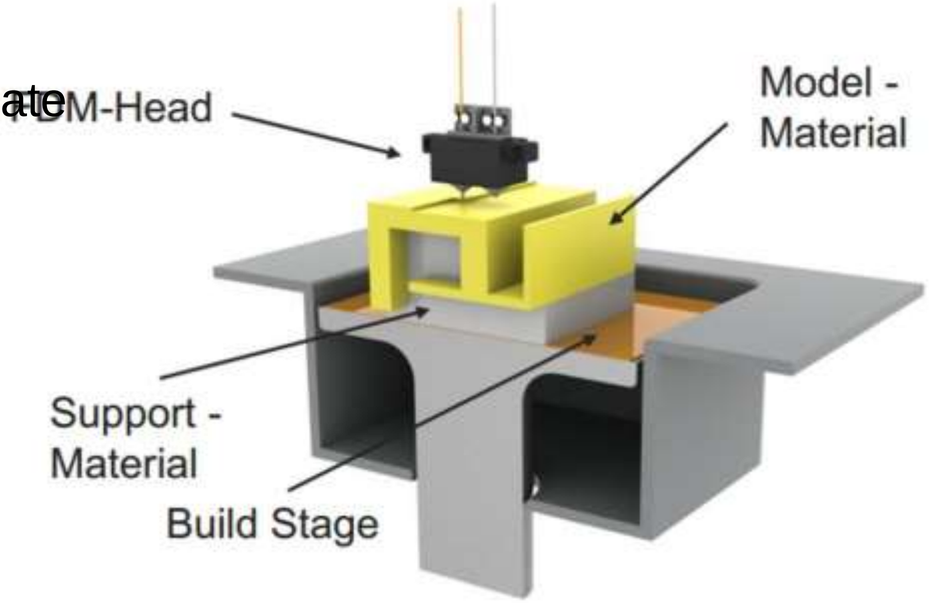
- Background
- Baseline
- Laser system
- Powder bed
- Integration
- Software
- Electronics
- Risk Mitigation
- V&V

FDM - Fused Deposition Modeling

The material is melted and extruded onto the print surface by the nozzle. The nozzle, print surface, or both may move.

Not feasible

- propellant cannot be held in molten state without decomposing [2]
- maximum ~30min of pliability
- additional safety concerns holding propellant at high temps for extended periods under pressure

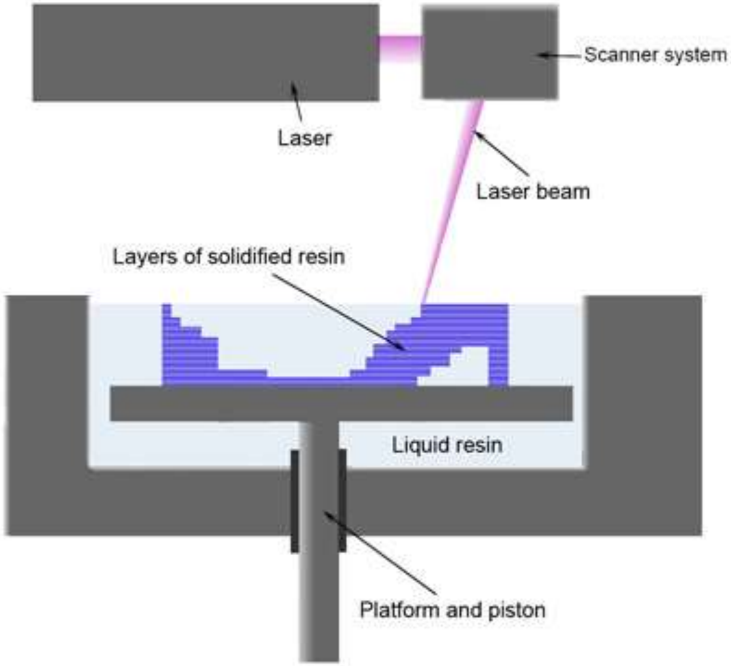


SLA - Stereolithography

Focus a beam of ultraviolet light on a vat of photopolymer.
The beam cures each layer of the resin onto a moveable platform.

Not feasible

- photoresin is prohibitively expensive
- photopolymer is the only possible fuel
- No time to test/too much research



Baseline Design Trade Study

Design Decision: Modify Laser Cutter Machine

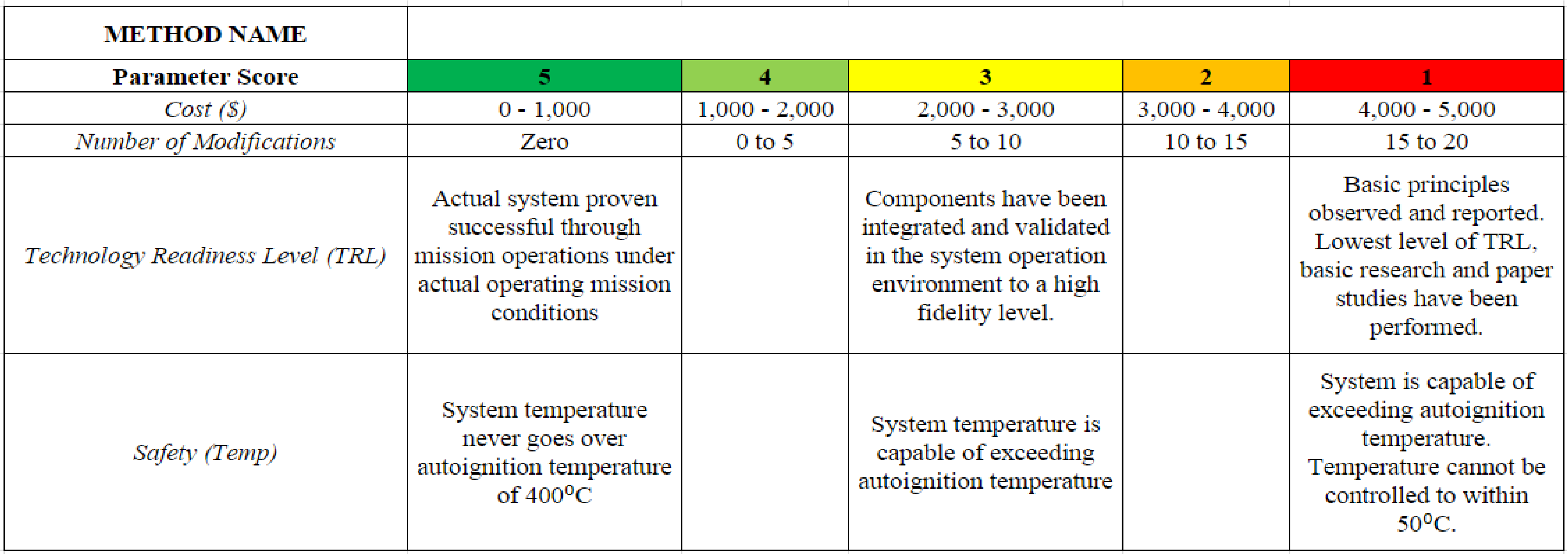
- Laser must be integrated and calibrated by the team
- Print chamber must be designed and fabricated
- Higher cost
- Team must design and build system around safety requirements

		Lulzbot	*Laser Cutter*
Metric	**Weight**	**Score**	**Score**
Laser	**25%**	**3**	**5**
Print Chamber	**10%**	**0**	**3**
Safety	**25%**	**2**	**4**
Est. Cost	**15%**	**2**	**3**
Est. Time	**10%**	**0**	**2**
Precedent	**15%**	**2**	**4**

Trade Study

Methods compared in trade study

- Fused Deposition Modeling (FDM)
- Selective Laser Sintering (SLS)
- Stereolithography (SLA)



METHOD NAME					
Parameter Score	**5**	**4**	**3**	**2**	**1**
Cost ($)	0 - 1,000	1,000 - 2,000	2,000 - 3,000	3,000 - 4,000	4,000 - 5,000
Number of Modifications	Zero	0 to 5	5 to 10	10 to 15	15 to 20
Technology Readiness Level (TRL)	Actual system proven successful through mission operations under actual operating mission conditions		Components have been integrated and validated in the system operation environment to a high fidelity level.		Basic principles observed and reported. Lowest level of TRL, basic research and paper studies have been performed.
Safety (Temp)	System temperature never goes over autoignition temperature of 400^{o}C		System temperature is capable of exceeding autoignition temperature		System is capable of exceeding autoignition temperature. Temperature cannot be controlled to within 50^{o}C.

Trade Study Results

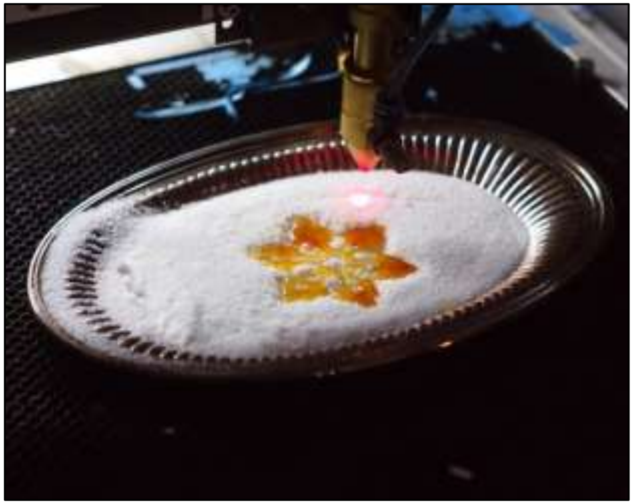
Winner: Selective Laser Sintering (SLS)

- TRL: Multiple demonstrations of feasibility with sugar as printed material
- Safety: Energy output of laser can be finely tuned to avoid combustion
- Modifications: Fewer modifications than standard FDM printers to convert a laser cutter

Functional Requirement:

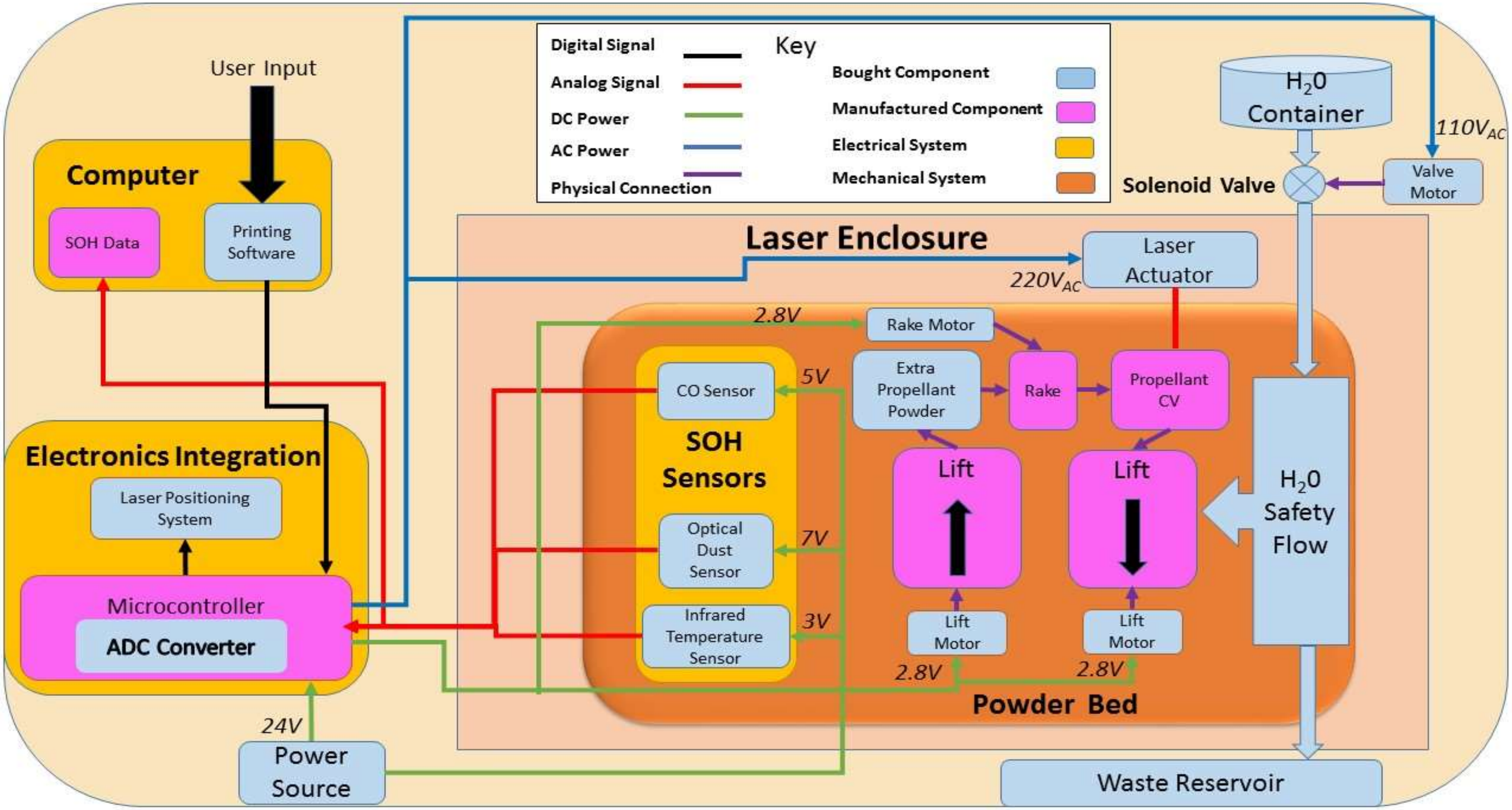
FR 1: The project shall produce a 3D printer capable of automated additive manufacturing.

Maker Faire mascot sugar model[6]

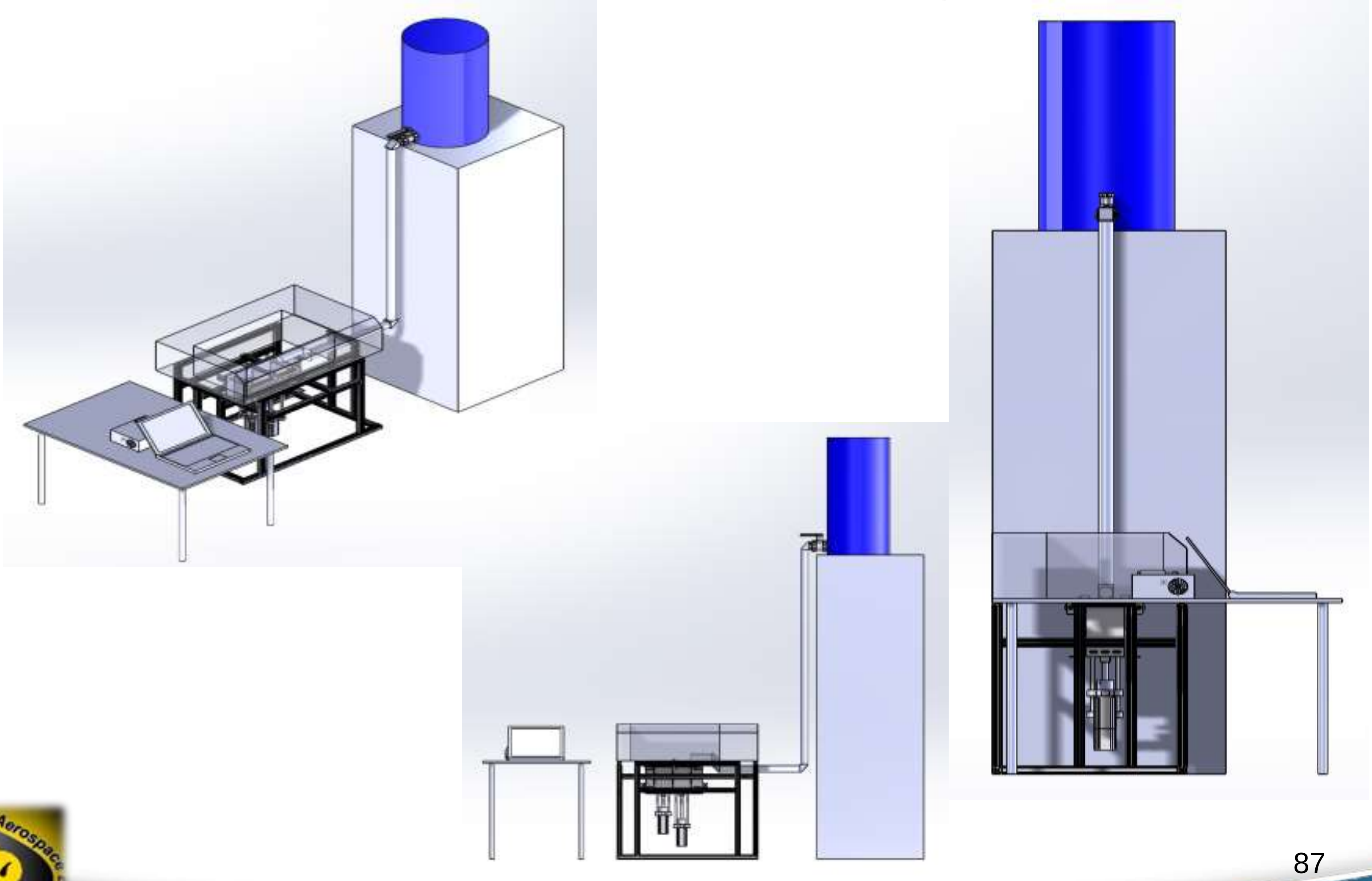


SLS printing pure sucrose[7]

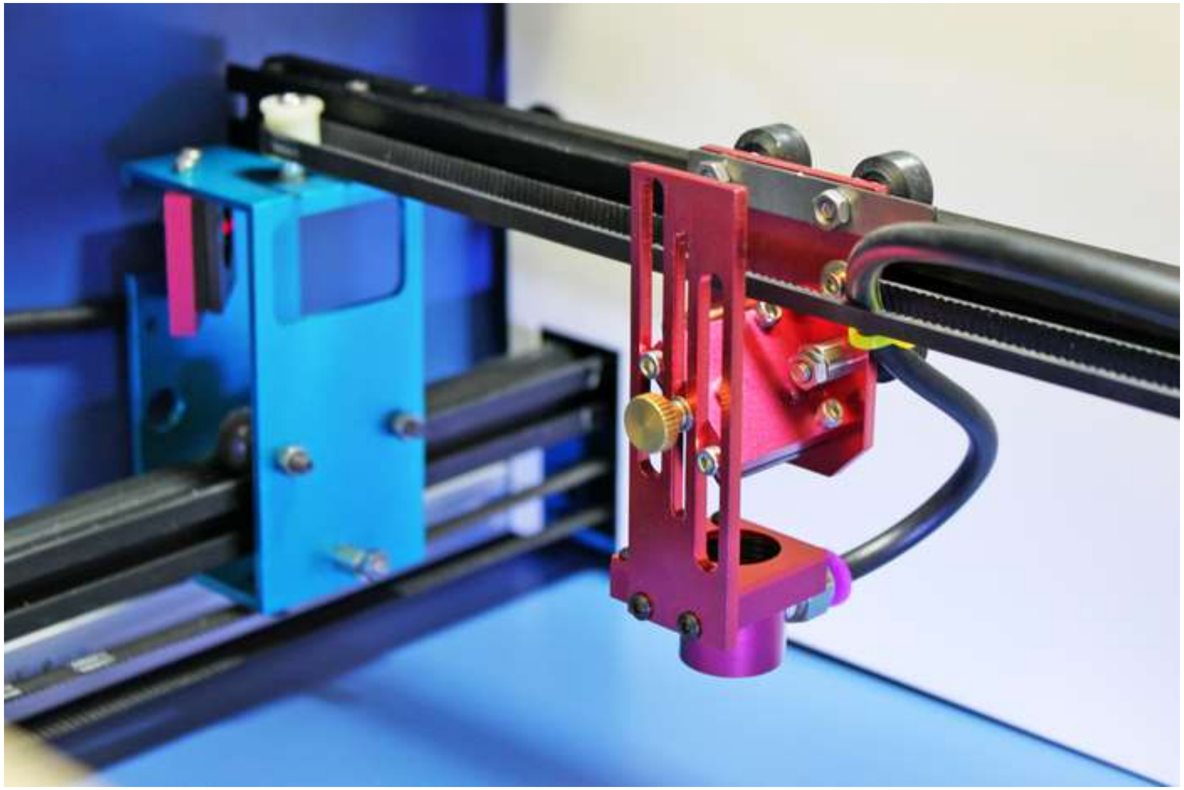
System Functional Block Diagram



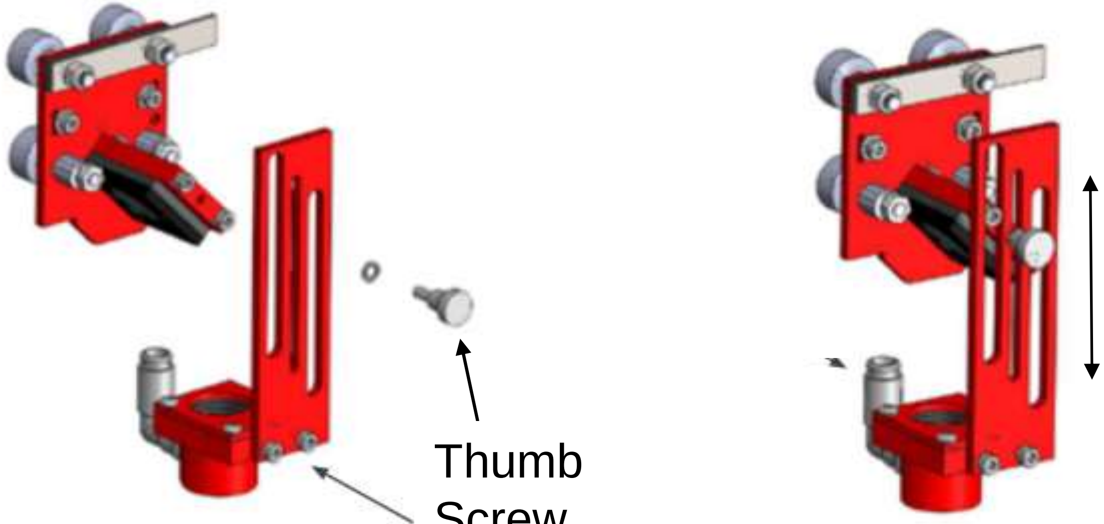
Baseline Design



Laser Carriage Close Up



Laser Carriage Adjustment

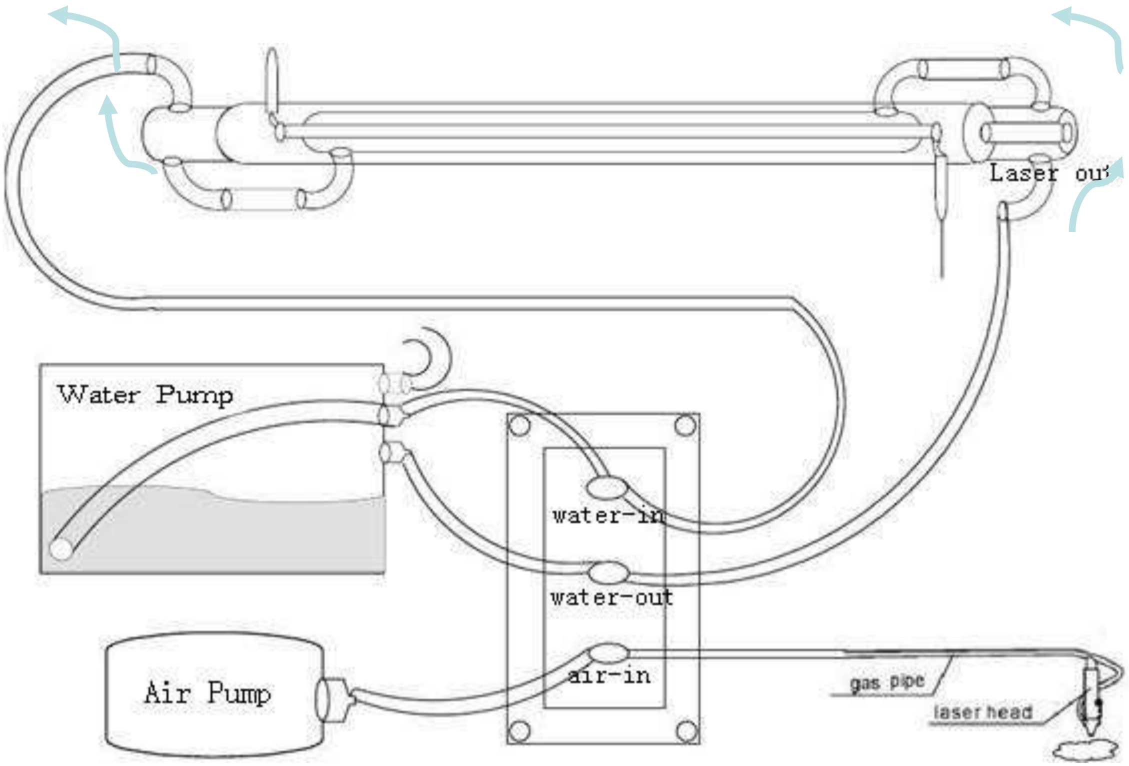


Thumb Screw

Focusing Lens

5 cm Vertical Adjustment

Laser Cutter – Water Chiller Usage



Power Attenuation Methods

- Primary:
  - Decrease Current
    - Controllable in Laser Cutter Software
  - Pulse Width Modulation
    - 8 Bit control in Laser Cutter Software
  - De-Focus Laser
    - Increases Spot Size and spreads out Laser Power
  - Slew Rate
    - Controllable in Laser Cutter Software
- Off-Ramp:
  - IR Neutral Density Filter
    - Optical Density: 2
    - Reduces Max Power to 0.4 Watts

Power Attenuation Methods

- First verify rough alignment with a laser pointer
- Hold paper in front of mirror
- Activate laser for 10 s
- Adjust previous mirror to tune laser position
- Verify that laser beam-pattern is centered on the mirror
- Repeat for each mirror and lens

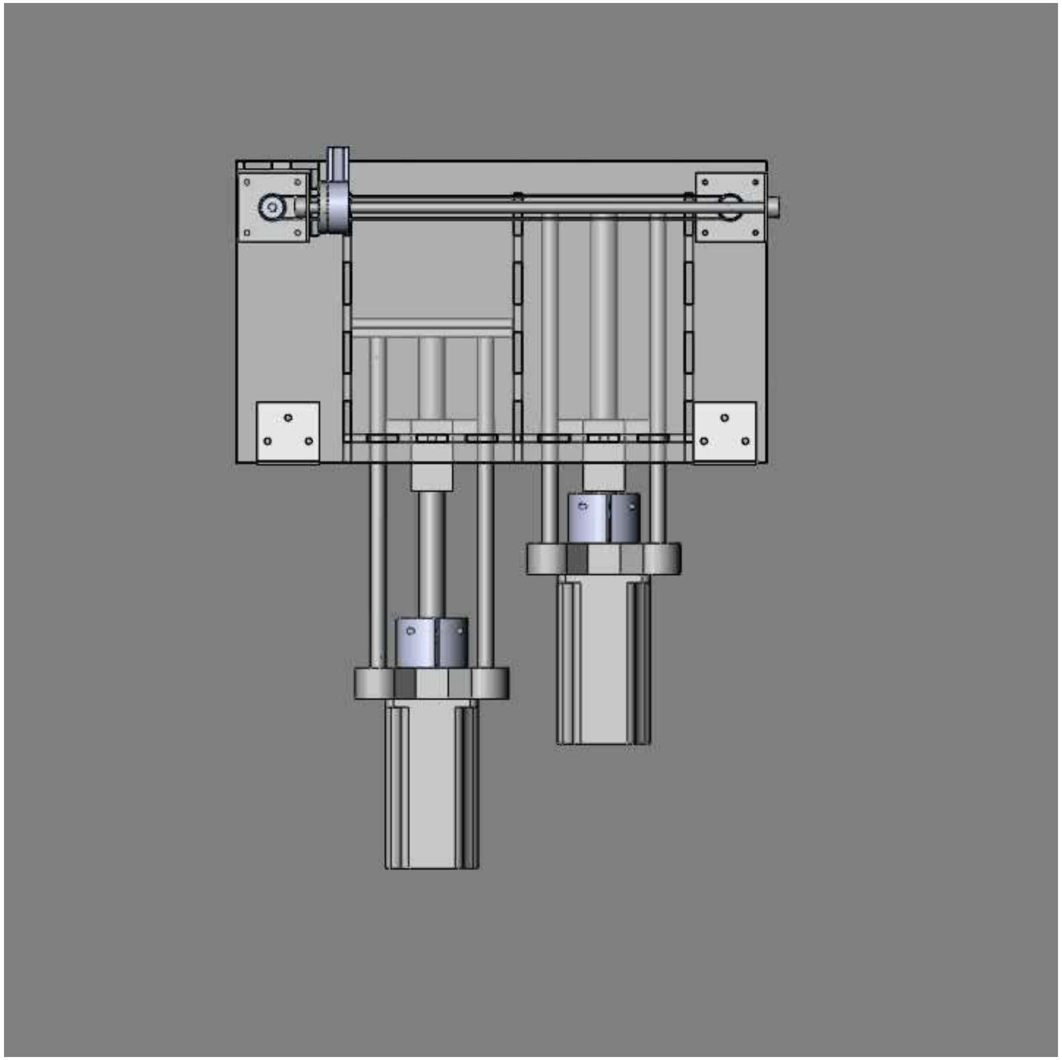
Build-from-Scratch Option

Part	Quantity	Cost	Assembly Time (per person)
Aluminum Frame (600 x 400 mm)	1	525.00	Pre-Assembled
Side Paneling (Aluminum)	~ 30 ft^2	Unknown	~ 4 weeks to cut and assemble
X-Y Stage	1	725.00	Pre-Assembled, ~ 1 week to integrate
Reflecting Mirror	3	90.00	N/A
Focusing Lens	1	50.00	N/A
45 W Laser Tube	1	195.00	Small, <1 day to install
20 – 45 W Power Supply Unit	1	205.00	Small. ~3 days to integrate
Water Chiller	1	600.00	Small. ~ 2 days to integrate
Heat Sinks and Fans	3	50.00	~ 1 week to integrate
Motor Drivers	2	100.00	~ 2 weeks to integrate
Miscellaneous Materials	N/A	100.00	N/A
Total:	>15	>2680.00	6 – 8 weeks

Operation: Step 1

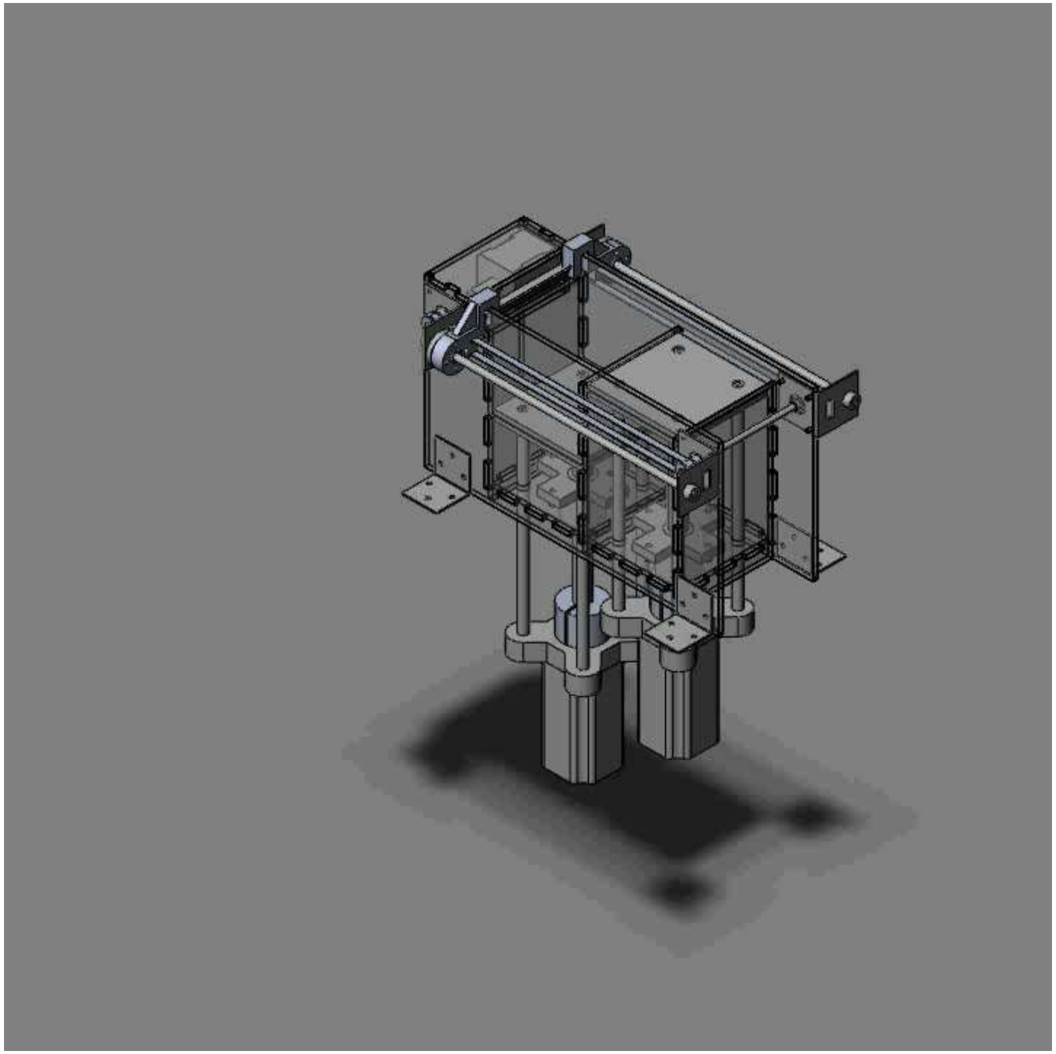
- Print Piston lowers by 1mm (0.039”)
- Reservoir Piston raises by 1.5mm (0.059”)

- Note: The rake never changes z-position, the print piston lowers, instead.



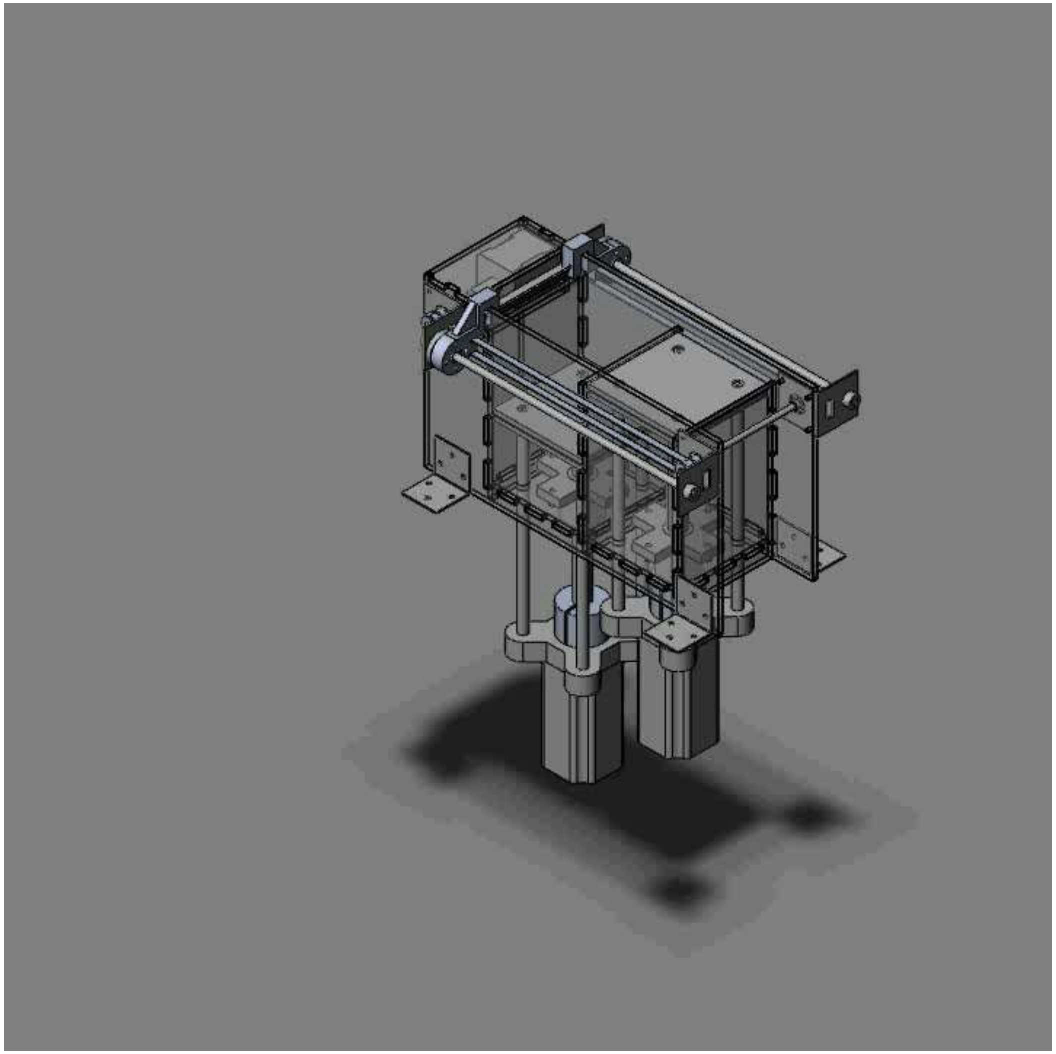
Operation: Step 1 (Isometric View)

- Print Piston lowers by 1mm (0.039”)
- Reservoir Piston raises by 1.5mm (0.059”)



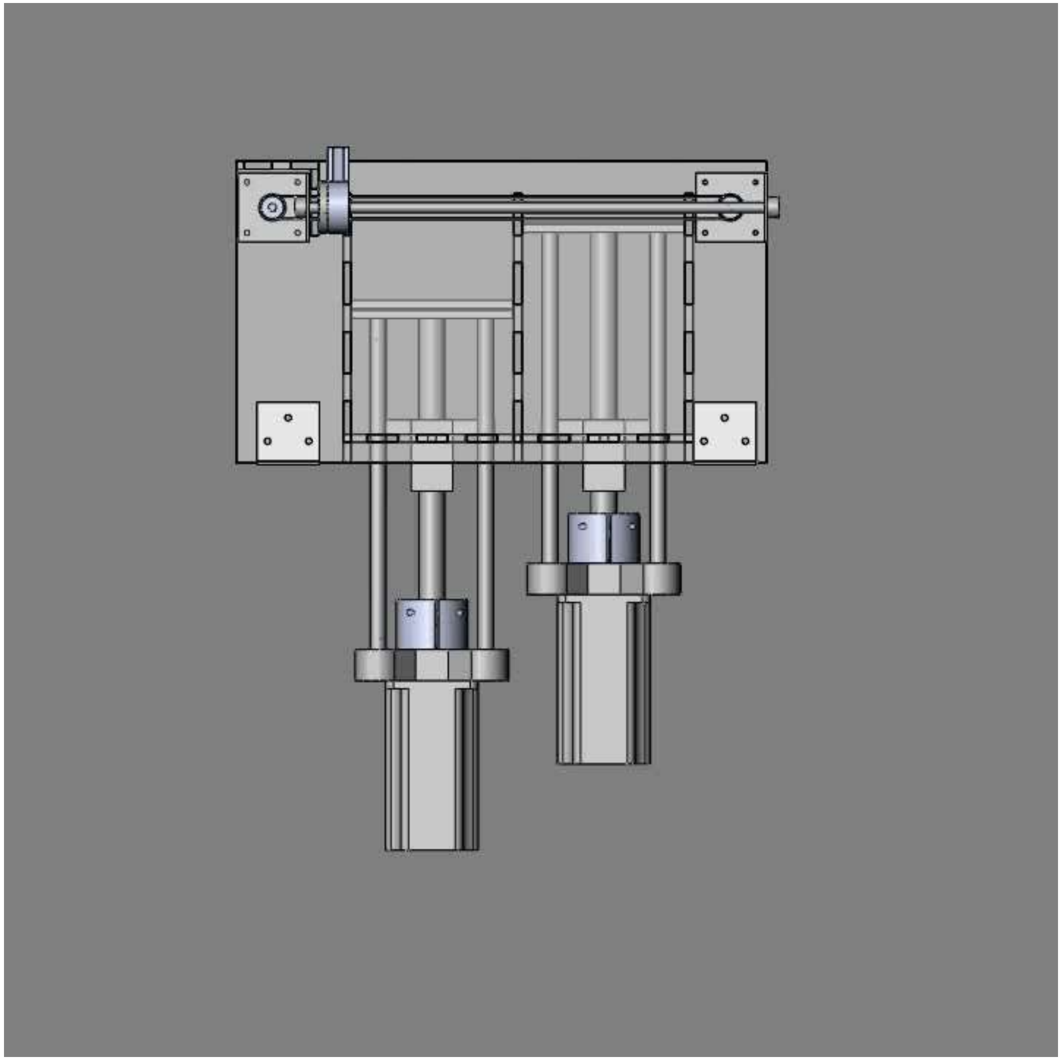
Operation: Step 1 (Technical Details)

- Reservoir Piston raises by 1.5mm (0.059”)
- NEMA23 motor spins 1.8°/step
- Ball Nut Pitch: 13/64” (0.203”)
    - 0.203” vertical motion per turn
- Each step is 0.203*(1.8/360)=0.001015625” vertical motion per step.
- Print motor spins 39 steps
    - 70.2°, +0, -11 step error
- Reservoir motor spins 78 steps
    - 140.4°, ±39 step error
- Torque needed to spin Ball Nut:
    - 0.051Nm
- Torque provided by motor:
    - 2.4Nm



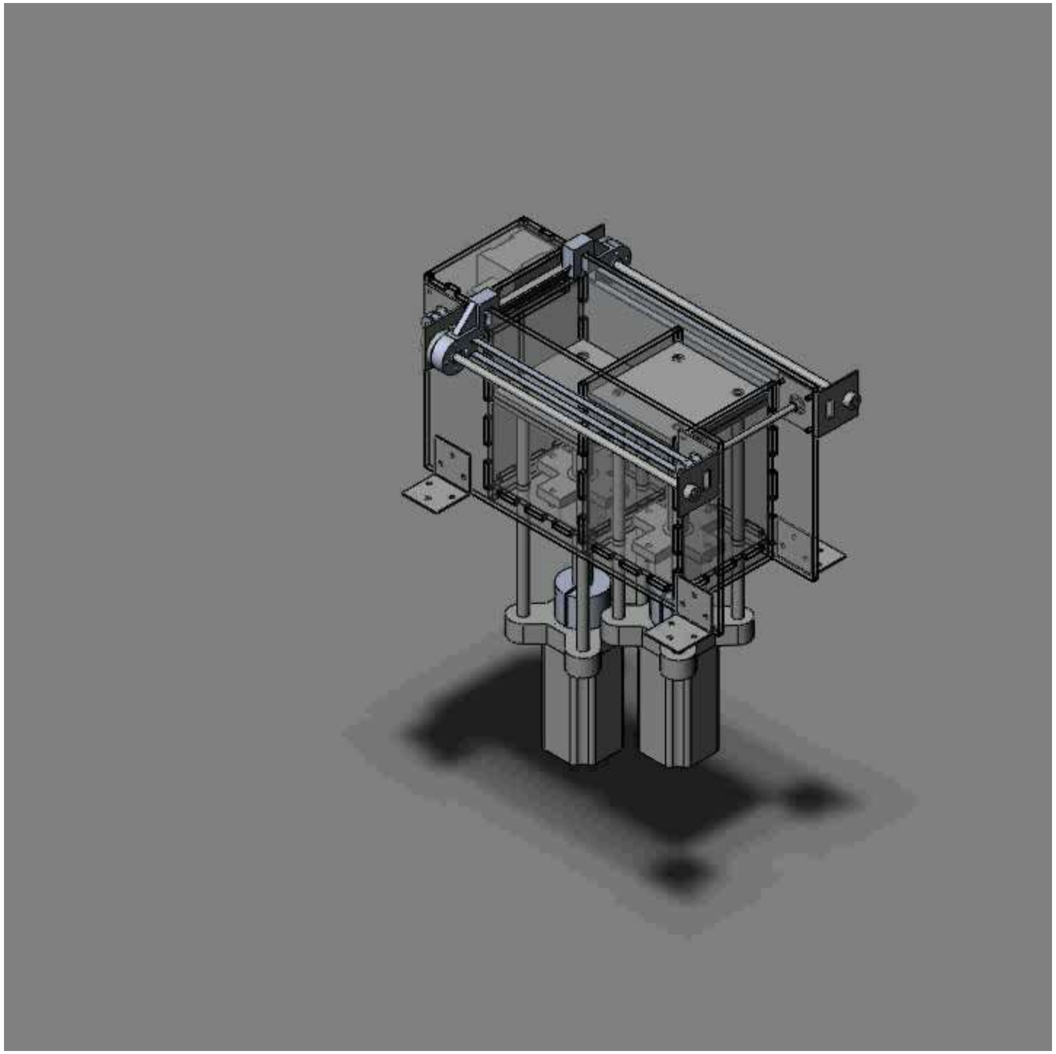
Operation: Step 2

- ➢Rake motor pulls a Teflon coated aluminum rake across the powder
- ➢Excess powder dumped over either end



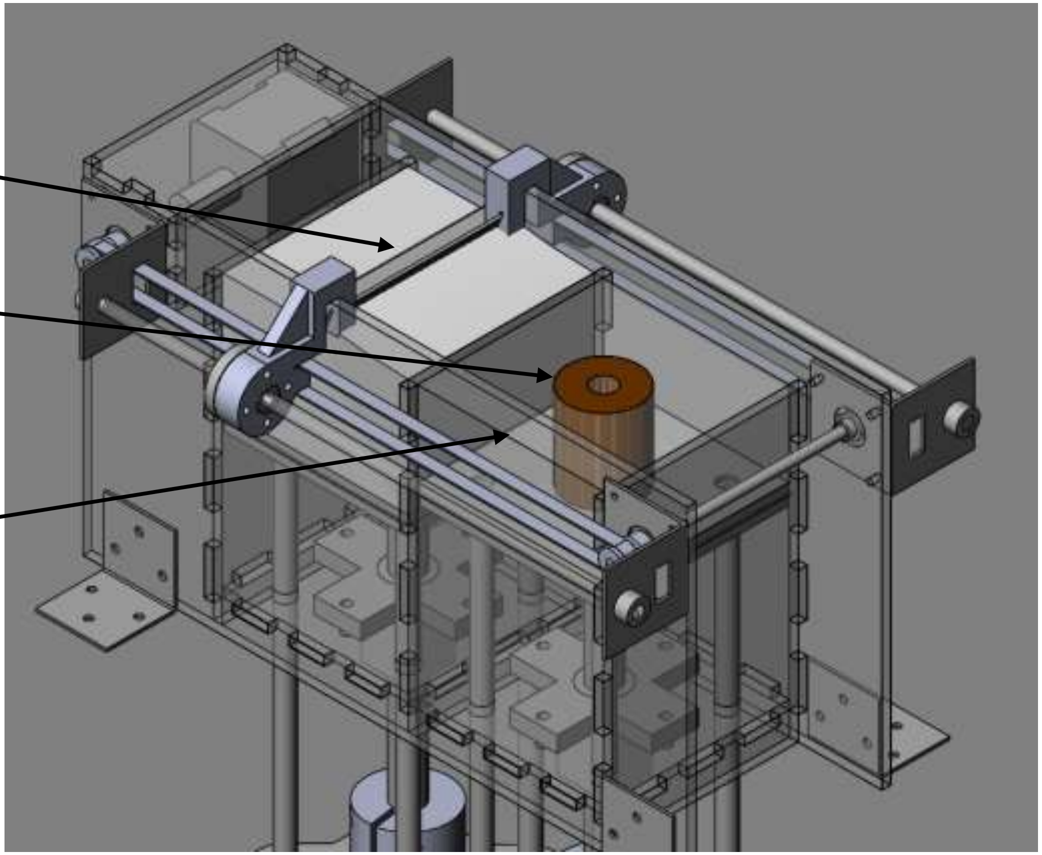
Operation: Step 2 (Isometric View)

- Rake motor pulls a Teflon coated aluminum rake across the powder
- Excess powder dumped over either end



Snapshot During Operation

- Powder lifted by Reservoir Piston being pushed/flattened by the rake
- Print area (with previous layers of sintered material) waiting for next layer
- Not shown: Laser head
- All previous layers are supported by surrounding unsintered powder

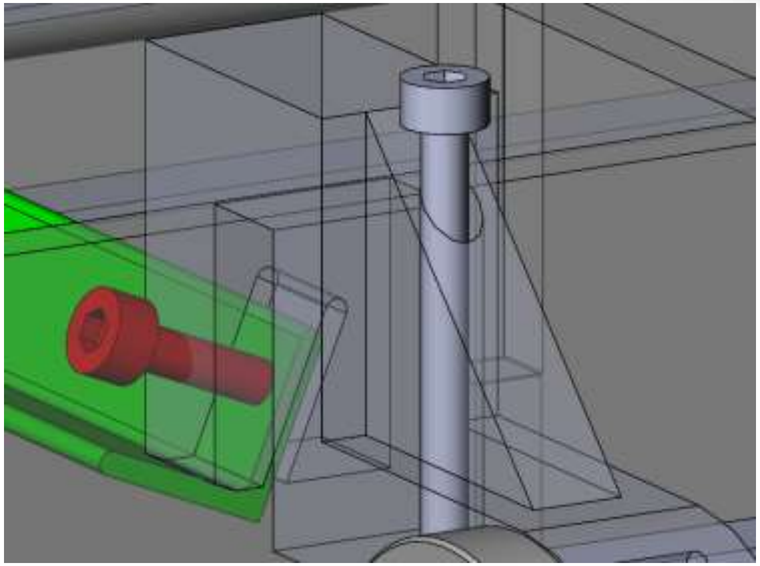


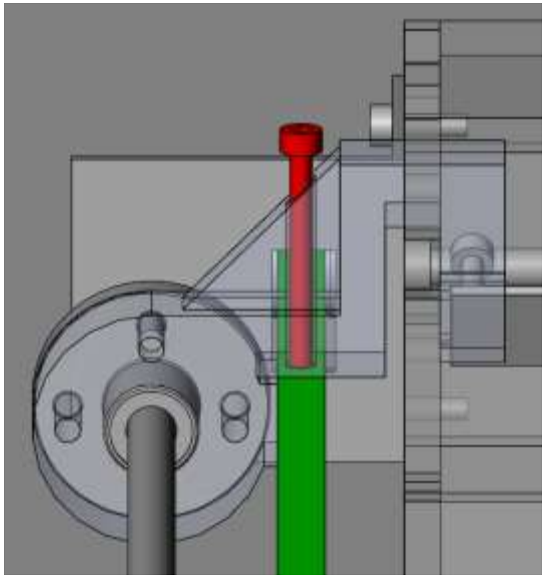
Step Timing

- At maximum load piston motors exert 0.05Nm
    - Max speed at those torques: 7rps
- Print motor travel distance: 0.039” (at 0.001” per 1.8°)
    - 39 steps required -> 70.2° -> 0.195 rotations -> 0.028 sec
- Reservoir motor dist.: 0.058”
    - 58 steps -> 104.4° -> 0.29 rot -> 0.041 sec
- Load on rake motor (powder, friction, etc.): 0.2Nm (assumed)
    - Max speed at those torques: 15rps
- Rake travel dist.: 8.45” (at 1.571” per rotation) (x2, across and back)
    - 8.45” -> 5.379 rotations -> 0.359 sec per trip -> 0.718 total rake time
- Theoretical time: 0.759 seconds
- Safe/Actual time: TBD experimentally

Rake Subassembly Holder Details

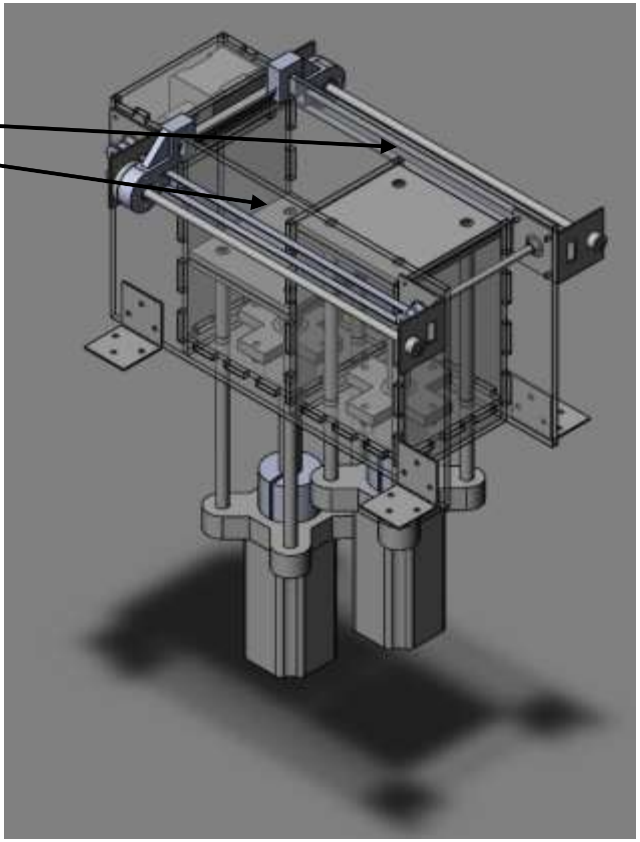
- Rake Holders 3D printed in ABS
- Set screws (Red) pinch on:
  - Rake (Top, Green), holding it 22.5° from vertical
  - Drive Belt (Bottom, Green), flexible toothed belt



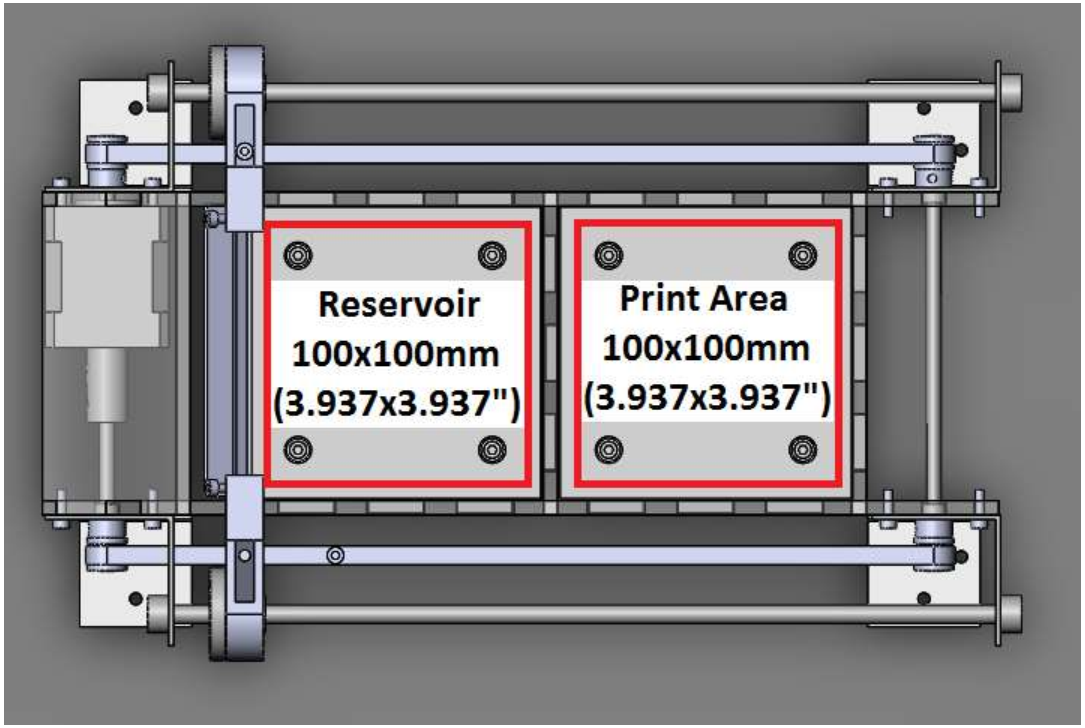


Gutter Subassembly

- Walls raised 19.95mm (0.785”)
- Keeps water/powder inside powder bed
- Allows water/powder to fall off either edge in a controlled manner

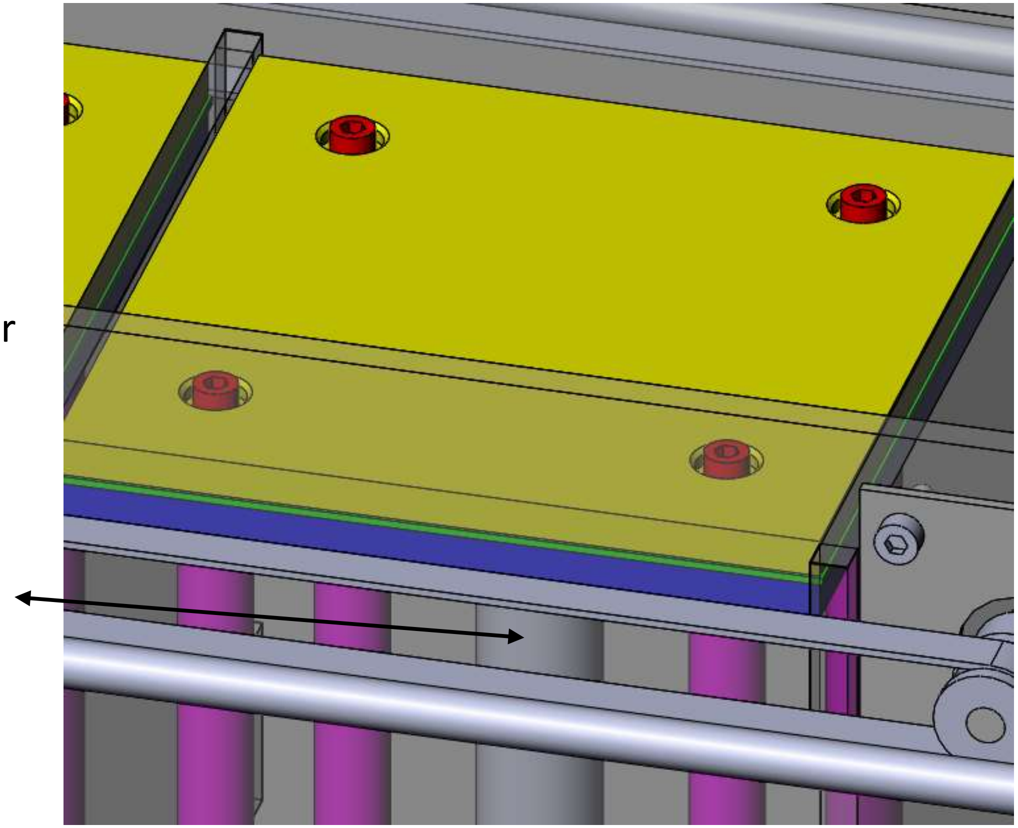


Print Areas


Reservoir
100x100mm
(3.937x3.937")
Print Area
100x100mm
(3.937x3.937")

Piston Heads

- 3 Layers
  - Top (Yellow): Aluminum print surface
  - Middle (Green): Powder-tight felt layer
  - Bottom (Blue): Aluminum
- Screws (Red) recessed into top plate
  - Screw through the head into Holder Rods (Magenta)
- Drive Shaft (not highlighted) is free floating



Torque Calculations

- Ball Screw/Nut:
- Designed to turn rotation into linear motion

$$T = \frac{P\eta_2 F}{2\pi} = 51Nmm = 0.051Nm$$

T = Torque   P = Pitch (13/64”, 5.159mm)

η_2 = Thread Efficiency (0.95)

F = Load (64.764N)

- 0.5-11 Precision Thread
- Not designed with this application in mind

$$T = F\left[\frac{P}{2\pi} + \frac{\mu_t r_t}{cos(30)}\right] = 0.139Nm$$

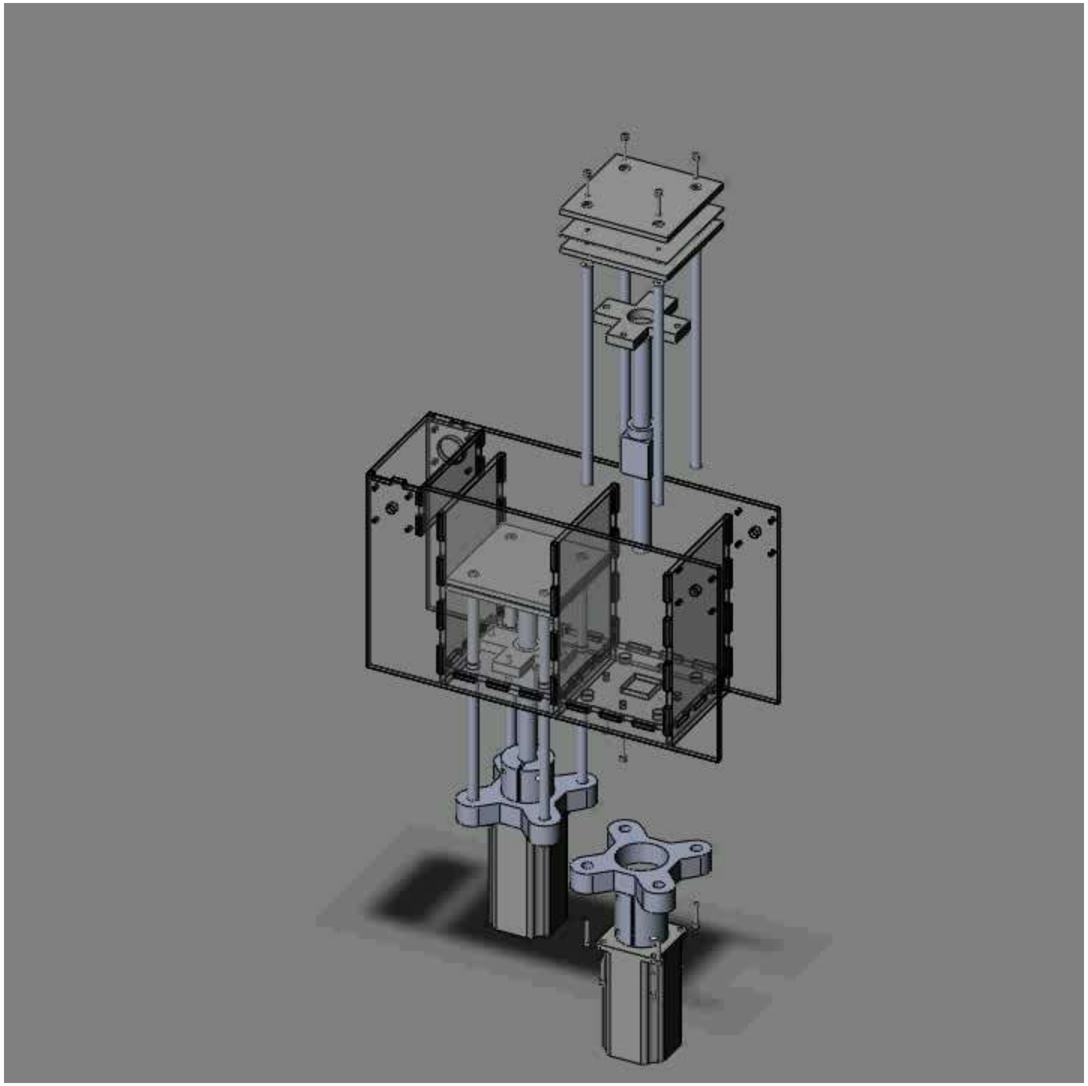
F = 64.764N   P = 1/10” = 2.309mm

μ_t = Thread Friction = 0.27 (Teflon/steel)

r_t = Radius of Thread (0.225”, 5.715mm)

Piston Assembly

1.Assemble 3 layer Piston Head, fix to Holder Rods
2.Screw the Ball Nut into the Support Plate
3.Affix Support Plate to the bottom of the Body
4.Feed Holder Rods through holes in the Body
5.Fix Drive Coupler to the Drive Screw
6.Fix Faceplate to the Motor
7.Fix Faceplate to the Holder Rods
8.Repeat for the other Piston

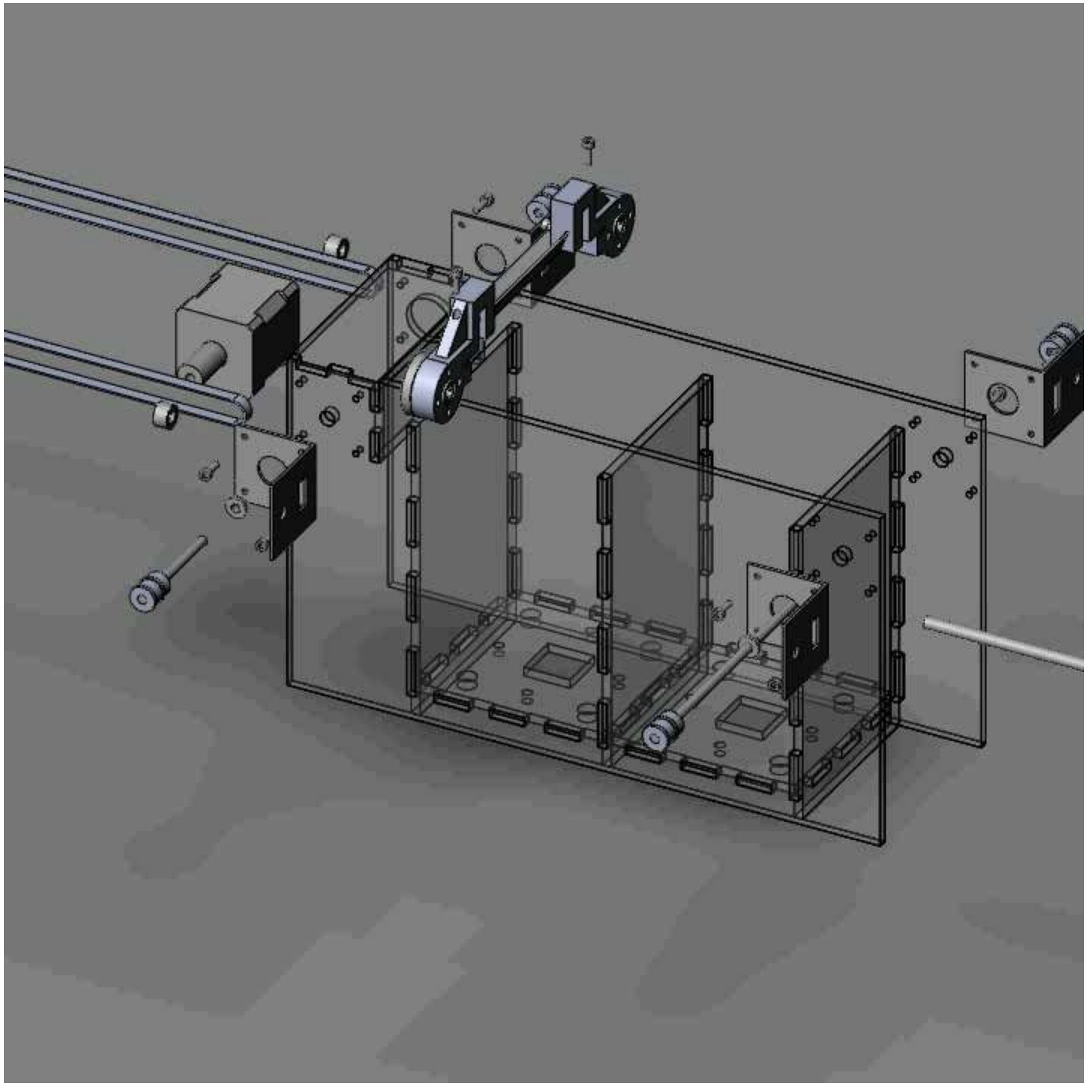


Rake Assembly

1. Fix Motor and Guide Supports in place
2. Attach Rake Axles
3. Place Rake in position
4. Run Guide Bars through the Rake Holders
5. Slip Drive Belt through the Guide Supports and onto the Pulleys and Rake Holder
6. Fix the Rake Holder to the Belt with the screws

Note:

- ➢The Belt is flexible in real life.
- ➢It is better to assemble the pistons, first.



Future Steps and Alternate Designs

- No Guide Rails for the Rake Holder
    - Pros: Cheaper, smaller footprint
    - Cons: Rake is less stable
- Aluminum Body
    - Pros: Assembly is more stable, fire damage is greatly reduced
    - Cons: Requires almost full redesign, may be prohibitively expensive
- Precision ACME Nut and Screw (instead of Ball Nut/Screw)
    - Pros: Much cheaper
    - Cons: Requires higher torque (1.3Nm vs 0.05Nm), less accurate z-positioning (0.004” vs. 0.001”)
- Teeth Added to the Rake Holder
    - Pros: Allows better grip on the Drive Belt
    - Cons: Adds complexity to design
- Removable side with thumb screws
    - Pros: Allows easy access to pistons without disassembly
    - Cons: Adds complexity to design

CPE #3: Powder Bed Feasibility

The Motosh Equation[10,11]

$$T_{in} = F_p\left[\frac{P}{2\pi} + \frac{\mu_t r_t}{\cos(\beta)} + \mu_n r_n\right]$$

F_P = Load on nut (~2.5kg, 24.525N)

P = Thread pitch

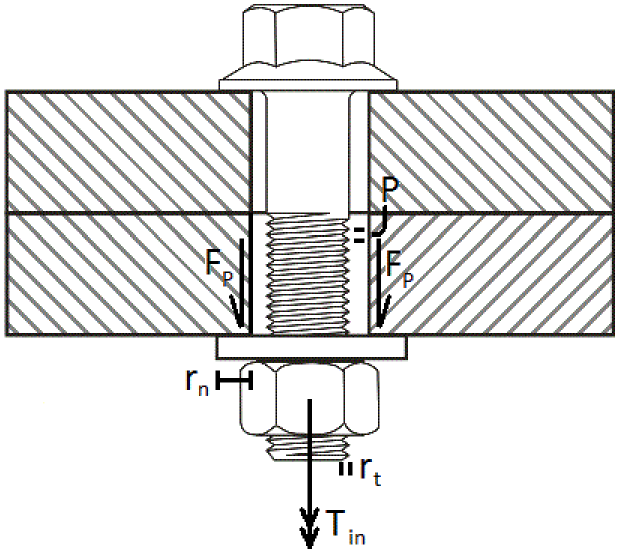
$\mu_{t/n}$ = Coef. of friction of thread surfac

$r_{t/n}$ = Radius of thread surface contac

β = Half angle of thread (30°)

T_{in} = Torque to spin nut (0.0273Nm)

Max torque of chosen motor: 0.43Nm

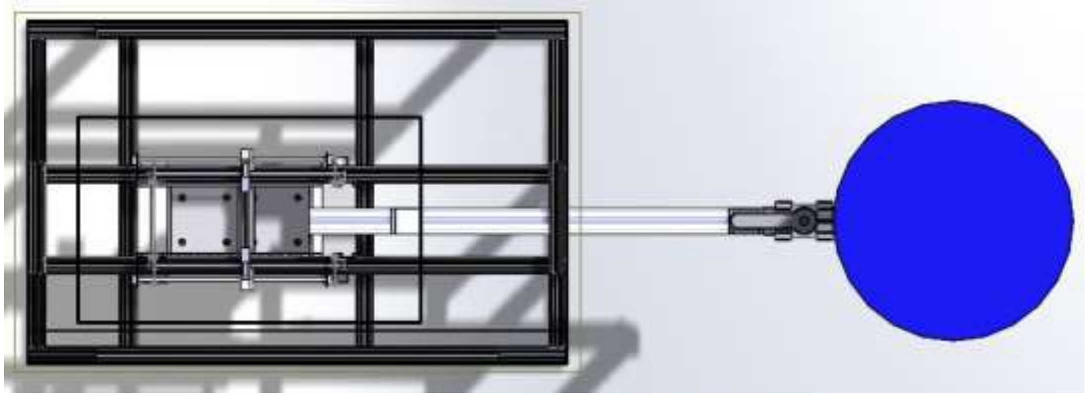


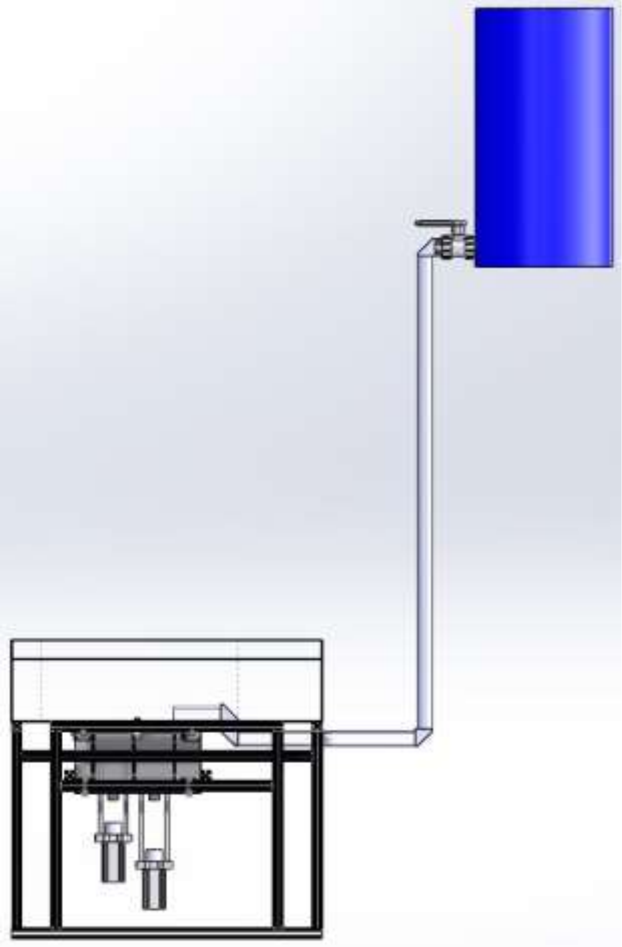
Parameters for the Motosh Equation[12]

Front and Top View of Overall System

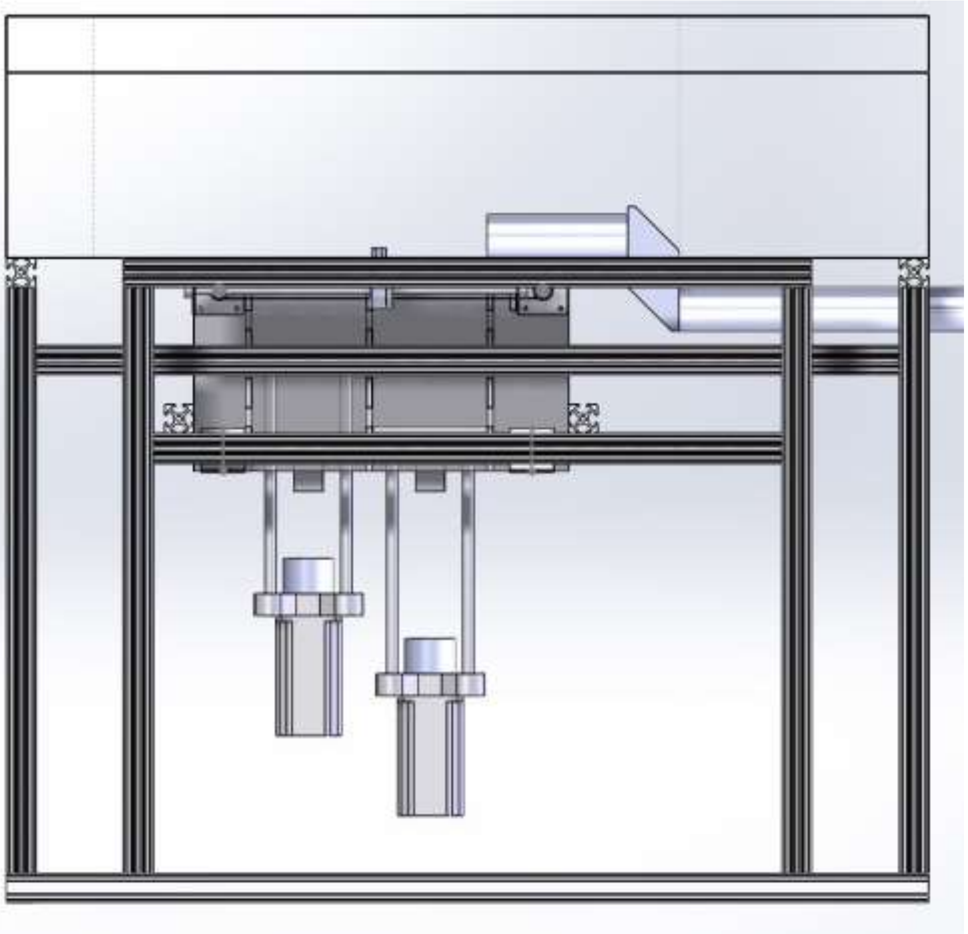
Subsystem Hardware Integration

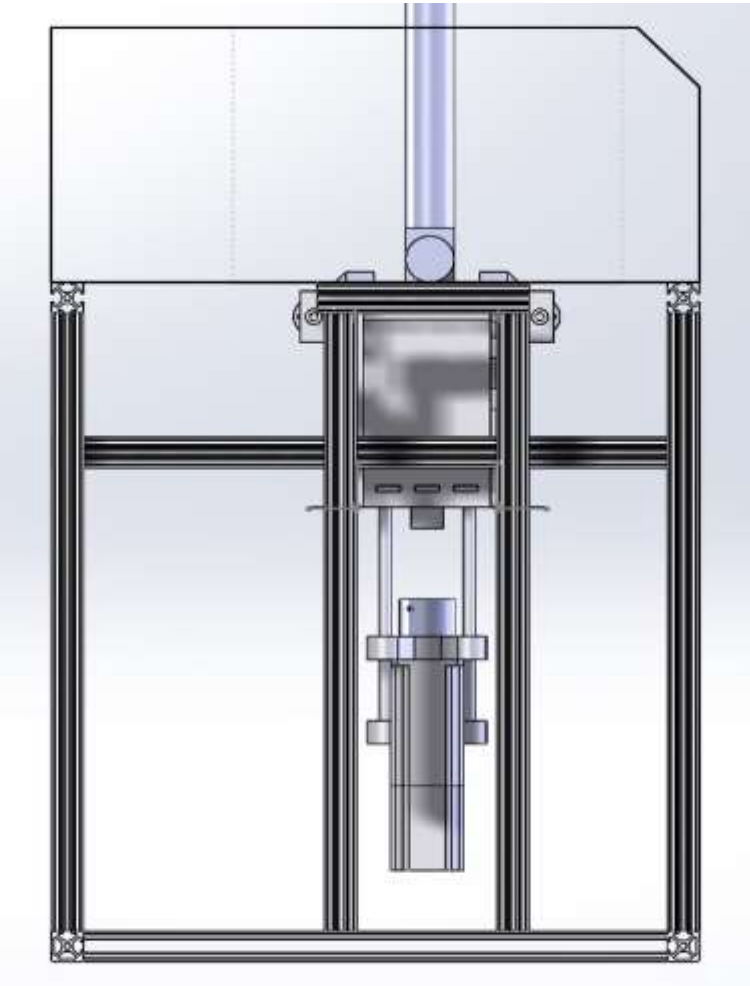
- Water Safety Subsystem
- Laser Cutter Frame
- Laser Cutter Subsystem
- Powder Bed Subsystem





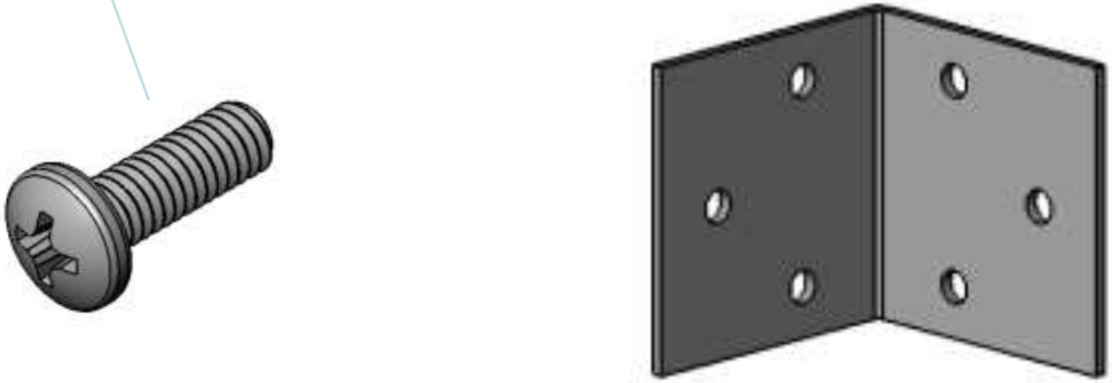
Front and Side View



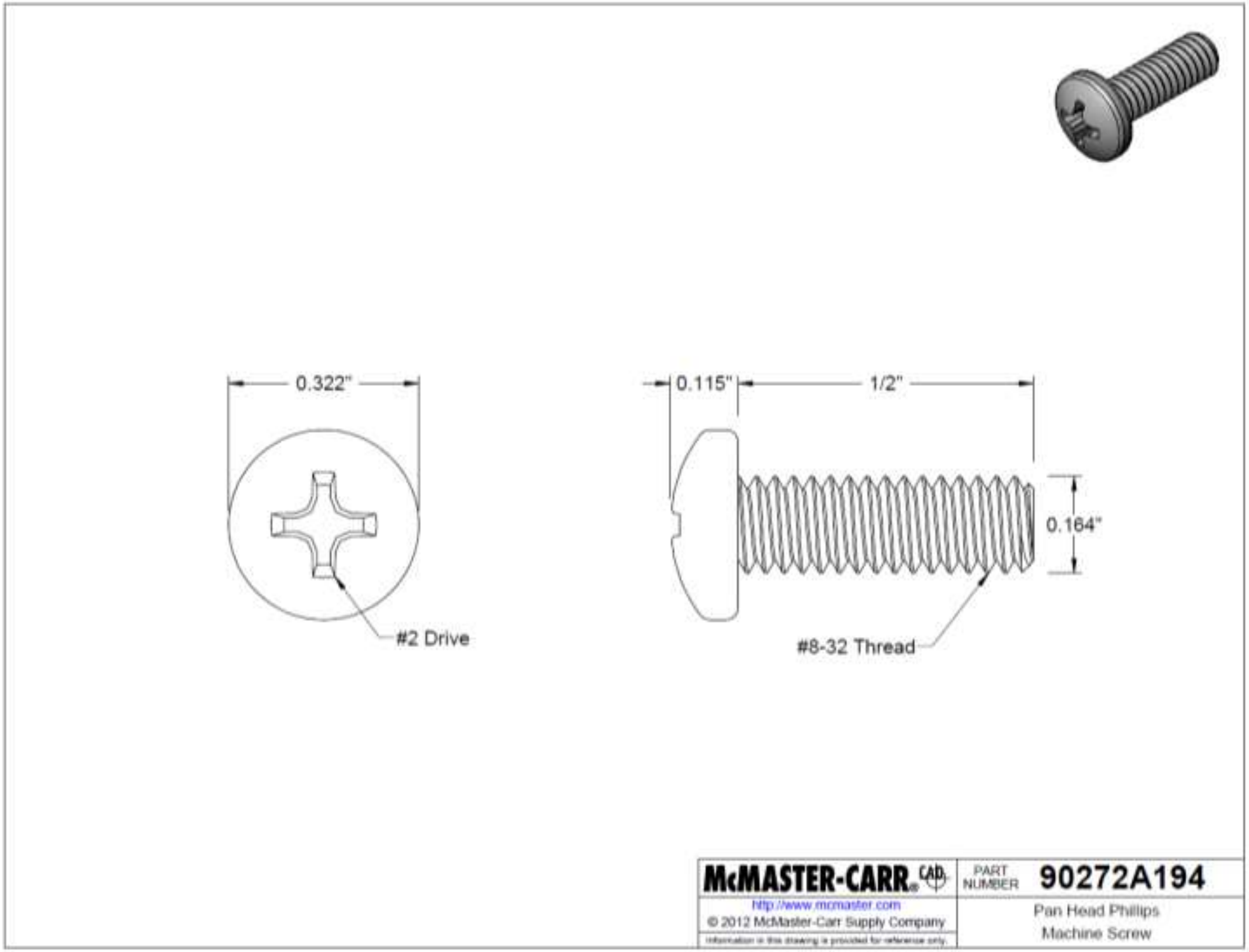


Powder Bed Integration Hardware

- 1.5” x 1.5” Bracket (4 Needed)
- 8 - 32 x ½” Screw (8 Needed)

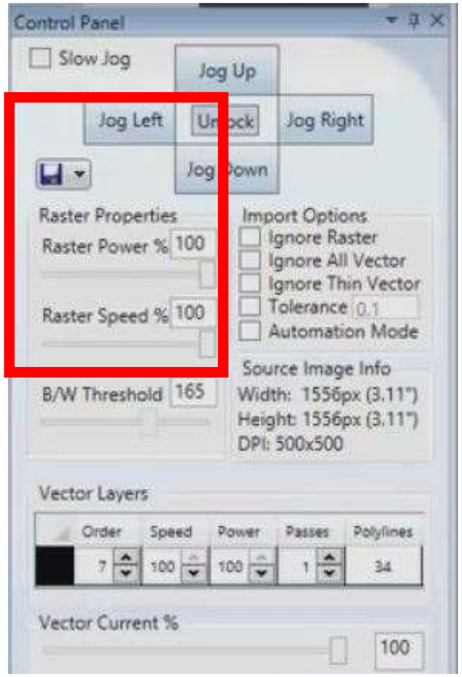


Screw Drawing



FSL Software Capabilities (Backup)

- RetinaEngraver program with engraver tools
- Accepts any standard image file (.jpeg .png .bmp)
  - 1-bit bitmaps with adjustable resolutions between 250 and 1000 Dots Per Inch (DPI)
- Laser head positioning, Print area, Print speed, Resolution (DPI), and Laser power all adjustable
- Engrave jobs can be saved and repeated without new user input
- Estimates time needed for each layer



☐ Slow Jog

Raster Properties

Raster Power % 100

Raster Speed % 100

B/W Threshold 165

Import Options

☐ Ignore Raster
☐ Ignore All Vector
☐ Ignore Thin Vector
☐ Tolerance 0.1
☐ Automation Mode

Source Image Info

Width: 1556px (3.11")
Height: 1556px (3.11")
DPI: 500x500

Vector Layers

	Order	Speed	Power	Passes	Polylines
■	7	100	100	1	34

Vector Current % 100

Estimated Job: 00:00:00

Sikuli GUI Automation (Backup)

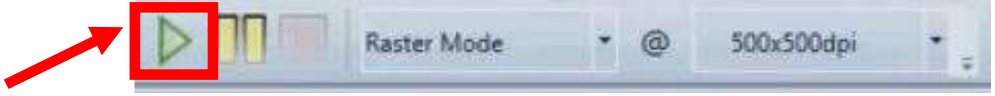
- Input number of layers and time per layer

Estimated Job: 00:00:00

- Sikuli with Python programming capable of image recognition for any on-screen program
- Pseudo code for automation

1) Run powder bed Arduino through IDE

2) Pause in Python until print bed completes and SoH sensors activated



Raster Mode @ 500x500dpi

3) Start print job through RetinaEngrave

4) Pause in Python for laser cutter

5) Complete layer and stop process

6) Loop 1-5 until SRM is complete

Arduino and SoH Software (Backup)

- Arduino script that raises/lowers motors then moves rake
  - Test code complete and takes 13 to 15 seconds to complete one cycle
- Switch statement between Motor control and SoH sensors
  - Begin script with motor increments
  - At end of motor control, switch to SoH checks until Arduino is reset
- SoH sensors checked in sequence at Arduino clock rate (16MHz)
- On reset, Arduino switches back to motor control until a new layer is complete

Arduino and SoH Off-Ramp (Backup)

- Secondary Arduino able to constantly check SoH during all phases of printing
- Able to constantly check the SoH at 16MHz
- Same design as before
  - Powered through USB connection
  - Connected to Temperature and CO sensors
  - Alert crew through LED and Buzzer

Component List

Component	Part Number	Component	Part Number
+ Piston Motor	23HS41-1804S	Rake Encoder	AMT102-V
+ Piston Motor Driver	DRV8825	Rake Snap Switch 1	TS0101F020P
+ Piston Encoder	AMT102-V	Rake Switch 2	TS0101F020P
+ Piston Snap Switch	TS0101F020P	CO Sensor	MQ-7
- Piston Motor	23HS41-1804S	Infrared Thermometer	MLX90614A
- Piston Motor Driver	DRV8825	Emergency Buzzer	Piezo SBZ-100
+ Piston Encoder	AMT102-V	Emergency LED	YSL-R531R3C-A13
+ Piston Snap Switch	TS0101F020P	12VDC External Power Supply	PSS12-035
Rake Motor	17HS19-1684D	24 VDC External Power Supply	PSS24-100
Rake Motor Driver	DRV8825		

Arduino Mega

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	54 (15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz
Length	101.52 mm
Width	53.3 mm
Weight	37 g

Piston Motors

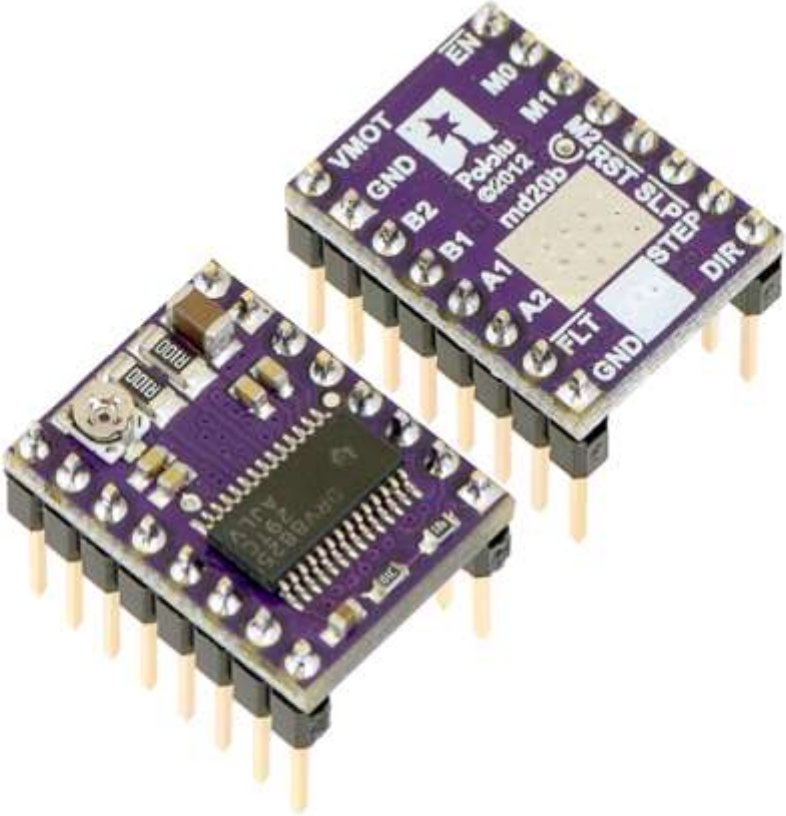
Manufacturer Part Number	23HS41-1804S
Motor Type	Bipolar Stepper
Step Angle	1.8°
Holding Torque	2.4Nm(340oz.in)
Rated Current/phase	1.8A
Phase Resistance	2.75ohms
Recommended Voltage	24-48V
Inductance	17mH±20%(1KHz)

Rake Motor

Manufacturer Part Number	17HS19-1684D
Motor Type	Bipolar Stepper
Step Angle	1.8°
Holding Torque	44Ncm(62.3oz.in)
Rated Current/phase	1.68A
Phase Resistance	1.65ohms
Recommended Voltage	12-24V
Inductance	2.8mH±20%(1KHz)

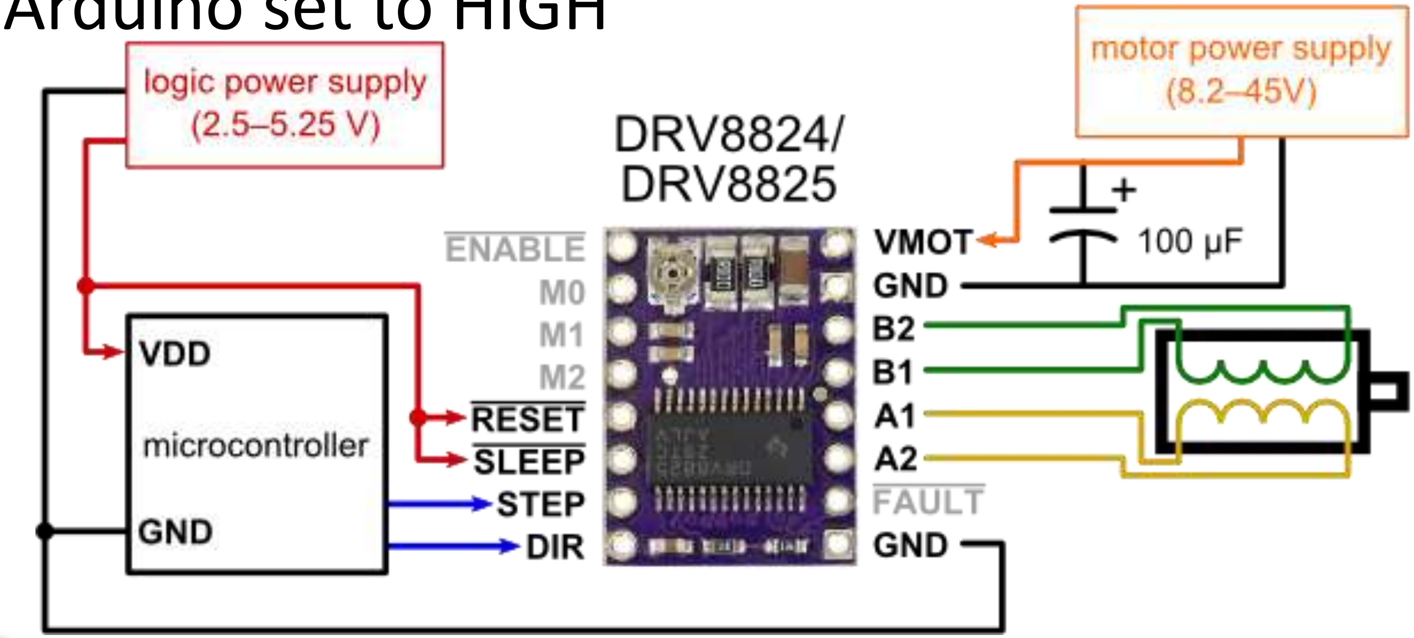
Motor Driver

Minimum operating voltage:	8.2 V
Maximum operating voltage:	45 V
Continuous current per phase:	1.5 A
Maximum current per phase:	2.2 A
Minimum logic voltage:	2.5 V
Maximum logic voltage:	5.25 V
Microstep resolutions:	full, 1/2, 1/4, 1/8, 1/16, and 1/32



Driver Minimal Hookup Guide

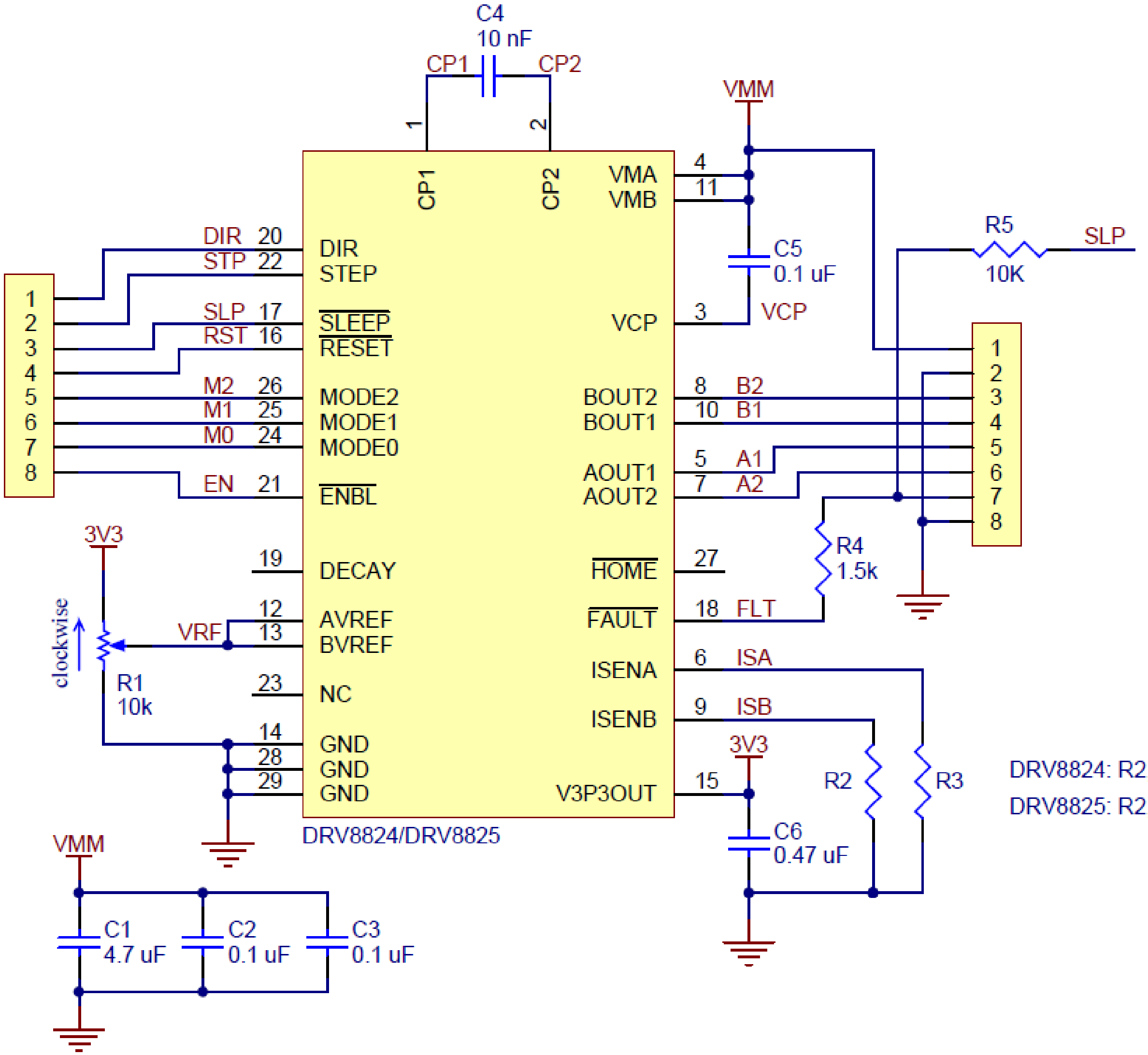
- Pins M0, M1, M2 will be hooked up to digital pins on the Arduino to enable the ability to microstep.
- ENABLE Pin will be hooked up to a digital pin on the Arduino set to HIGH



Driver Micro Step Settings

M0	M1	M2	Microstep Resolution
Low	Low	Low	Full step
High	Low	Low	Half step
Low	High	Low	1/4 step
High	High	Low	1/8 step
Low	Low	High	1/16 step
High	Low	High	1/32 step
Low	High	High	1/32 step
High	High	High	1/32 step

Motor Driver Schematic



DRV8824: R2,R3 = 0.33Ω

DRV8825: R2,R3 = 0.10Ω

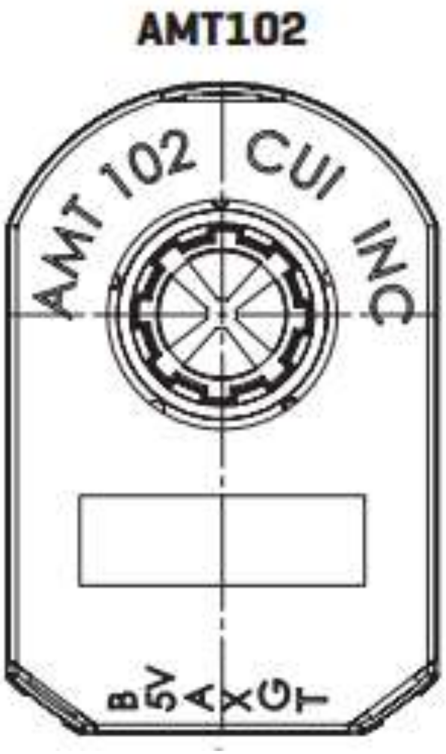
Motor Encoder

- Hollow Shaft with adaptable interior diameters from 2 mm to 8 mm

Part Number	AMT102 - V
Power Supply	5 V
Input Current	6 mA
Output High	4.2 V
Output Low	0.4 V
Rise/Fall Time	30 ns
Pulses Per Revolution	2048

Motor Encoder Pin Connections

Pin Connector	Function
B	B Channel
5 V	+5 V supply
A	A channel
X	Index Channel
G	Ground
T	Not Used



Motor Encoder Waveform

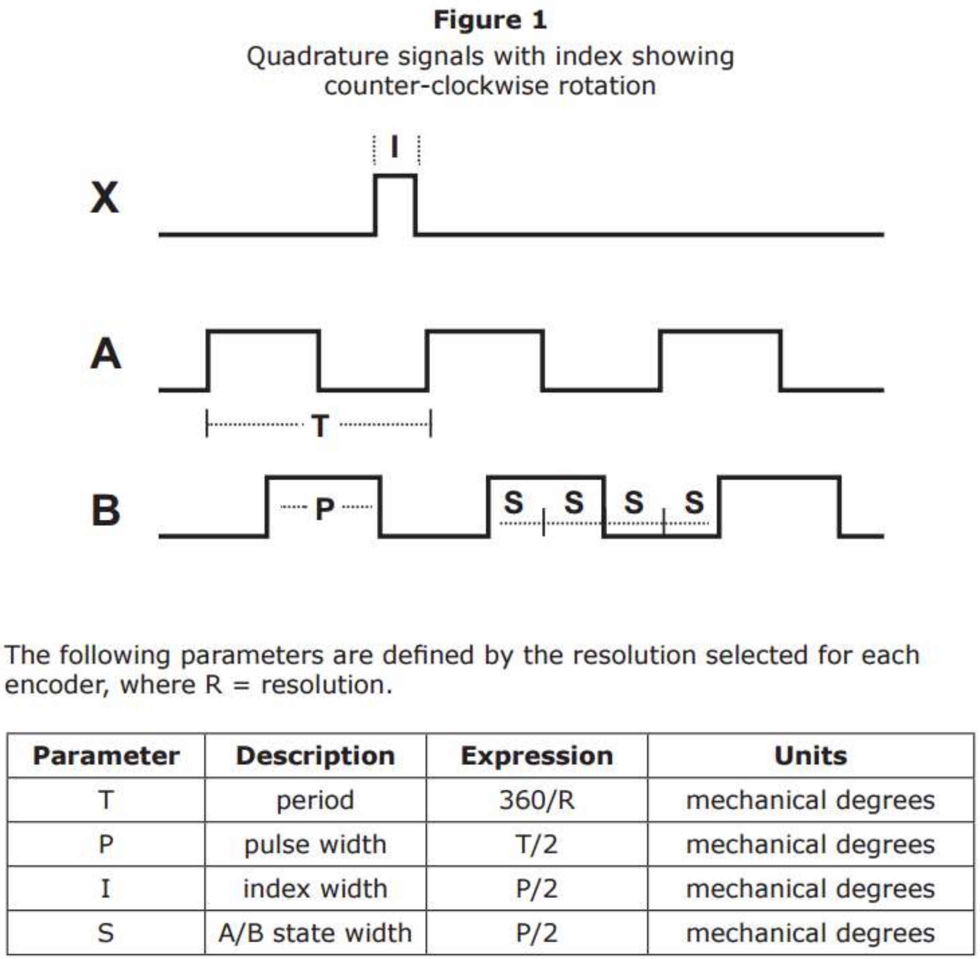


Figure 1
Quadrature signals with index showing
counter-clockwise rotation

The following parameters are defined by the resolution selected for each encoder, where R = resolution.

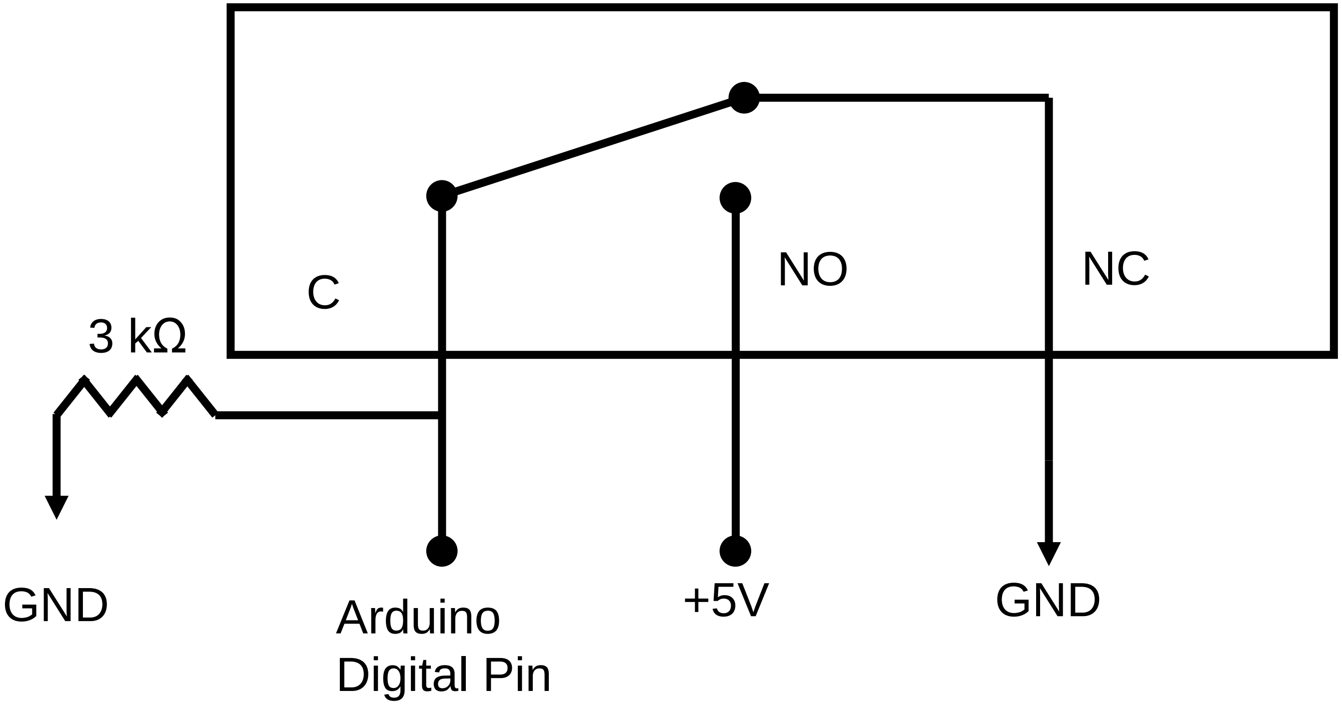
Parameter	Description	Expression	Units
T	period	360/R	mechanical degrees
P	pulse width	T/2	mechanical degrees
I	index width	P/2	mechanical degrees
S	A/B state width	P/2	mechanical degrees

Snap Switch: TS0101F020P

- Rated for 6 V, .3A
- Common = C
- Normally Open: NO
- Normally Closed: NC

Wire Diagrams (Backup)

- Snap Switch Wire Diagram



External Power Supplies

	PSS12-035	PSS24-100
Input Voltage [VAC]	85 - 264	85 – 264
Input Frequency [Hz]	47 – 63	47 – 63
Max Input Current [A]	0.75	2
Leakage current [mA]	1	1
Output Voltage/ Adjustment Range [VDC]	12/11-14	24/22-28
Output Power [W]	35	100
Output Current [A]	3	4.17
Ripple Voltage [mVpp]	100	150
Startup Time [ms]	2500	1000

CO Sensor: MQ-7

Model			MQ-7
Sensor Type			Semiconductor
Standard Encapsulation			Plastic cap
Target Gas			carbon monoxide
Detection range			10～500ppm CO
Standard Circuit Conditions	Loop Voltage	V_c	≤10V DC
	Heater Voltage	V_H	5.0V±0.1V AC or DC（High tem.） 1.5V±0.1V AC or DC（Low tem.）
	Heater Time	T_L	60 S±1S（High tem.）， 90 S±1S（Low tem.）
	Load Resistance	R_L	Adjustable
Sensor character under standard test conditions	Heater Resistance	R_H	29Ω±3Ω（room tem.）
	Heater consumption	P_H	≤900mW
	Sensitivity	S	Rs(in air)/Rs(in 150ppm CO)≥5
	Output Voltage	Vs	2.5V～4.3V (in 150ppm CO)
	Concentration Slope	α	≤0.6(R_{300ppm}/R_{50ppm} CO)
Standard test conditions	Tem. Humidity		20℃±2℃；55%±5%RH
	Standard test circuit		Vc:5.0V±0.1V； V_H（High tem.）： 5.0V±0.1V； V_H（Low tem.）： 1.5V±0.1V
	Preheat time		Over 48 hours

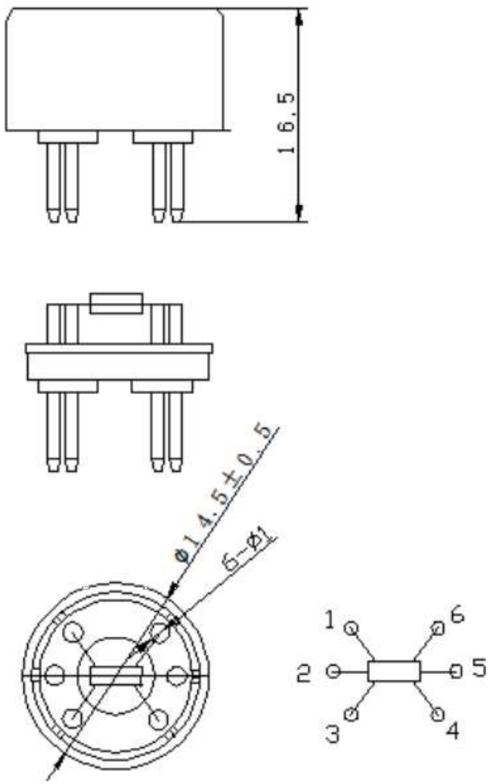
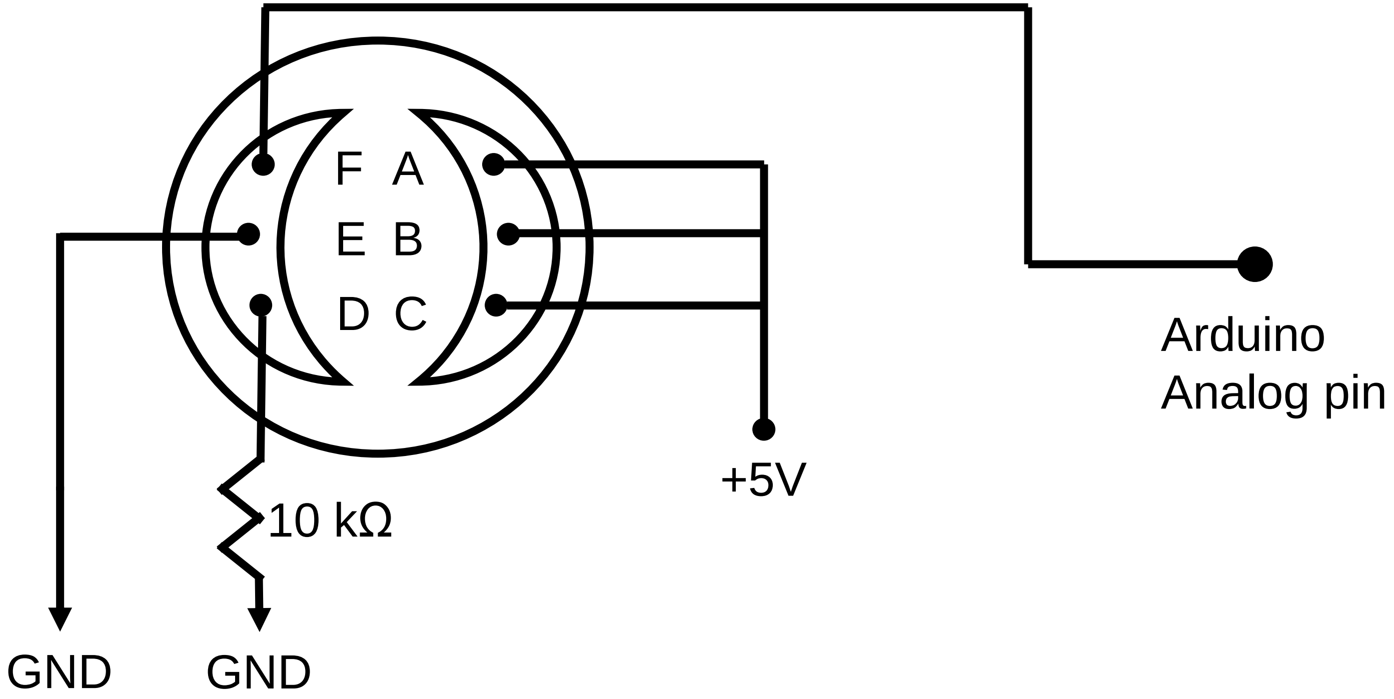


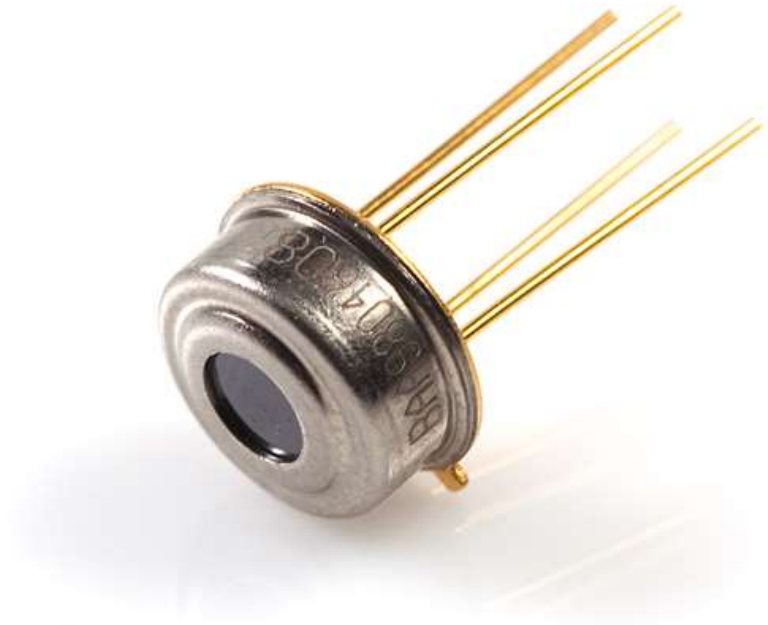
Fig1.Sensor Structure

Unit: mm

Carbon Monoxide Wire Diagram



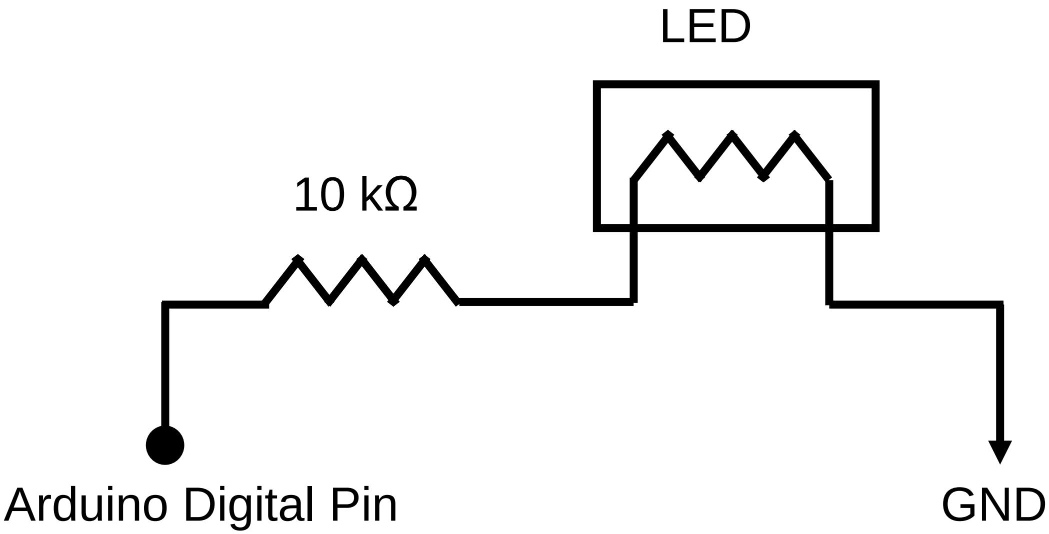
Infrared Thermometer:



LED

- 5 V_{in}
- 2.4 V drop
- I_{max} = 20 mA
- 9000 mCd Bright

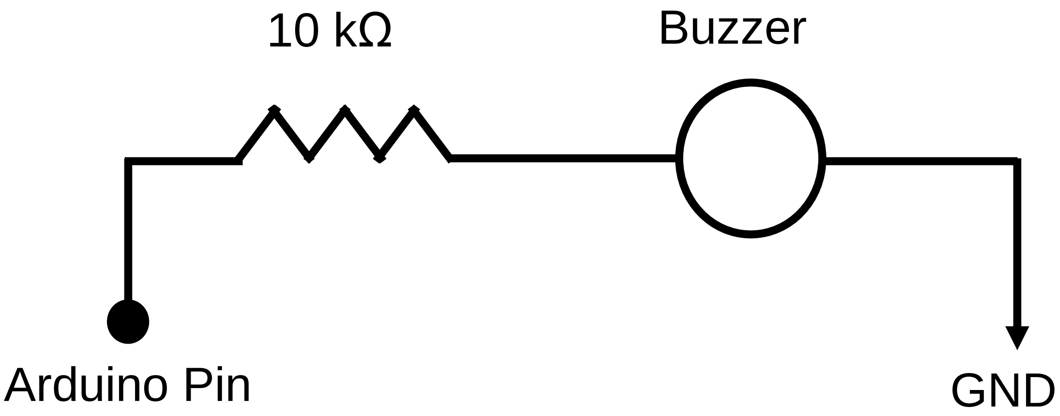
LED Wire Diagram



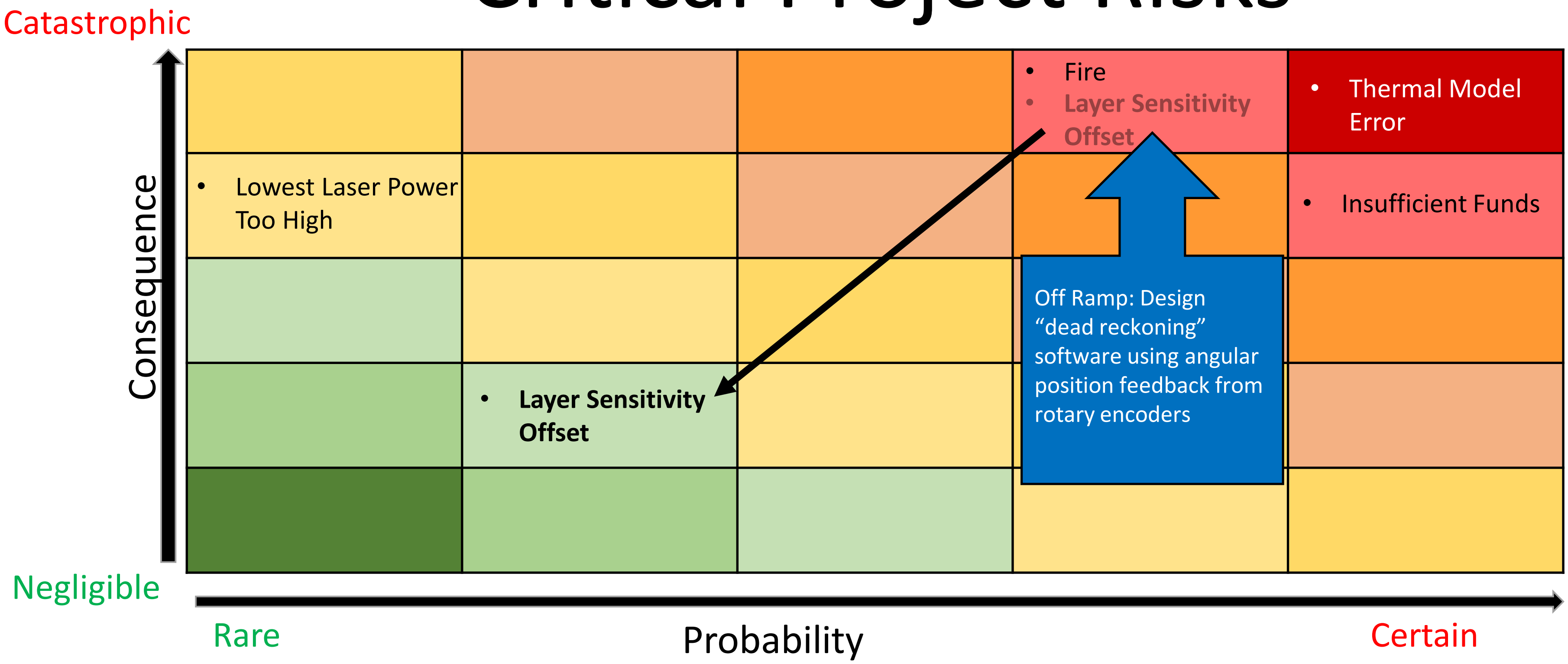
Buzzer

- Piezo SBZ-100
- 103 Db
- 3-28 V_{in}
- 10mA I_{in}
- V_{in}: Red wire
- GND: Black Wire

Buzzer Wire Diagram



Critical Project Risks



- Fire
- Layer Sensitivity Offset

- Thermal Model Error

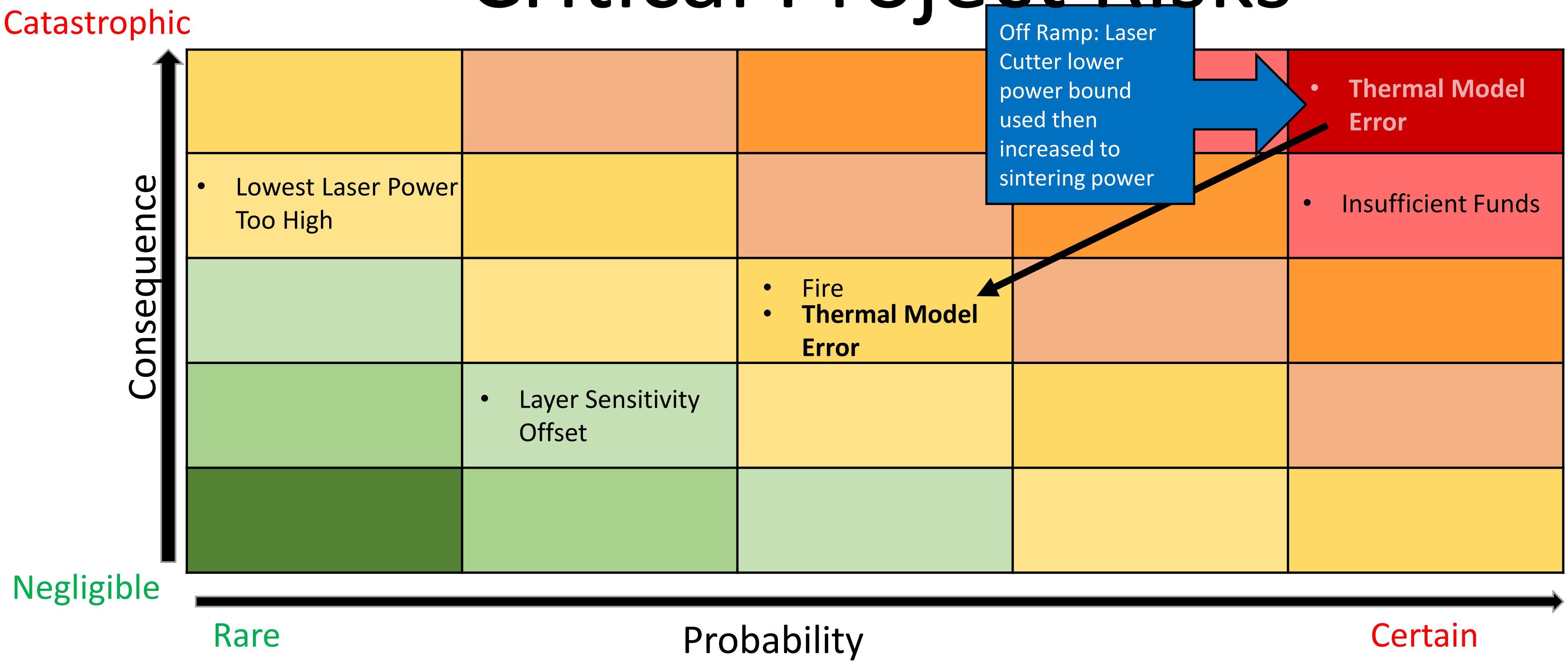
- Lowest Laser Power Too High

- Insufficient Funds

- **Layer Sensitivity Offset**

Off Ramp: Design “dead reckoning” software using angular position feedback from rotary encoders

Critical Project Risks



Catastrophic

Consequence

Negligible

				- **Thermal Model Error**
- Lowest Laser Power Too High				- Insufficient Funds
		- Fire - **Thermal Model Error**		
	- Layer Sensitivity Offset			

Rare

Probability

Certain

Off Ramp: Laser Cutter lower power bound used then increased to sintering power

Test Plan: Overview

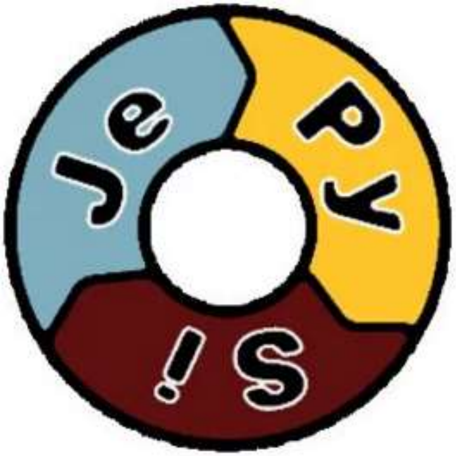
- Week 1-2
  - Software, firmware
  - Thermal conductivity
  - Latent Heat of sintering
  - SoH sensors
- Week 3-4
  - Water Safety
  - Rake and Lifts
  - COTS laser cutter test
- Week 5-6
  - Powder Bed Test
- Week 8-10
  - Laser Power
  - Beam Profile
- Week 11
  - Full Printing
- Week 13
  - Instron testing/comparison

Test Plan: COTS test

- Does the hardware/software work as shipped?
- Wood engrave
  - Team picture/memorabilia?
- BAC lab
- Identify laser issues early

Test Plan: Software Test

- Laser cutter proprietary software
  - Verified in COTS test
- JePySi
  - Self-debugging
  - Image recognition not 100% reliab
    - Several iterations of image database update
  - Can test unlimited times without hardware



Test Plan: Black Body

- Two tests
  - Measure laser power before and after each mirror
    - Plot % power in GUI vs actual power delivered
    - Before modification
  - Measure attenuation via PWM and/or ND filter
    - Proper printing power
    - After modification
- Safety notes
  - Busemann Advanced Concepts Lab
  - Override laser open case auto-off
  - Hands off while plugged in