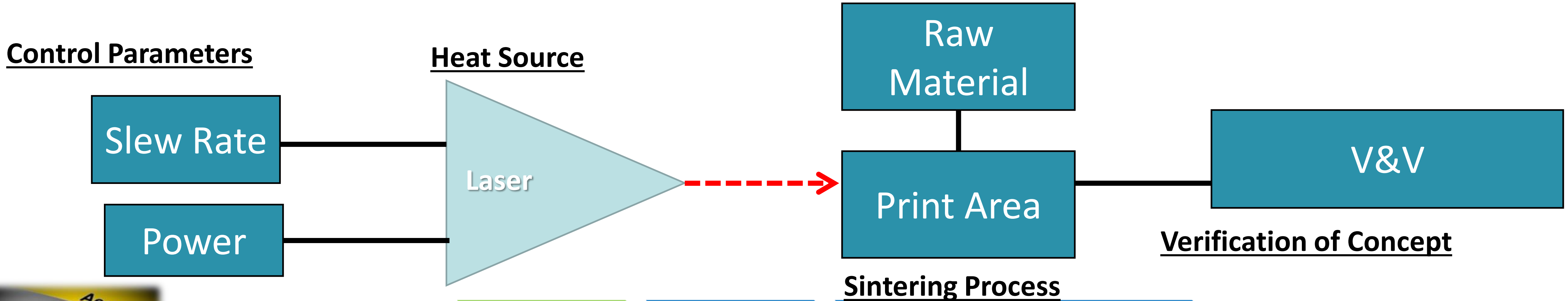
Manufacturing Status Review (MSR)

Solid Propellant Additive Manufacturing (SPAM)

Project Purpose

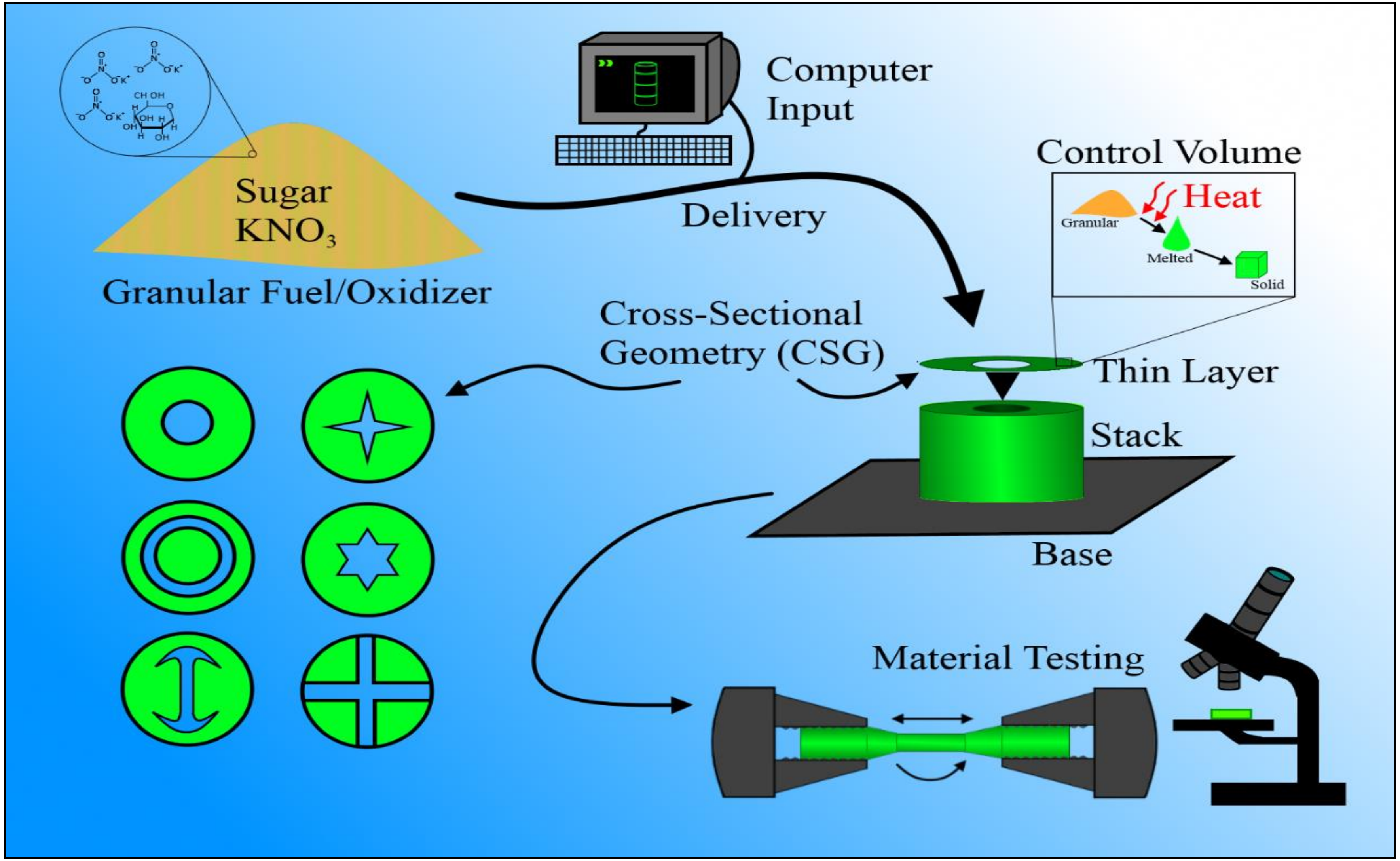
SPAM = ROCKET FUEL PRINTER

Sinter at least one ≤1mm layer of "rocket candy" propellant

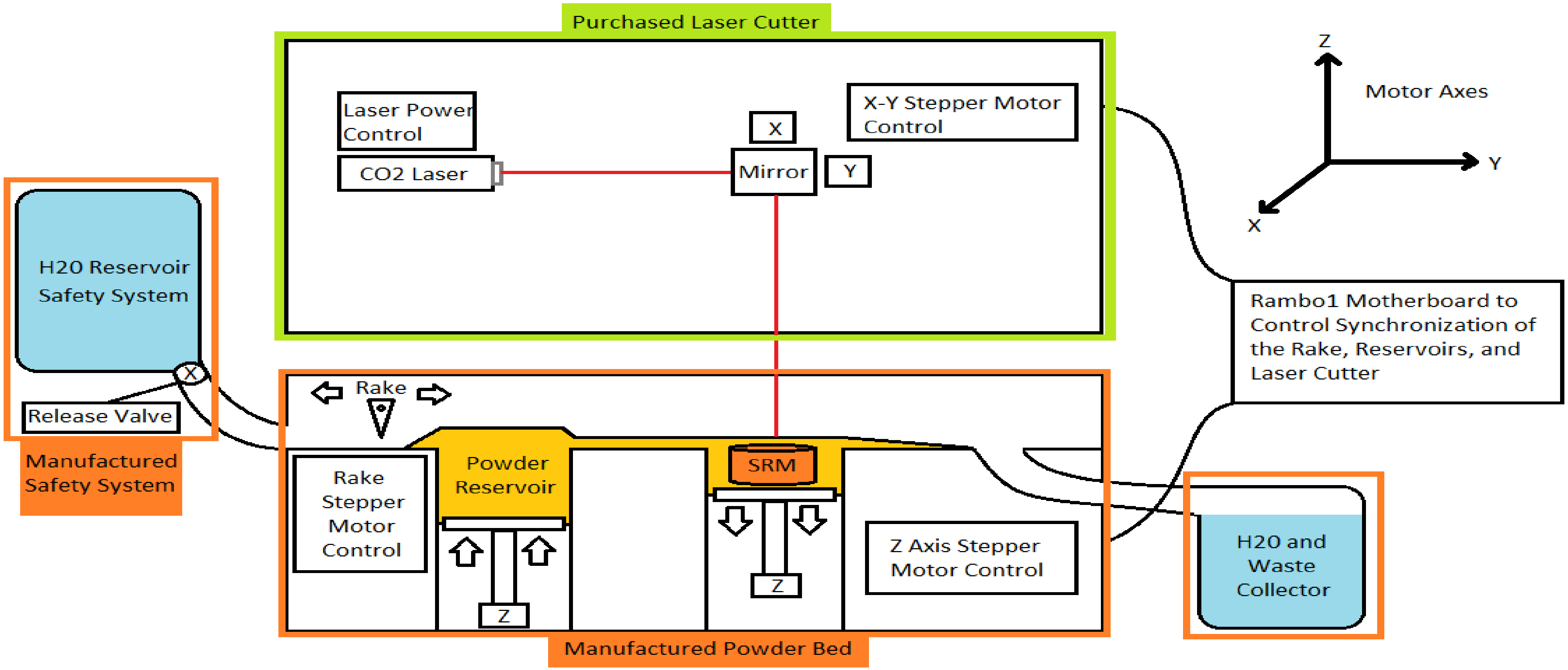


Full Project Concept of Operations

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

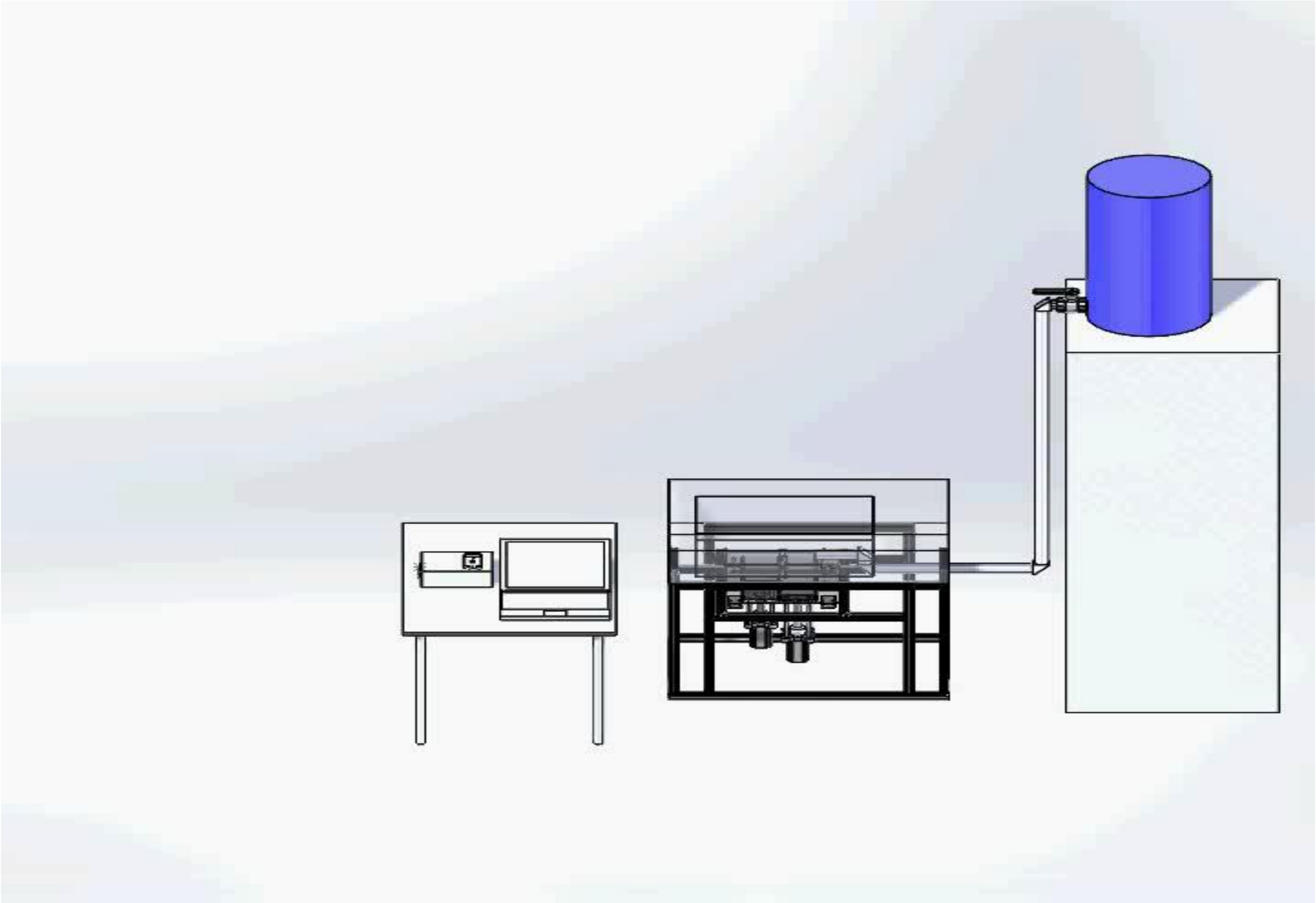


Printer Concept of Operations



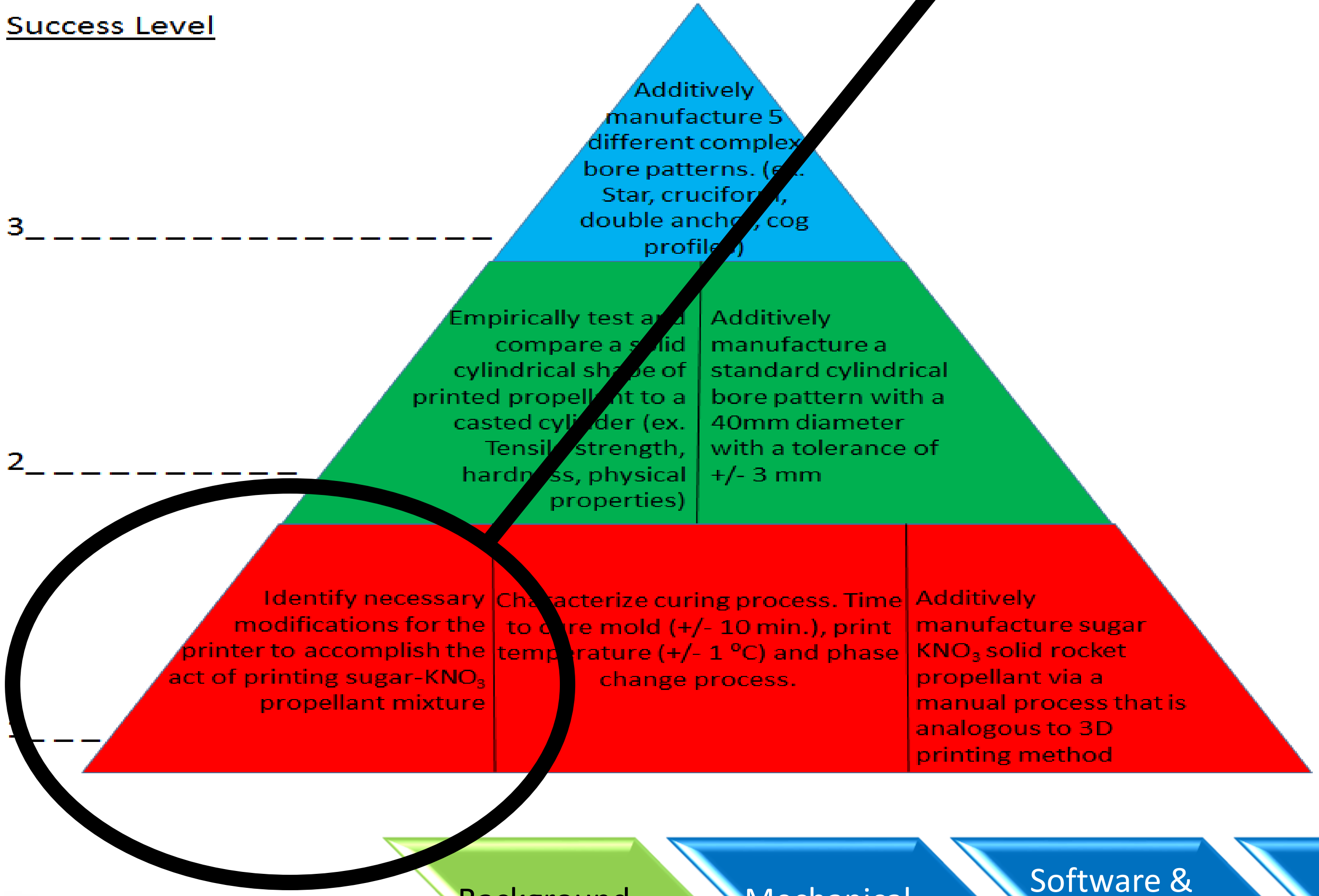
Design Solution

No Major Modifications Since CDR



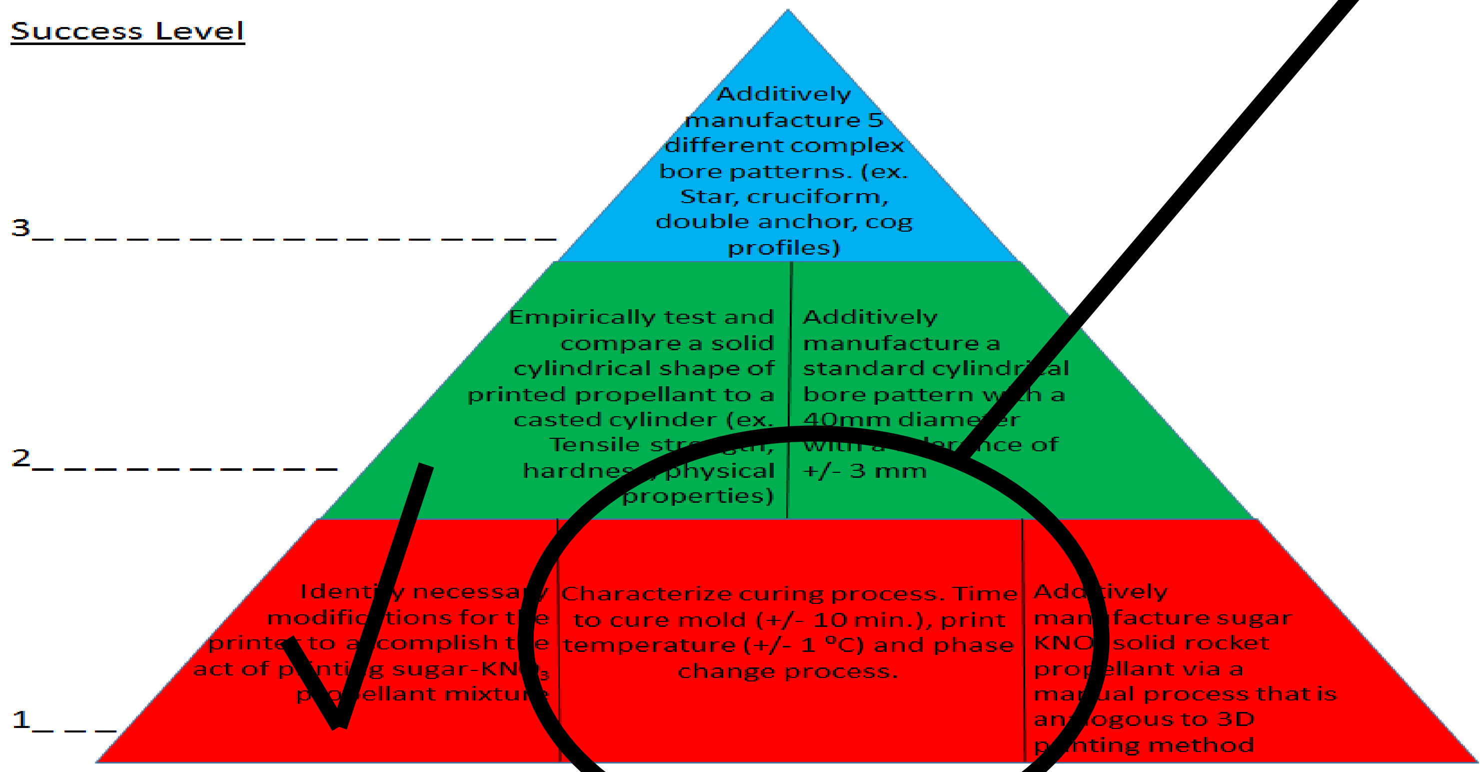
Levels of Success -- Progress

- Identify necessary modifications for the printer to accomplish the act of printing sugar-KNO3 propellant mixture

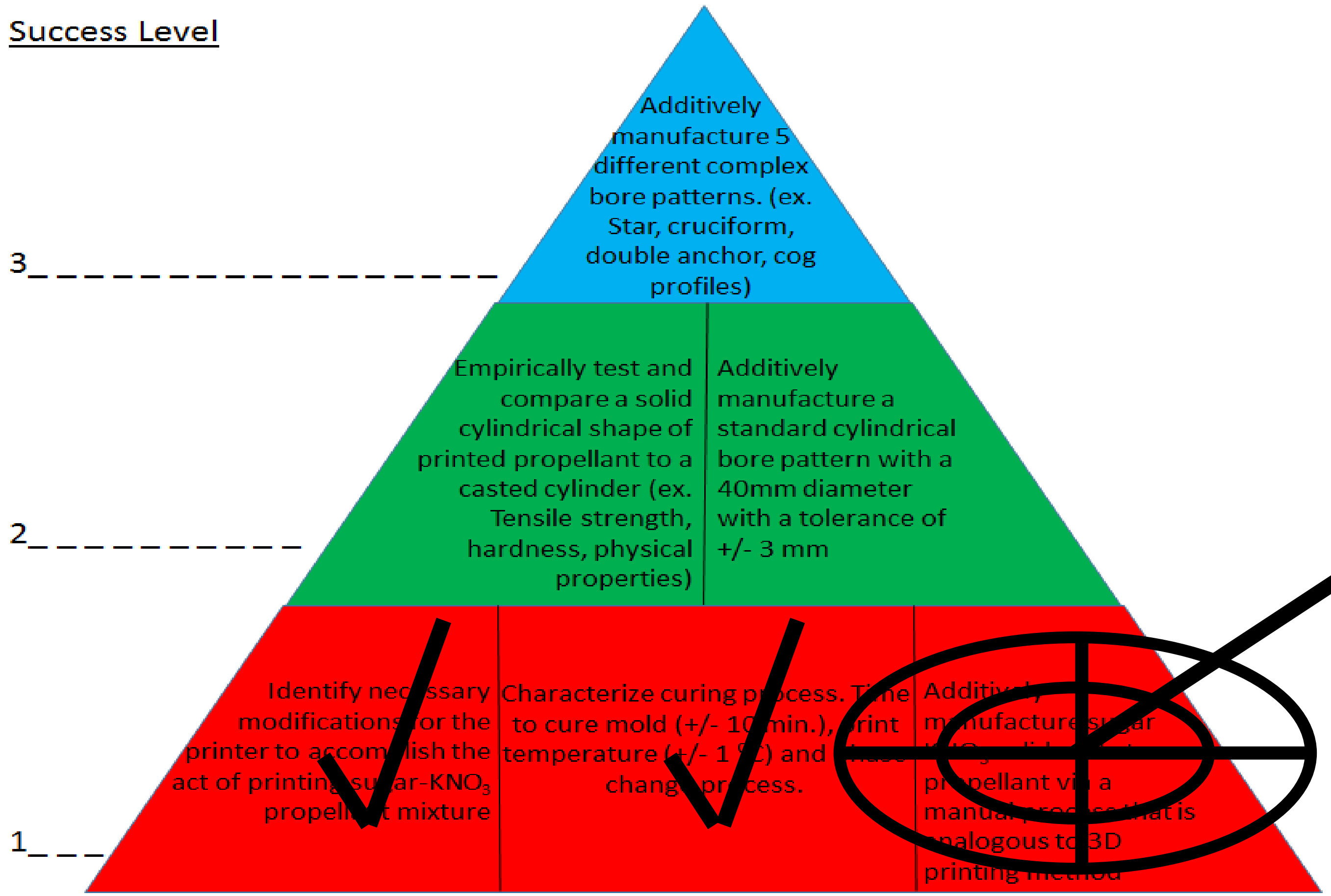


Levels of Success -- Progress

- Characterize curing process, time to cure mold (+/-10 min), print temperature (+/-1°C) and phase change process

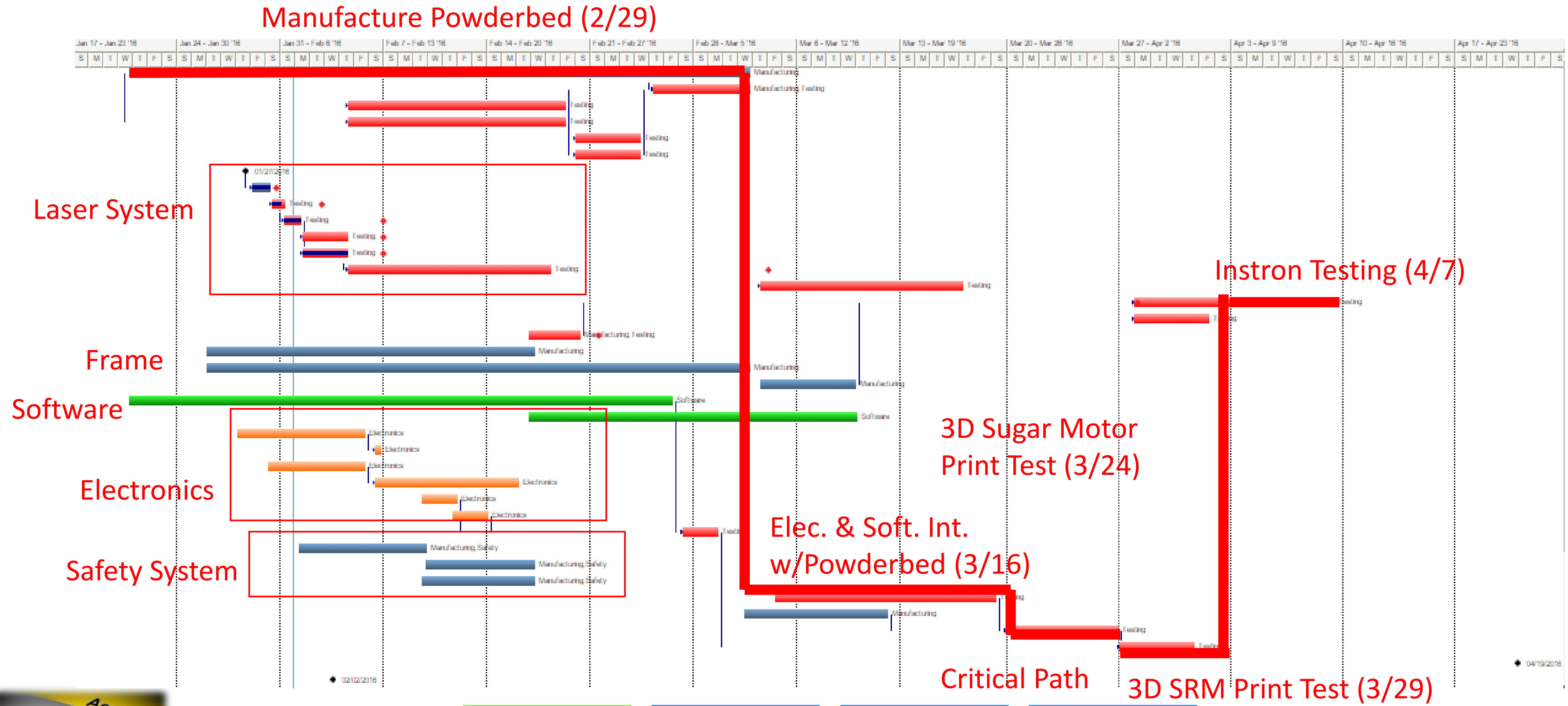


Levels of Success -- Progress



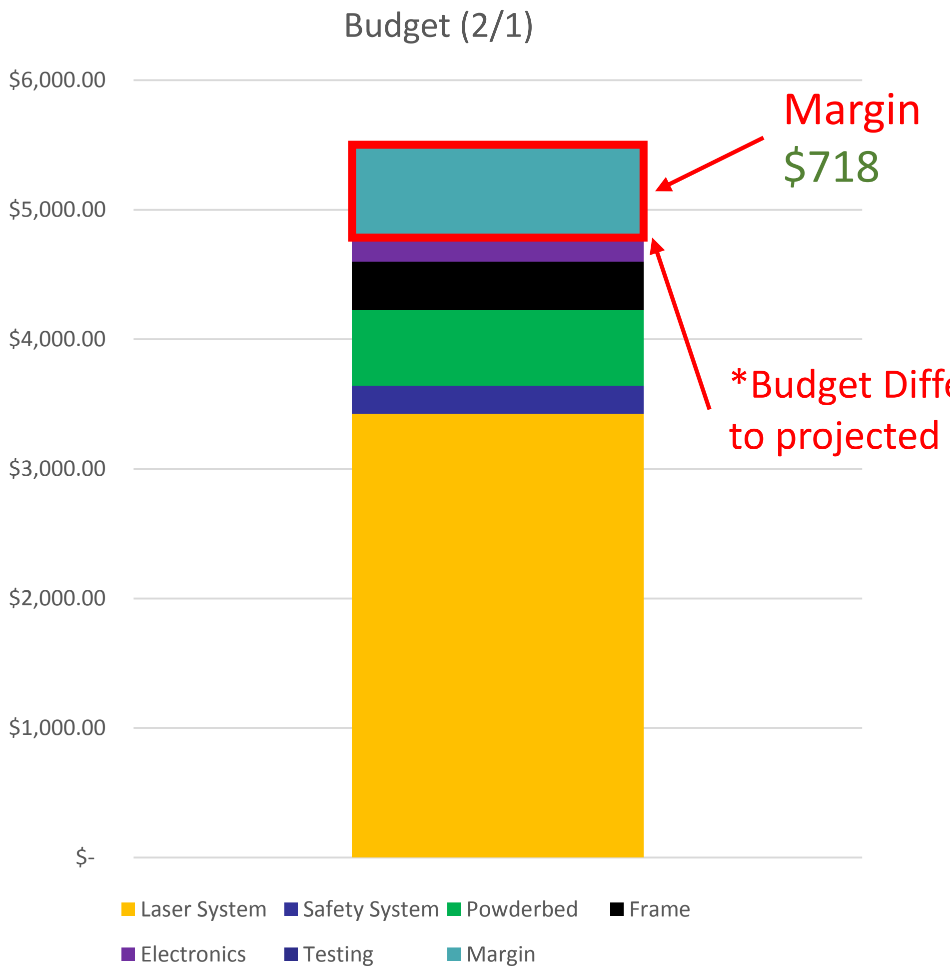
- Additively manufacture sugar KNO3 solid rocket propellant via a manual process that is analogous to 3D printing method

Overall Schedule

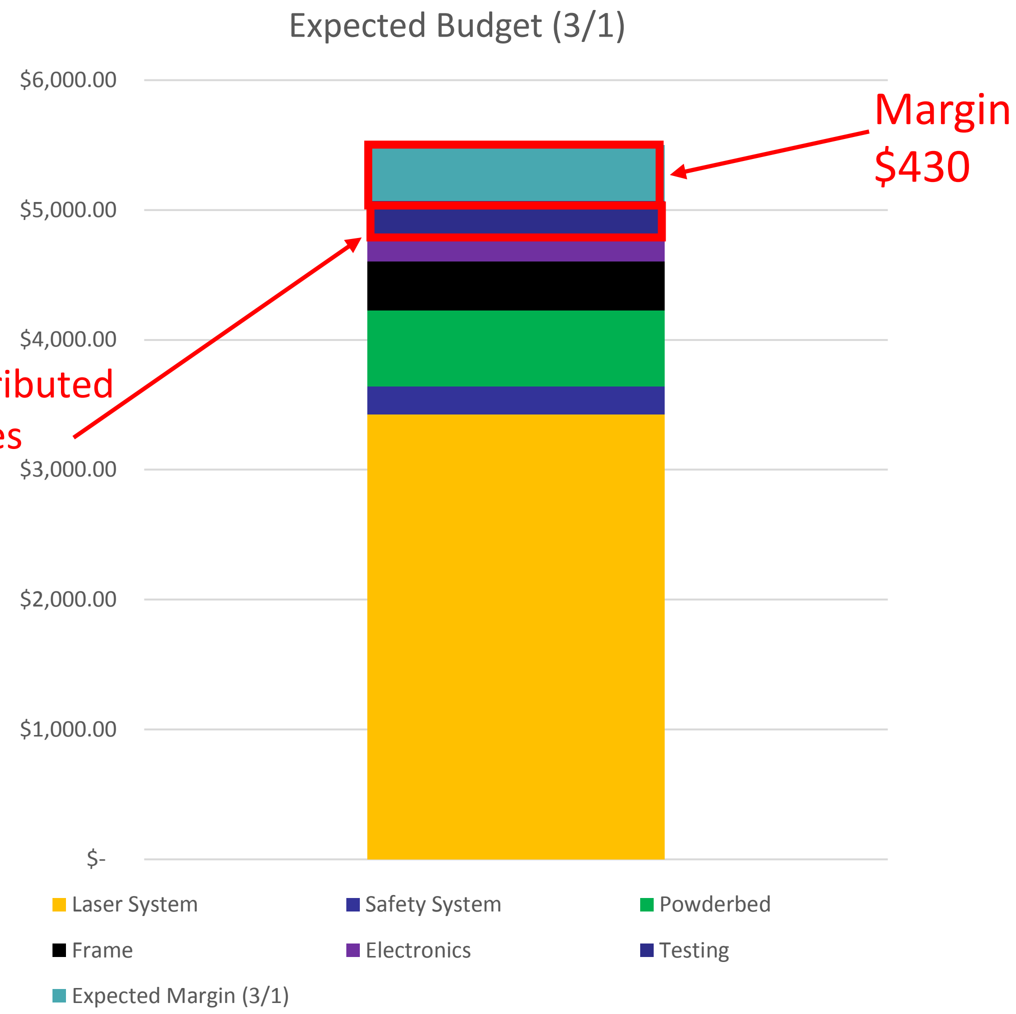


Background | Mechanical | Software & Electronics | Laser & Testing

Financial Status

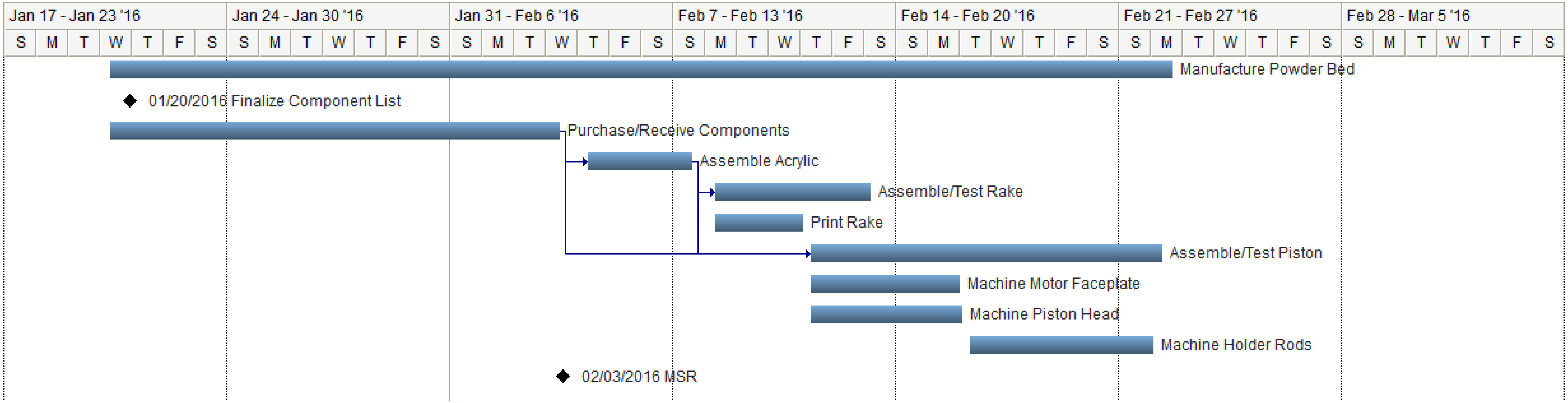


*Budget Differences are attributed to projected testing expenses



Mechanical Systems Status

Subsystem Schedule

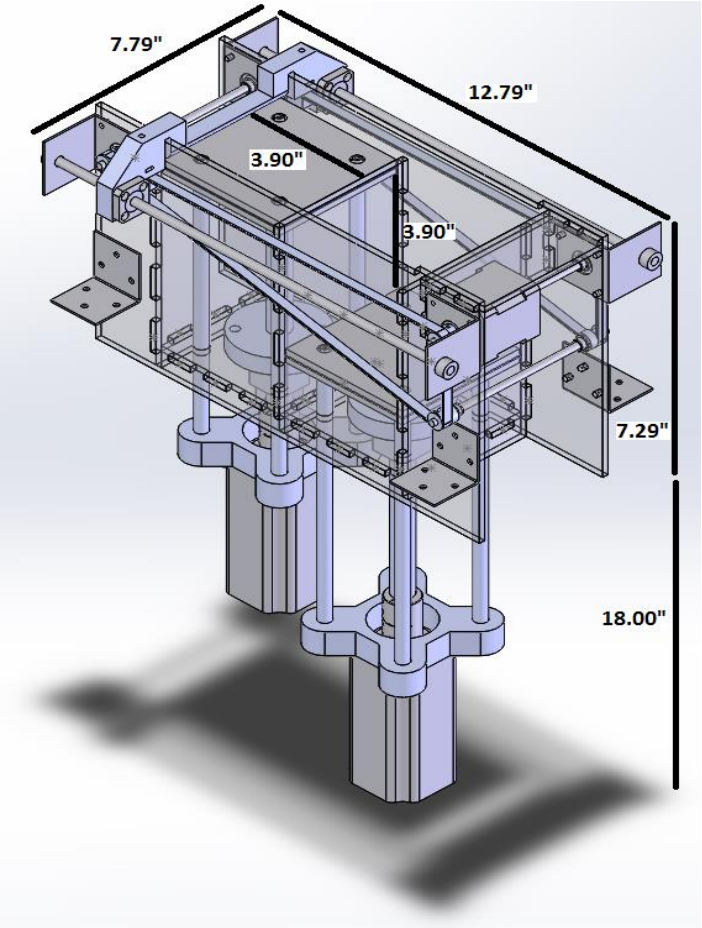


Most tasks can be completed concurrently as materials are received

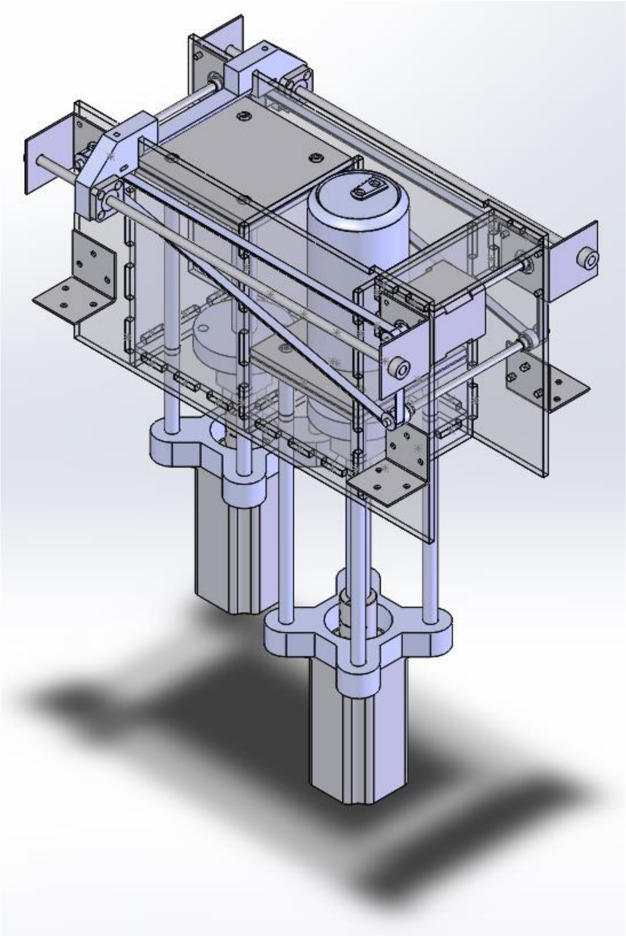
Powder Bed Overview

- ➢Stores and delivers powder to be sintered
- ➢Provides a volume in which the layers will stack
- ➢Provides vertical motion needed to transition to a new layer

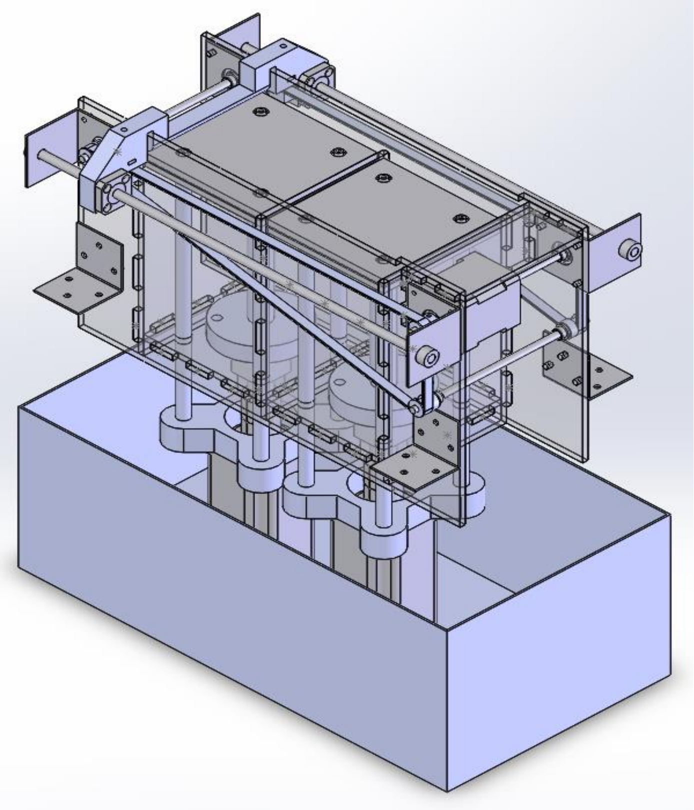
Requirement I.D.	Description
2.4	The Manufacturing System shall be capable of autonomous sintering.



Powder Bed Scale



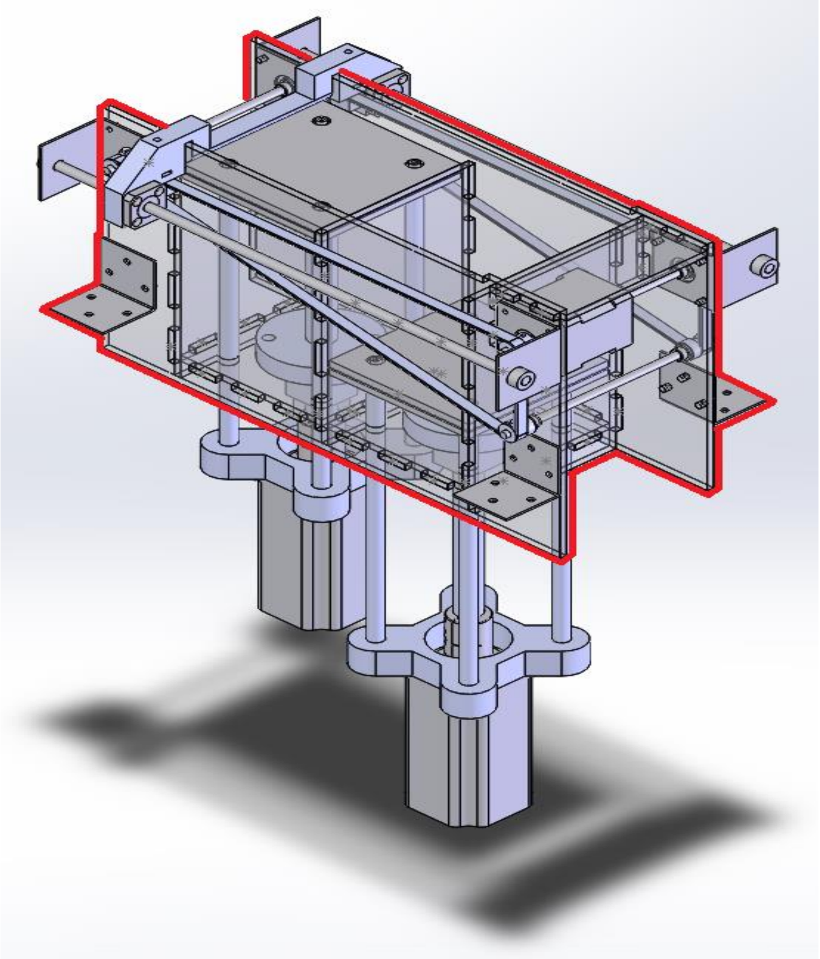
A standard soda can fit in a lowered piston



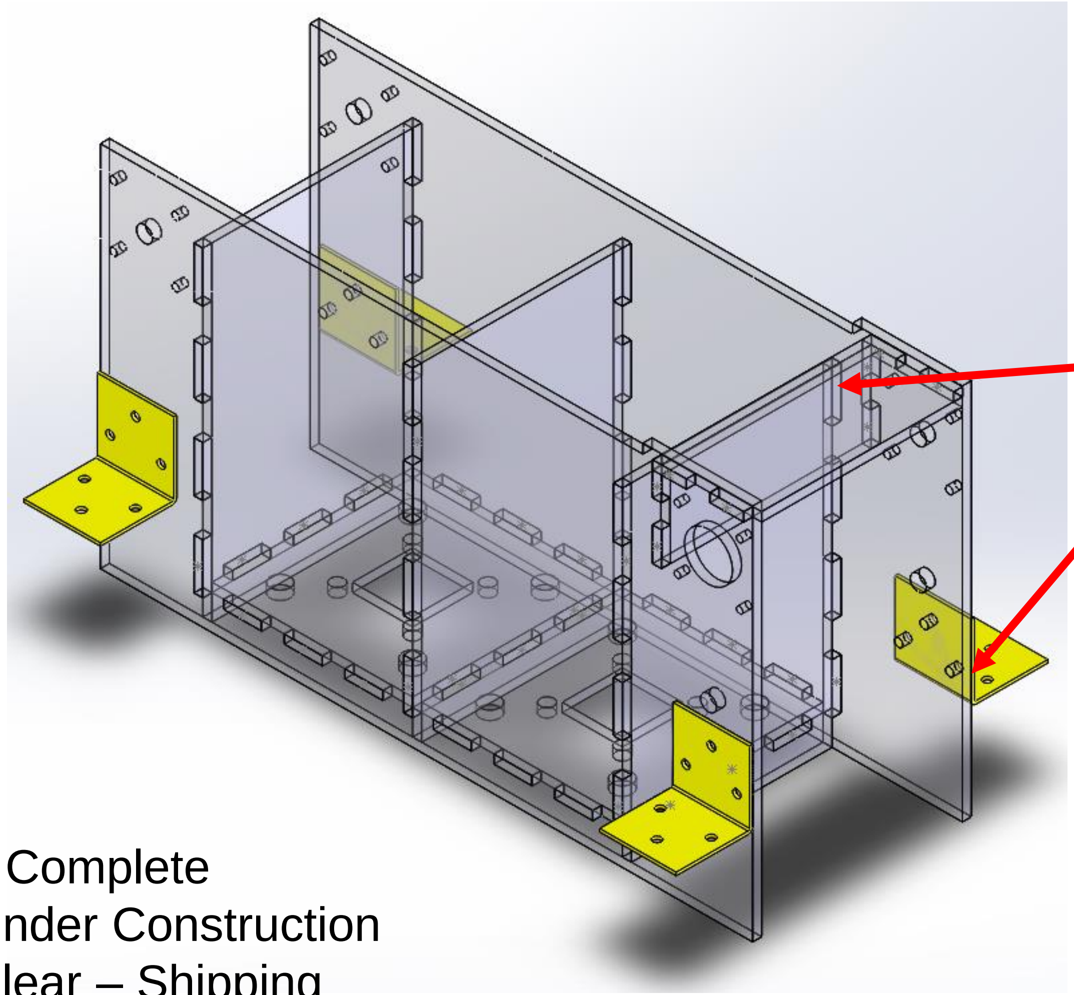
The footprint of the Powder Bed will fit in a shoebox

Powder Bed - Body

- Acrylic body and metal brackets
- Laser cut and held together with epoxy
- Houses further components and attaches Powder Bed to the Frame



Powder Bed- Body



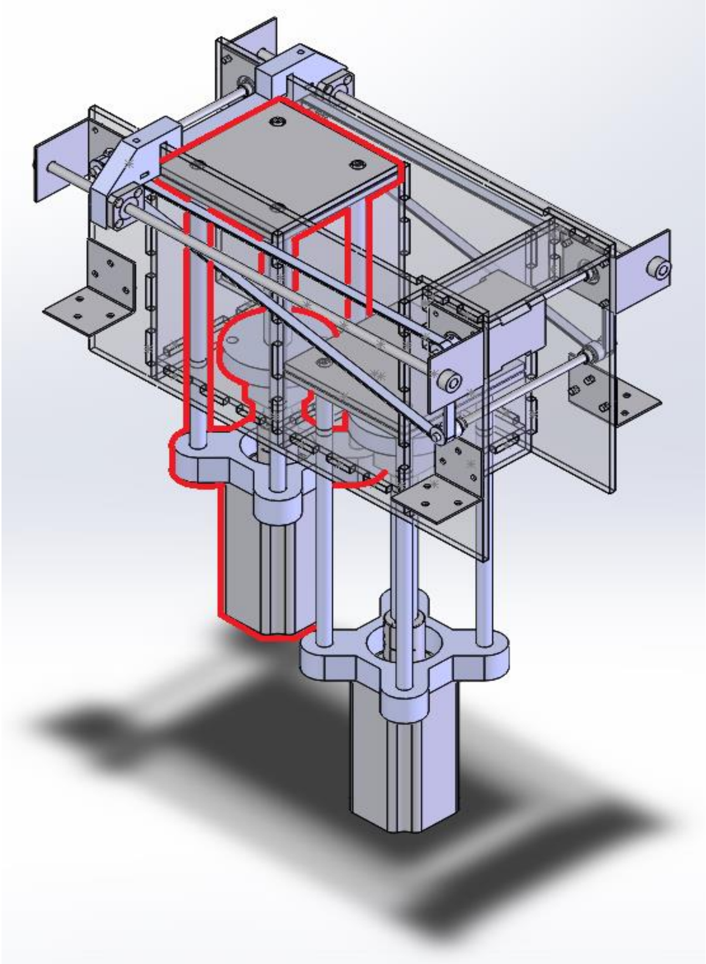
Component	Status (% Complete)	Total Required Manufacturing Hours	Planned Completion Date
Acrylic Body	0%	12	February 8th
Mounting Brackets	0%	1	February 8th

- Construction begins when components arrive

Green – Complete
Blue – Under Construction
Yellow/Clear – Shipping

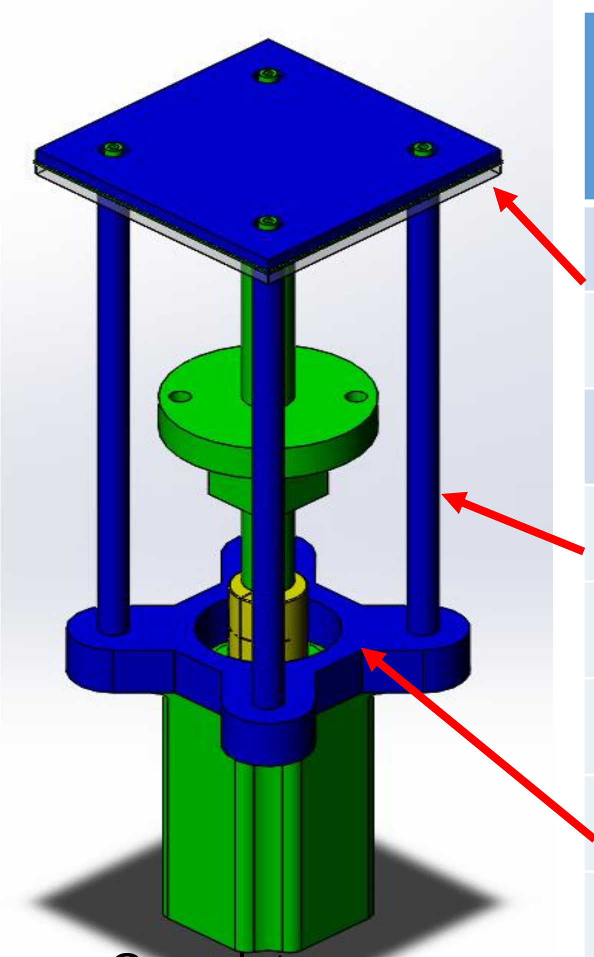
Powder Bed - Piston

- Ball screw/nut driven shaft raises and lowers a piston head
- Custom milled aluminum head provides a robust printing surface
- Felt gasket minimizes powder leak
- Entire assembly driven by a NEMA 23 motor



Requirement I.D.	Description
2.4.1	A piston controlled chamber shall hold a reservoir of powder to be used for sintering
2.4.2	A piston controlled chamber shall lower the sintering area to allow for another layer of propellant powder

Powder Bed - Piston



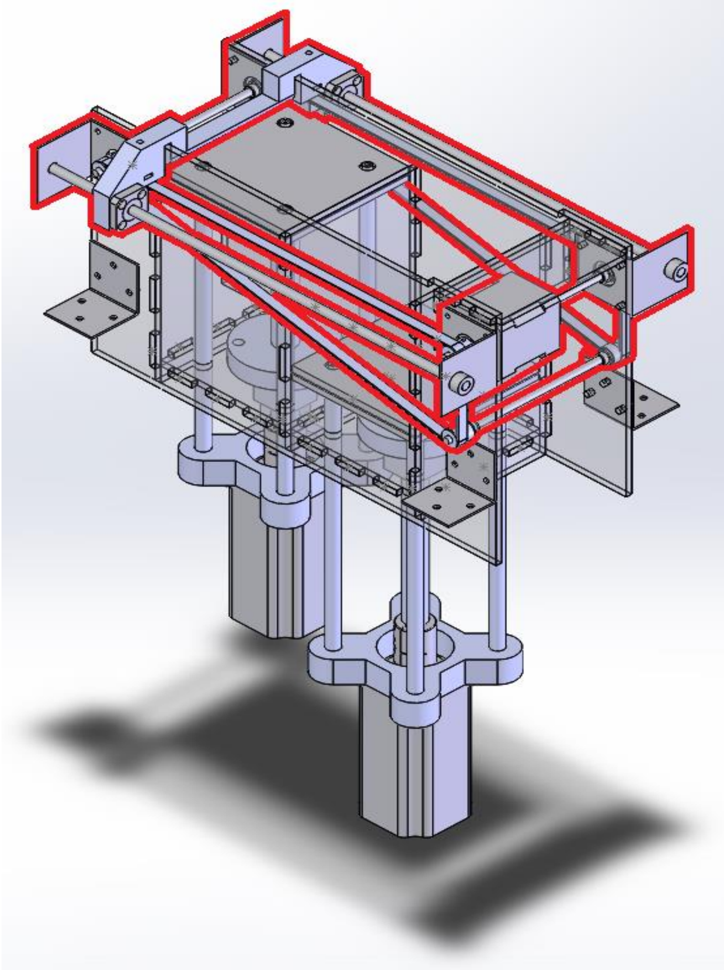
Green – Complete
Blue – Under Construction
Yellow/Clear – Shipping

Component	Status (% Complete)	Total Required Manufacturing Hours	Planned Completion Date
Aluminum Piston Head	20%	6	February 15th
Felt Gasket	75%	1	February 15th
Acrylic Piston 'Bottom'	10%	1	February 15th
Holder Rod	10%	12	February 22nd
Ball Nut/Screw	100%	2	February 11th
Drive Shaft Coupler	0%	1	February 22nd
Aluminum Faceplate	20%	8	February 15th
NEMA 23 Stepper Motor	100%	1	February 11th

Most components are trivial, some require milling, drilling, and tapping of holes which take considerably more time.

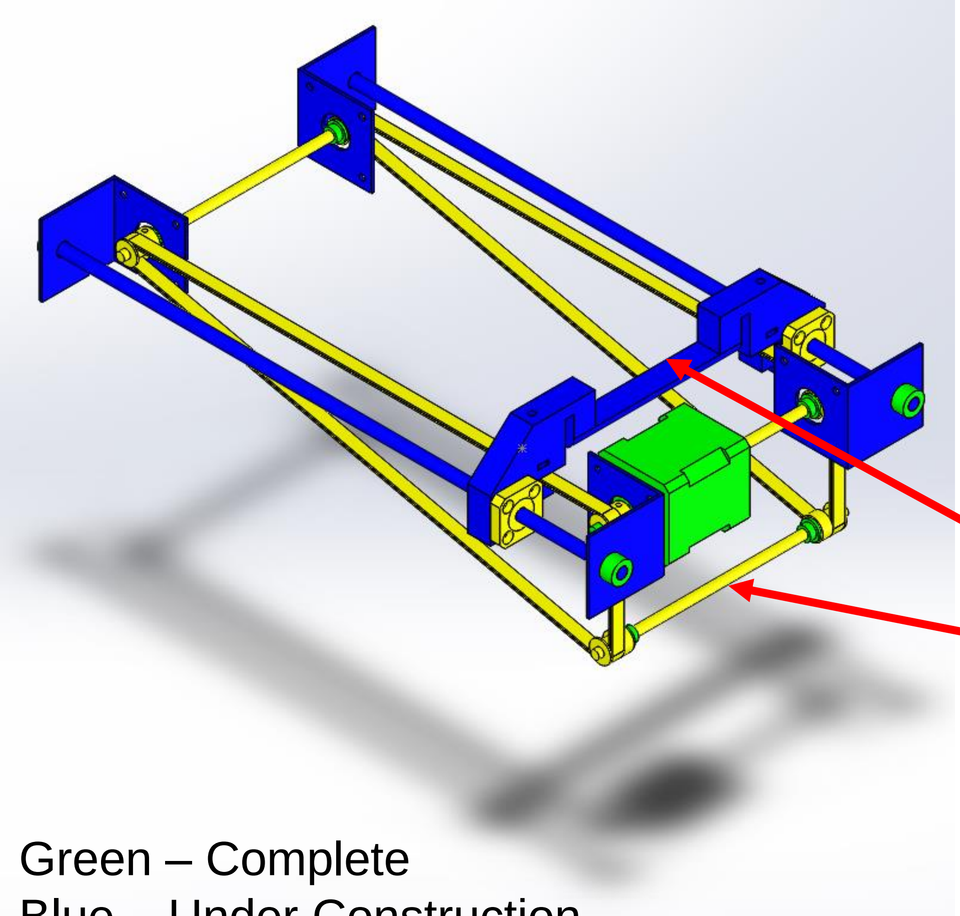
Powder Bed - Rake

- 3D printed rake pushes powder from reservoir piston to print piston
- Driven by a NEMA 17 Stepper Motor
- Support rods keep the rake level



Requirement I.D.	Description
2.4.3	A rake system shall move powder from the reservoir to the sintering area in a single sweep

Powder Bed - Rake

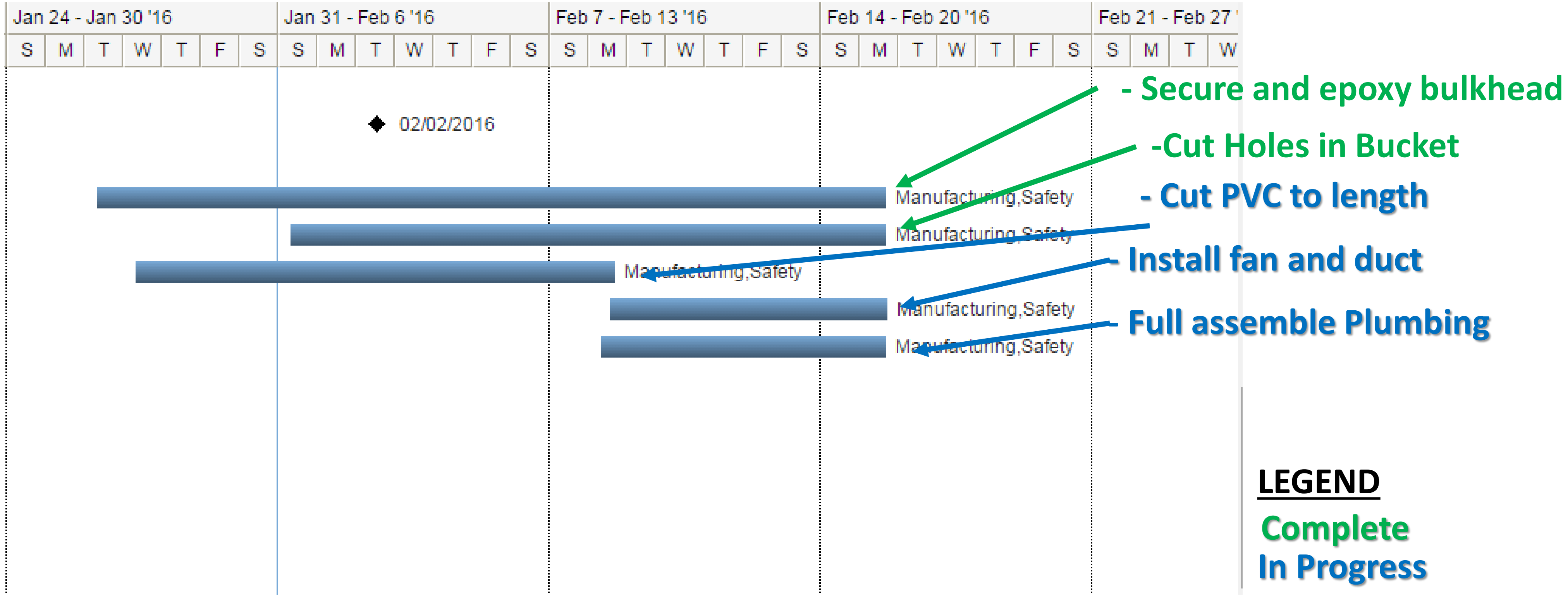


Component	Status (% Complete)	Total Required Manufacturing Hours	Planned Completion Date
Support Brackets	20%	6	February 10th
Support Rods	80%	2	February 10th
NEMA 17 Motor	100%	1	February 3rd
Belt/Pulley	80%	2	February 3rd
Rake	10%	12	February 10th
5mm Axle	0%	2	February 13th

Green – Complete
Blue – Under Construction
Yellow/Clear – Shipping

Axles are expected to take several weeks to arrive, final assembly will be within schedule, but much later than other components.

Subsystem Schedule



LEGEND

Complete

In Progress

Not Started

Background | Mechanical | Software & Electronics | Laser & Testing

Subsystem Completion Table

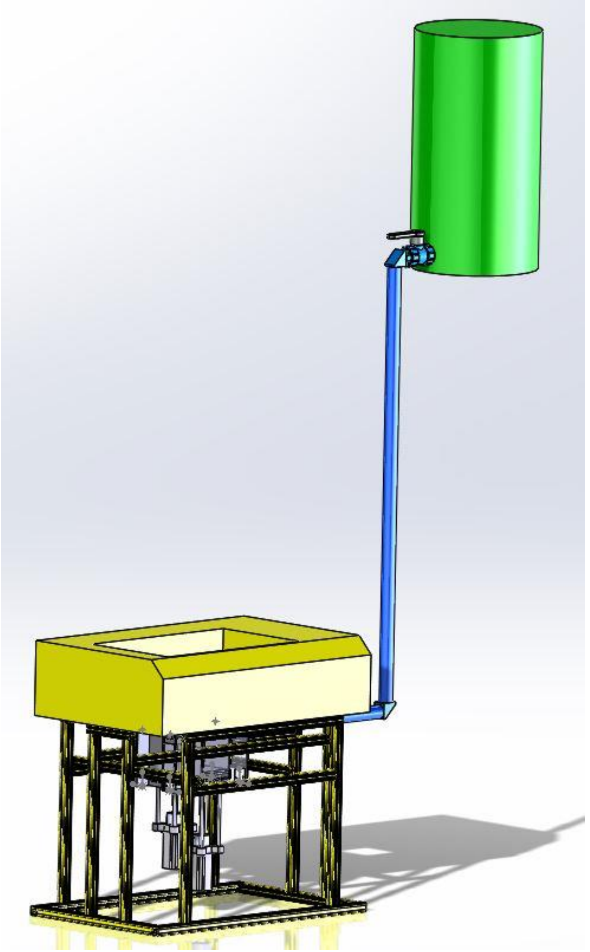
Component	Status (% Complete)	Total Required Manufacturing Hours	Planned Completion Date
Bucket Holes	100%	1	February 8th
Bulkhead	100%	2	February 8th
Cut PVC to length	10%	2	February 8th
Install fan and duct	10%	3	February 15th
Fully Assemble Plumbing	38%	9	February 15th

Laser Cutter Frame Subsystem

Overall System Design

Color Coding Scheme:

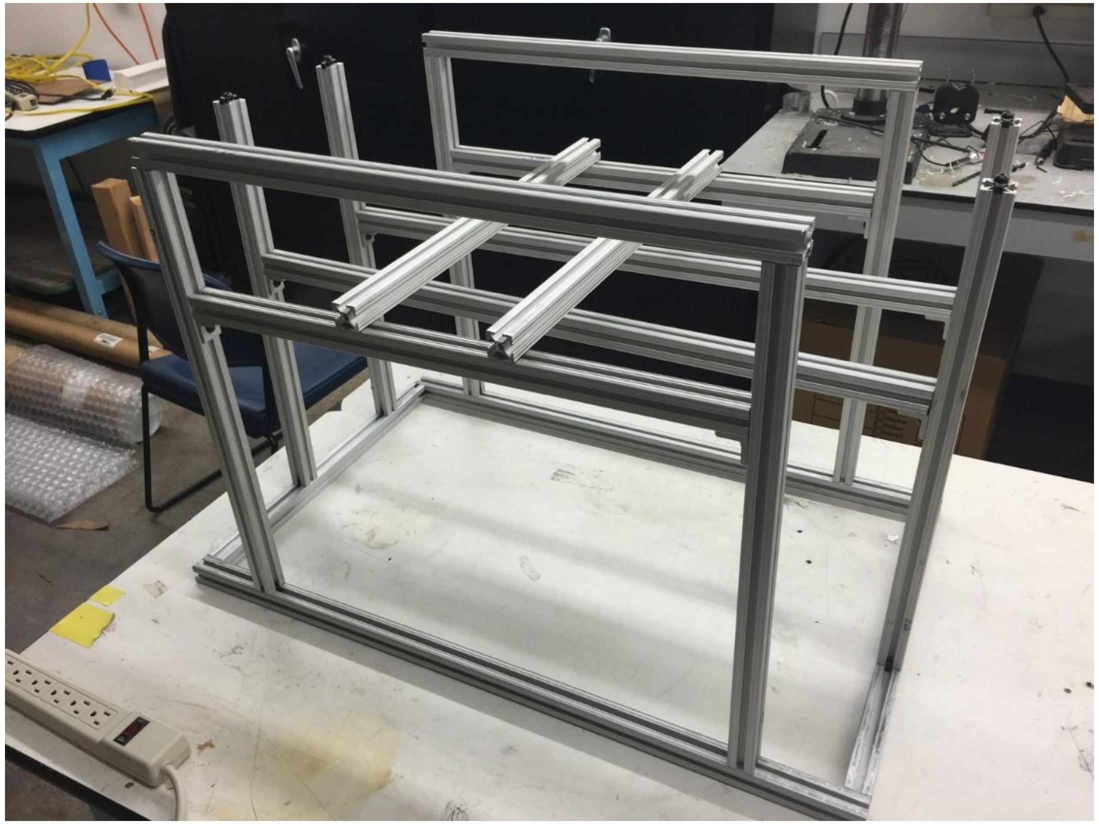
- Red – Not ordered
- Yellow – Ordered, in route
- Light Blue – In progress
- Green – Finished

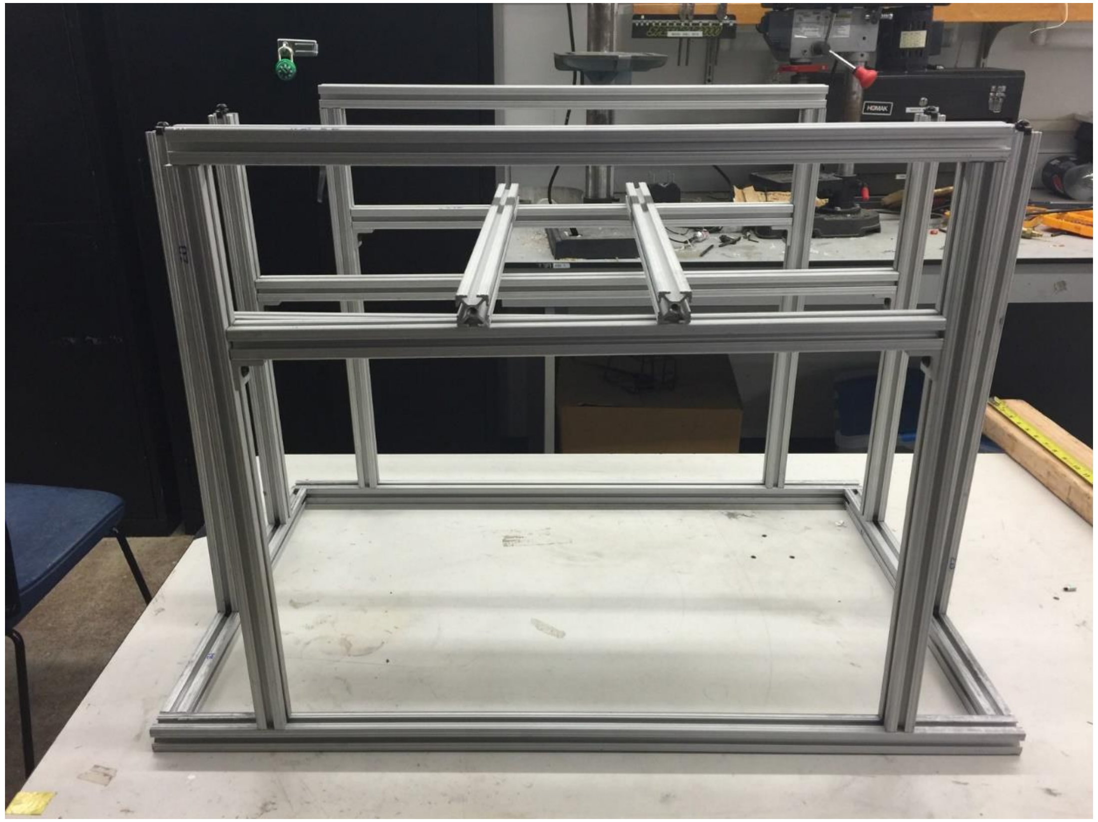


Subsystem Schedule Overview

- Frame Manufacturing
  - Cut and size aluminum - COMPLETE
  - Edge aluminum bar ends - COMPLETE
  - Tap ¼”-20 holes in each bar - COMPLETE
  - Assemble frame – waiting on Powder bed (lock tight and finish)
- Frame Integration
  - Attach laser cutter to top of frame by February 5th
  - Attach powder bed to frame by February 10th

Frame Subsystem - Progress





Frame Subsystem - Progress

87.5%

Frame Fabrication and Assembly

100%

Cut aluminum

100%

Edge aluminum

100%

Tap ¼"-20 threads in Al

50%

Assemble frame

0.00%

Frame Integration

0%

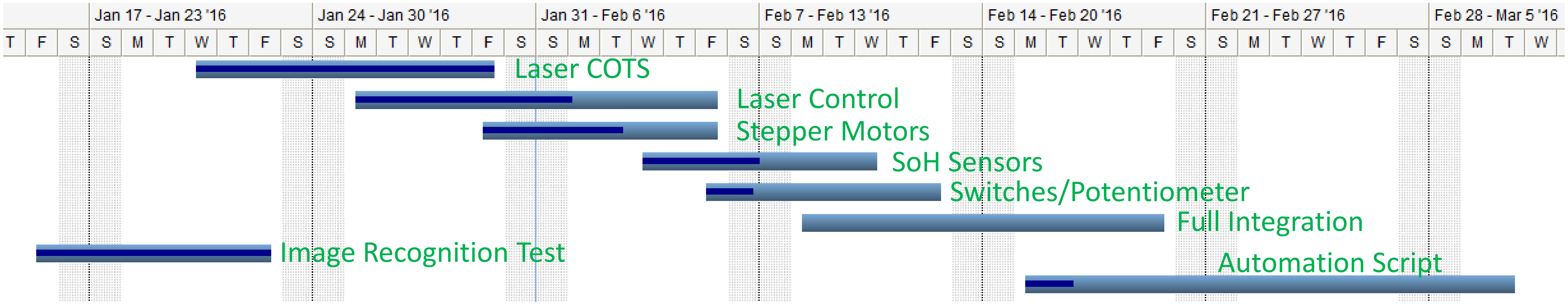
Integrate laser cutter with frame

0%

Integrate powder bed with frame

Software & Electronics Status

Software Schedule



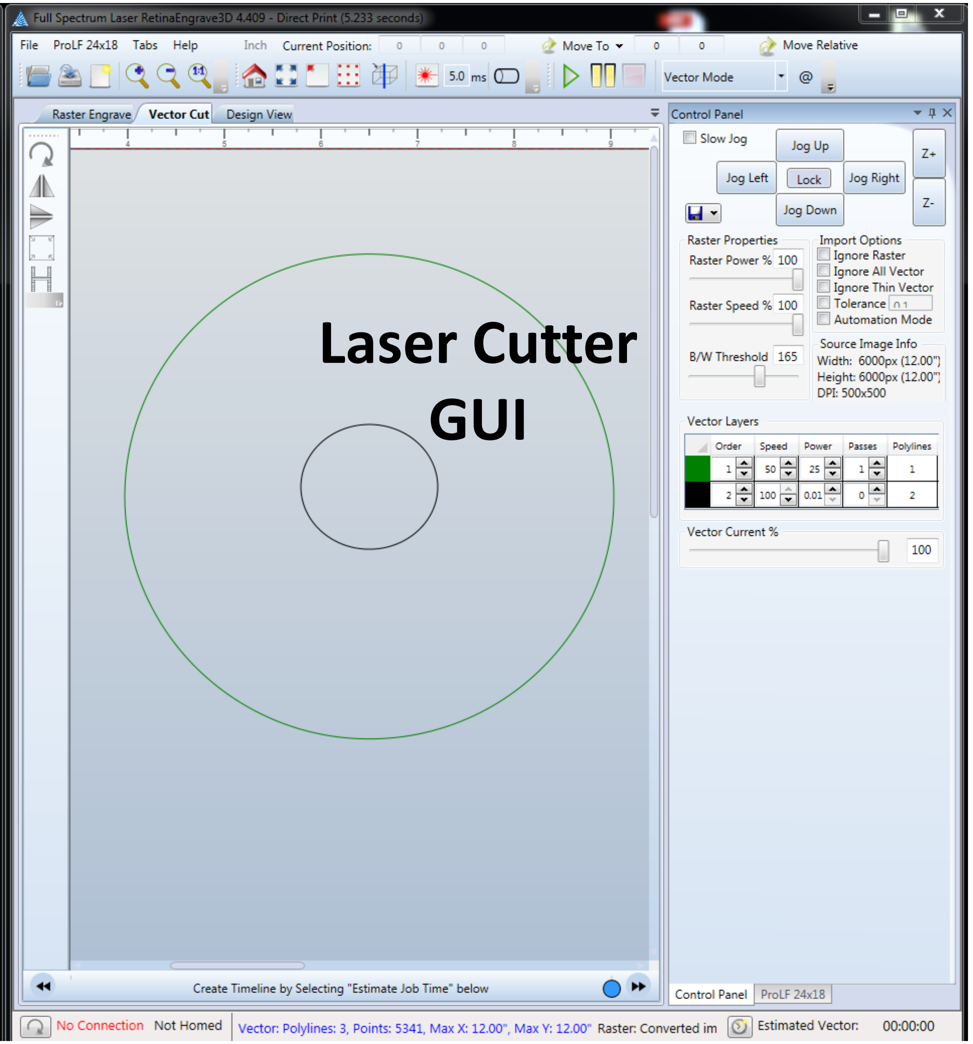
Software Overview

- Three Programs in use:
  - Retina Engrave Program: Laser Cutter Control
    - Runs on User's Laptop
  - Arduino Firmware Code: Powder Bed Control
    - Uploads from Laptop to Arduino Mega Microcontroller
  - Sikuli Python Code: Image Recognition Software
    - Runs on User's Laptop

- Firmware deadline February 15th is critical for full system testing

Laptop Display During Operation

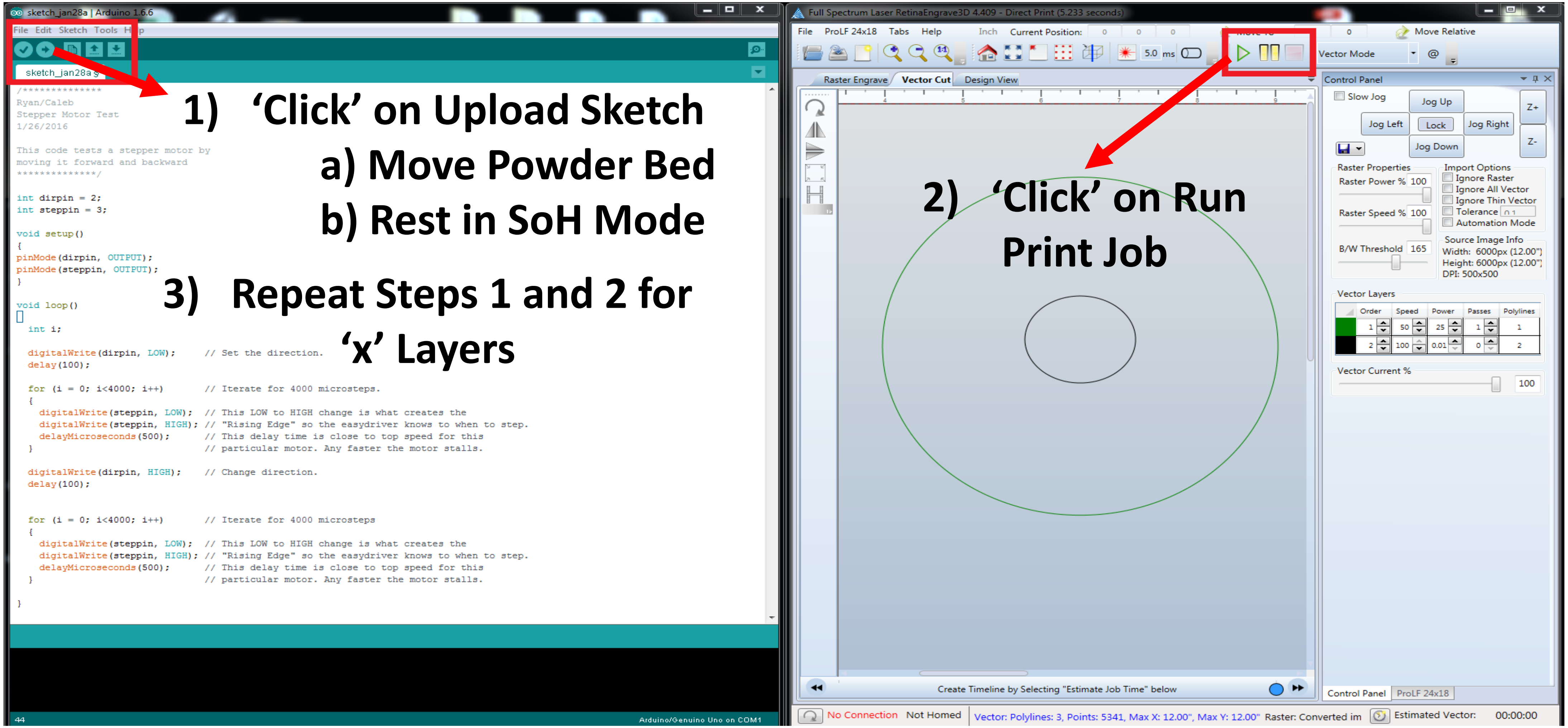
Microcontroller Code



Laser Cutter GUI

Background | Mechanical | Software & Electronics | Laser & Testing

Automation



1) 'Click' on Upload Sketch
   a) Move Powder Bed
   b) Rest in SoH Mode

2) 'Click' on Run Print Job

3) Repeat Steps 1 and 2 for 'x' Layers

Software Progress

Retina Engrave

- Out of Box Set-up — 100% — 8 Days
- Laser Power/Speed Control — 60% — 10 Days

On Schedule

Arduino Firmware

- Stepper Motor Control — 60% — 7 Days
- Utilize SoH Sensors — 50% — 6 Days
- Switch and Potentiometer Control — 25% — 6 Days

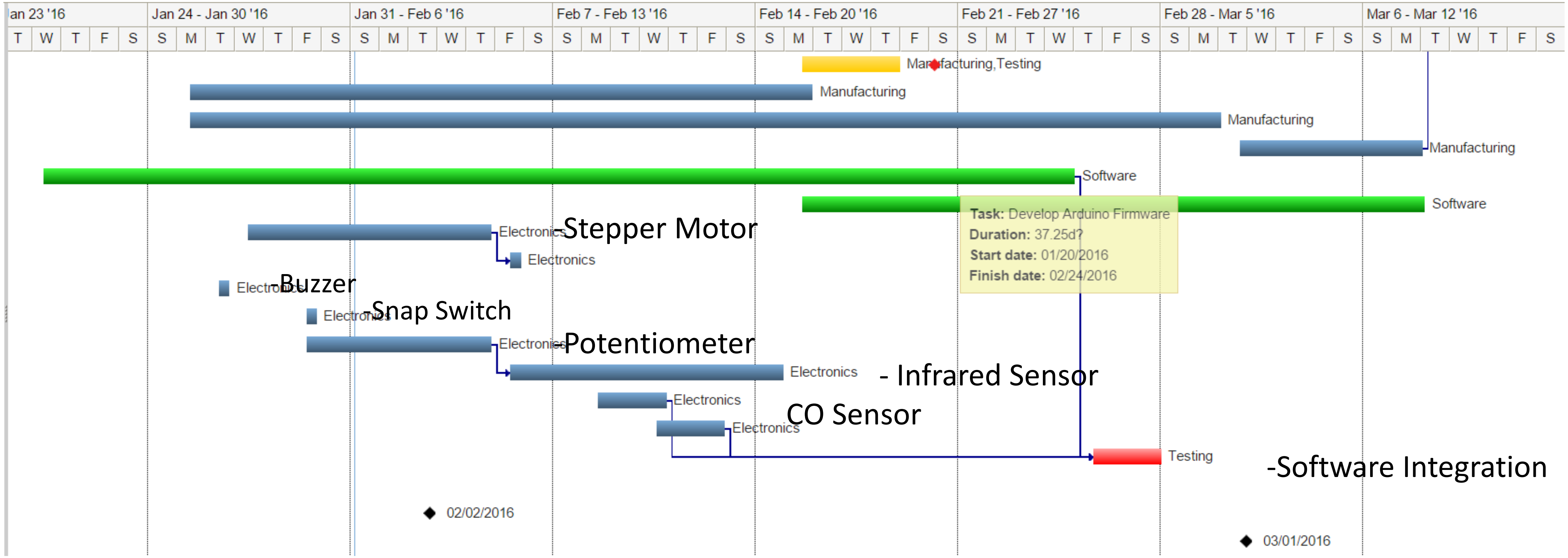
7 Days Ahead of Schedule

Sikuli Automation

- Test Screen Recognition — 100% — 6 Days
- Automation Script — 10% — 12 Days

On Schedule

Subsystem Schedule



Background | Mechanical | Software & Electronics | Laser & Testing

Stepper Motor Manufacturing & Testing

- Manufacturing: Soldering and Component Testing
- Verify Stepper Motor meets requirements
  - Solder wires to motor driver
  - Command Stepper to move 10 steps (18^0). Measure total distance rotated.
  - Command Stepper to move 10 Rotations (3600^0 of total rotation). Measure error from initial starting position
  - In-line testing with software- motor integration

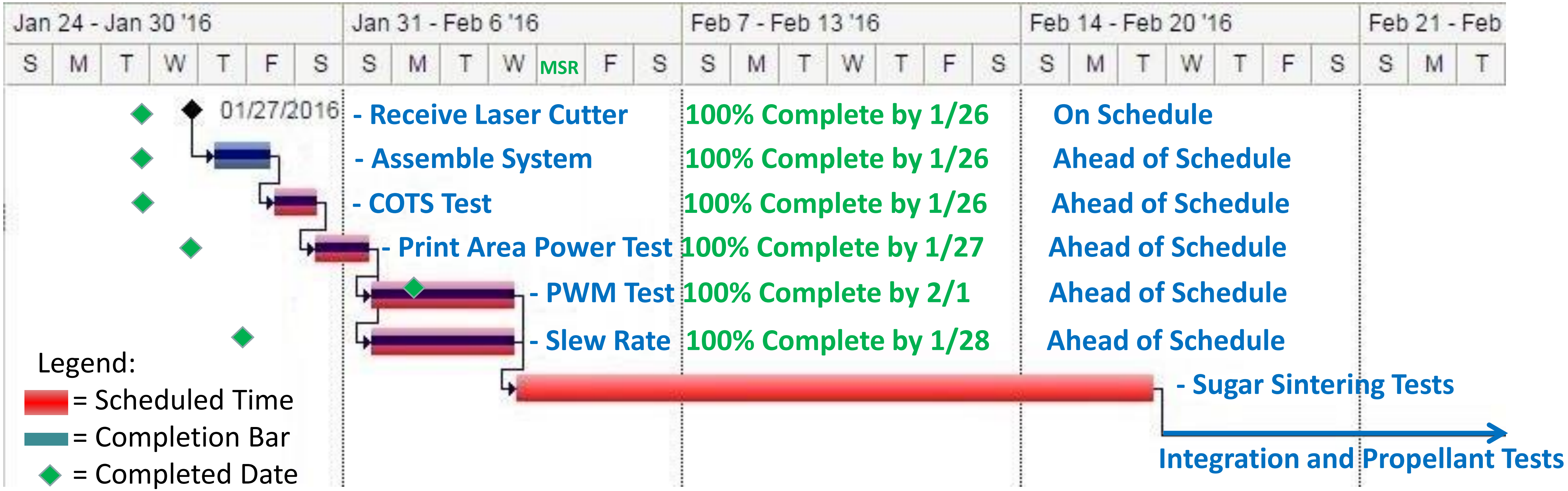
Requirement I.D.	Description
1.4	sintered propellant layers 1 mm ± 30%
2.4.1	vertically move the reservoir chamber piston by 1 mm ± 0.3 mm
2.4.2	vertically move the sintering area piston by 1 mm ± 0.3 mm
2.4.3	autonomously move 10 cm^3 of powder from the reservoir to the sintering area

Slide Including Subsystem and Completion Table

Component(s)	Status (% Complete)	Total Required Hours	Planned Completion Date
Stepper Motors and Drivers	50%	5	Feb 3rd
Snap Switches	100%	1	January 27th
Slide potentiometers	50%	4	Feb 5rd
Infrared Thermometer	25%	5	Feb 12th
CO sensor	25%	3	Feb 12th
LED	25%	1	Feb 5th
Buzzer	100%	1	January 27th

Laser System and Testing Status

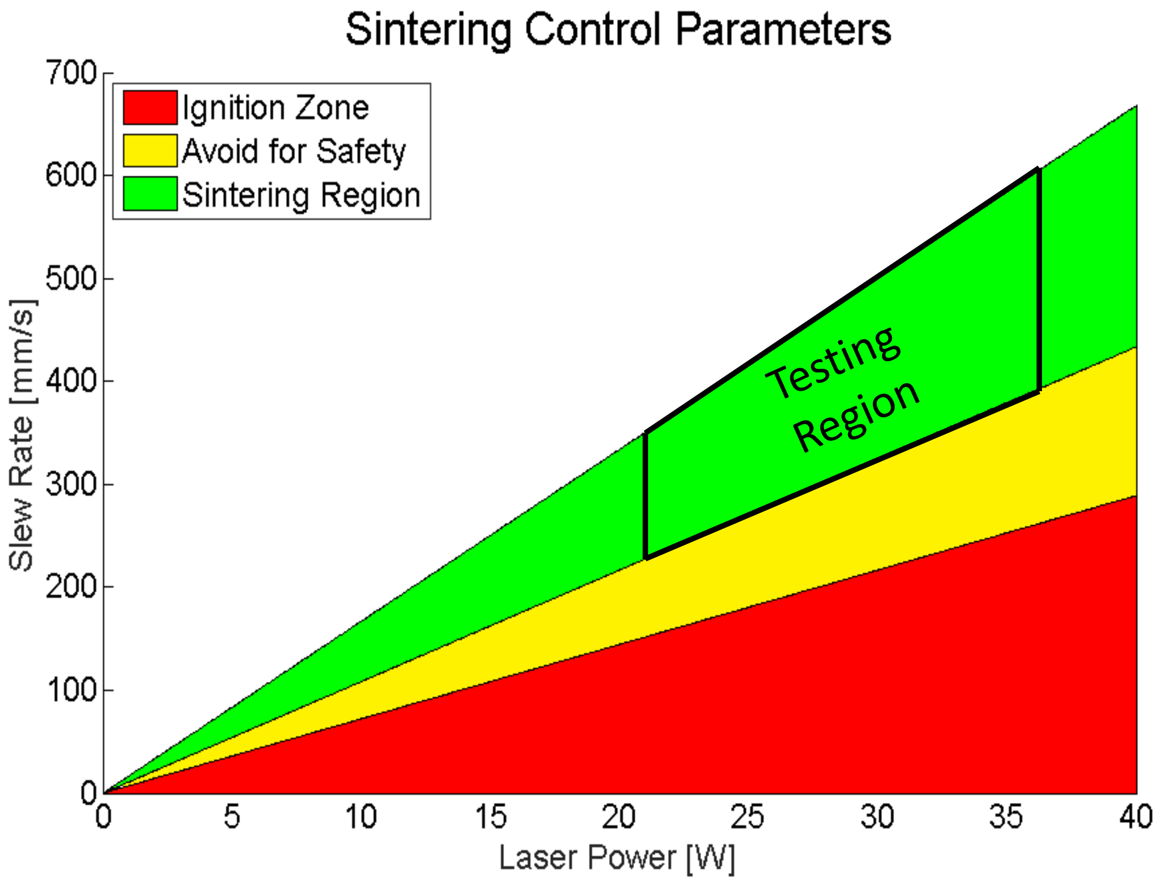
Laser Schedule



Thermal Model

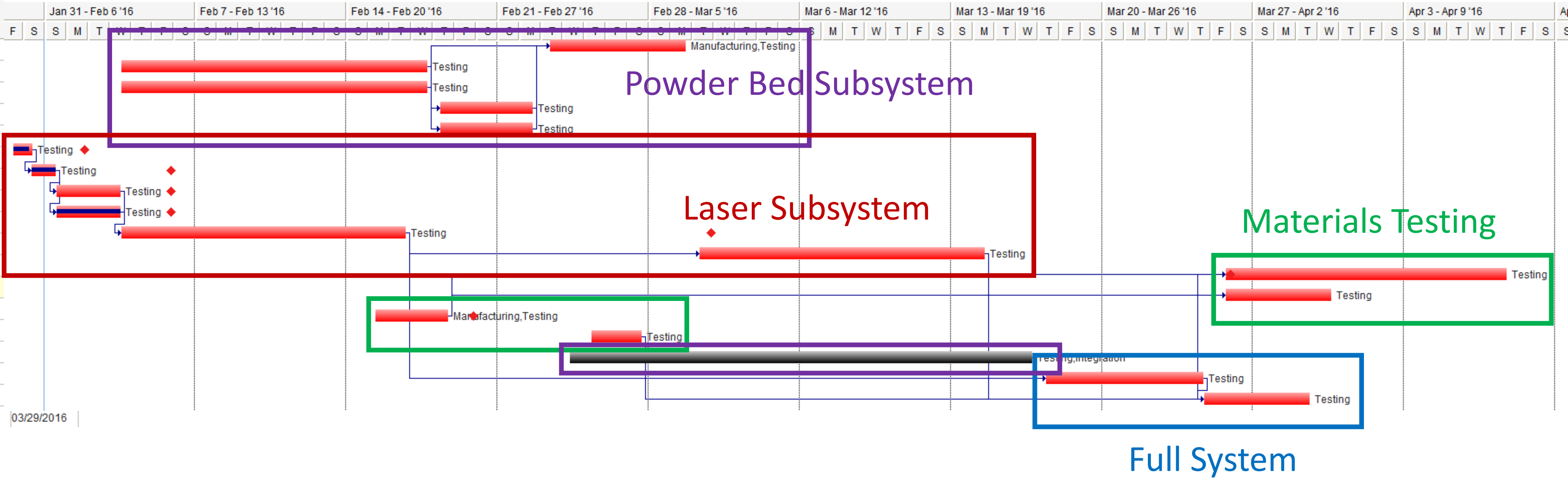
- Characterized Power and Rate controls ahead of schedule
- Proceed to sintering tests
  - Start with only sugar
  - Validate and update thermal model with sugar data

Requirement I.D.	Description
1.3.2	Laser shall raise the propellant powder to 180-185 °C for sintering



Testing Schedule Overview

Name	% Complete
Powder Bed System Test	0%
Pistons Functional Testing	0%
Rake Functional Testing	0%
Rake Performance Testing	0%
Pistons Performance Testing	0%
Laser Cutter COTS Test	80%
Print Area Laser Power Characterization - For Alignment	100%
PWM Power Characterization	0%
Slew Rate Characterization	100%
Sugar Sintering Test	0%
Propellant Sintering Tests	0%
Instron Testing	0%
Motors Material Testing	0%
Cast Propellant Epoxy Dip Prototype	0%
Burn Test	0%
Electronics and Software Integration and Test (powderbed)	0%
3D Sugar Print Test (Full System)	0%
3D SRM Print Test (Full System)	0%



Background | Mechanical | Software & Electronics | Laser & Testing

Looking Forward: Testing Progress

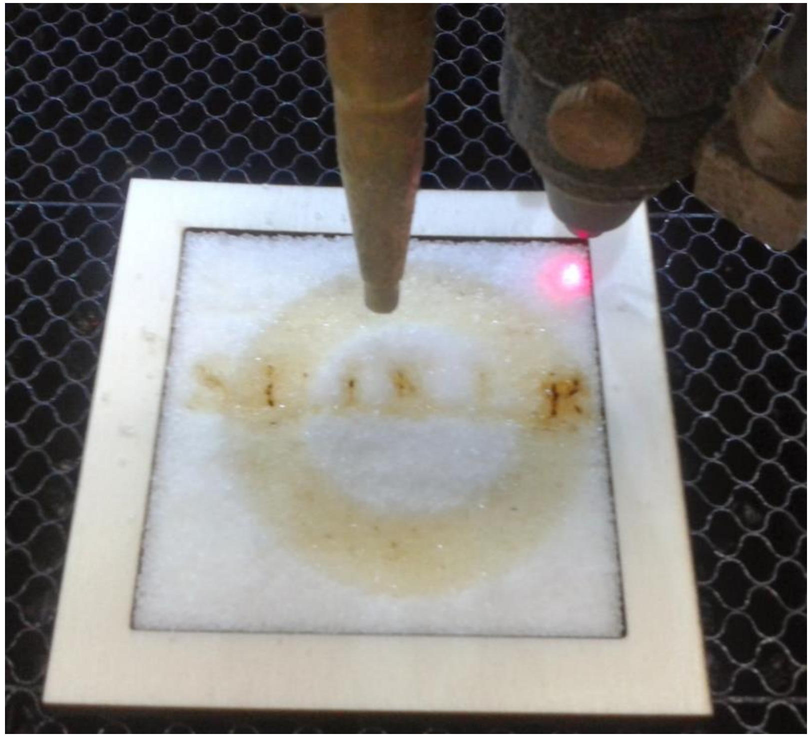
- Laser
  - 50% COTS test: laser accuracy upper bound
  - 100% Slew rate calibration
  - Laser power calibration
  - Sugar sinter grid characterization
  - Sugar sinter layer test
- Electronics
  - 70% Slide potentiometer calibration
  - Motor step size test
  - Driver temperature test
  - Fire sensors burn test
- Safety
  - 100% Flow rate test
  - Integration flow test
- Powder Bed
  - Piston depth test
  - Rake depth and uniformity test
  - Powder bed test
- Full System
  - Sugar print
  - Propellant
- Material Properties
  - 20% Instron load testing

Looking Forward: Highlights

- Laser
  - 50% COTS test: laser accuracy upper bound
  - 100% Slew rate calibration
  - Laser power calibration
  - Sugar sinter grid characterization
  - Sugar sinter layer test
- Electronics
  - 70% Slide potentiometer calibration
  - Motor step size test
  - Driver temperature test
  - Fire sensors burn test
- Safety
  - 100% Flow rate test
  - Integration flow test
- Powder Bed
  - Piston depth test
  - Rake depth and uniformity test
  - Powder bed test
- Full System
  - Sugar print
  - Propellant
- Material Properties
  - 20% Instron load testing

Upcoming Tests: Sugar Sinter

- Sugar Sinter test
  - Sinter a 1±.3 mm layer of a grain cross-section
  - Why is this important?
    - Adding KNO_3 is the last piece of **Level 1 Success**
  - No further manufacturing needed
  - Only need laser power calibration



"Sugar Sintering in a Lasercutter." *Fablab013*. Cooperatief Fablab013 U.A. Web. 28 Jan. 2016.

Upcoming Tests: Sugar Sinter

- Laser power output controlled by pulse width modulation (PWM)
  - Using black body meter, create PWM percentage to power delivered curve
- Validate thermal model predictions
  - Grid test to characterize sintering behavior over the operating range

Requirement	Description
1.1.1 & 1.3.2	Laser heats sugar to melting --- 180-185°C
1.4	Print layers of 1 mm ± 30%
3.4	Laser power measured to 1±0.5 W
4.3	Sintering process modeled/characterized.
4.3.1	Determine laser parameters (slew rate & power)

Upcoming Tests: Motor Instron Testing

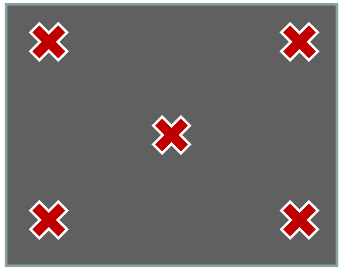
- Difficulties: debris containment
  - 6-sided enclosure
  - Does not interfere with data
- Possible solutions
  - Laser cut acrylic box
  - Acrylic shield with bag enclosure
- Budget and schedule impact
  - Estimated 25 hours to complete
  - Design by March 1 to give 2 week window for manufacture
  - No affect on schedule margin
  - Estimated $25 for acrylic, $30 for miscellaneous
  - Remaining budget margin: $217 + $500 (SAS contribution)

"Instron 5985." Web. 01 Feb. 2016.

Backup Slides

Upcoming Tests: Component Level

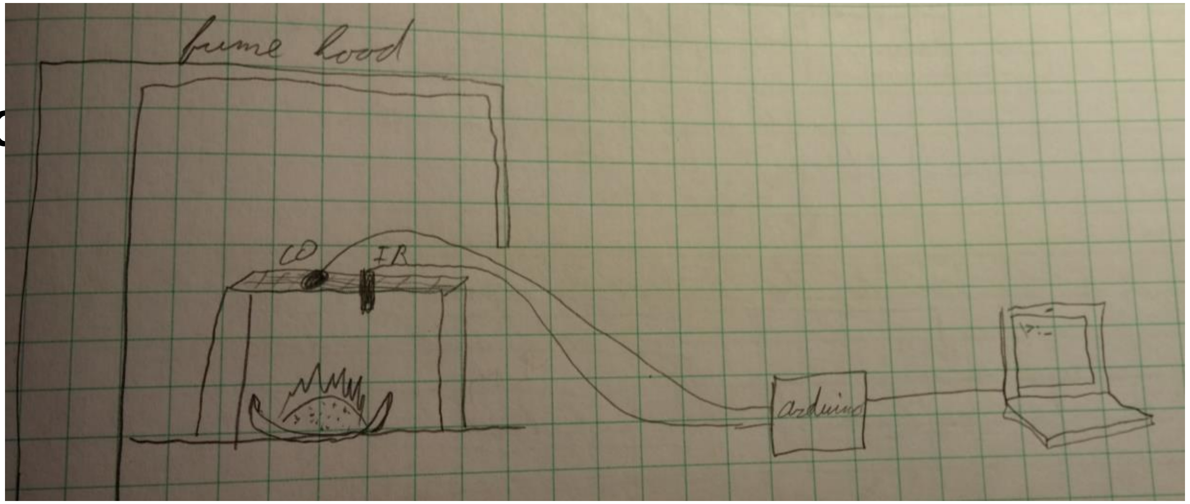
- Slide potentiometers
  - Calibration on CNC with positional accuracy of 0.002”, need 0.012” per requirements
  - Necessary to measure layer depth and stepper motor fidelity
- Rake depth test
  - 5 point depth measurement on print piston after rake sweep; 1 mm target
  - Ensure rake is not displacing and depositing powder out of tolerance



Requirement	Description
2.1.2	(Z) The Powder bed shall be capable of moving 1 ± 0.3 mm
2.4.1.1	A piston shall be capable of vertically moving the reservoir chamber 1 mm ± 0.3mm
2.4.2.1	A piston shall be capable of vertically moving the sintering area 1 mm ± 0.3mm

Upcoming Tests: Component Integration

- Fire Detection Subsystem
  - Can a fire event be detected reliably?
  - Fire detection test
  - Location: welding shop fume hood
  - Burn wood with limited air access
    - 300°C -- 600°C burn temp
    - Insufficient Oxygen causes CO production
  - Completion criteria
    - 5 trials
    - both sensors ID 3 fires consecutively,
    - at least one detects all 5
    - both miss 1



Laser System - COTS Test

- Objectives:
  - Verify Basic Functionality
  - Test PWM and Slew Rate Functionality
  - Measure X – Y Positional Accuracy
- Progress: 100% Complete
  - Tested basic functionality on 1/26 (On Schedule)
  - Mirror Alignment, Focusing Capabilities, Power and Slew Rate Controls

Requirement I.D.	Description
2.1.1	(X-Y) laser positioning within +/- 1 mm (2.5% of Motor Diameter)
2.2	The Manufacturing system shall be capable of manufacturing custom, user created propellant grain patterns.

Laser System - COTS Test

- Procedure:
  - Turn on Laser Cutter
  - Engrave simple shapes on scrap material using different PWM and Slew Rate settings
  - Design Sample Grain Patterns to-size in Solid Works
  - Engrave Sample Grain Patterns onto scrap material
  - Measure dimensions of Grain Patterns with Calipers to verify X-Y tolerances

Laser System – Print Area Power Test

- Objectives:
  - Measure and Correct for any power variations across print area
- Progress: 100% Complete
  - Experiment Conducted on 1/27 (Ahead of Schedule)
  - Mirrors were aligned when the cutter arrived

Requirement I.D.	Description
3.4	The laser power shall be measured to 1 +/- 0.5 W

Laser System – Print Area Power Test

- Procedure:
  - Affix receipt paper below lens
  - Fire laser and observe spot on receipt paper
  - Test fire laser on receipt paper in all four corners of print area
  - If the laser spot "walks" then the mirrors are misaligned
  - Adjust mirror alignment accordingly

Receipt

Laser System – PWM Characterization

- Objectives:
  - Correlate PWM control values (%) to power measurements (W)
- Progress: 100% Complete
  - Scheduled for 2/1 (On Schedule)
  - Waiting for Black Body Power Meter
  - Will fall behind if BB Power Meter does not arrive by next week

Requirement I.D.	Description
4.3.1	Laser Control Parameters shall be determined for proper sintering

Laser System – PWM Characterization

- Procedure:
  - Place BB power meter in laser path w/ clamps and camera facing dial
  - Fire laser and record max reading on the power meter.
  - Adjust PWM setting in software. Repeat measurement.
  - Analyze readings and construct trend. We expect a linear relationship.

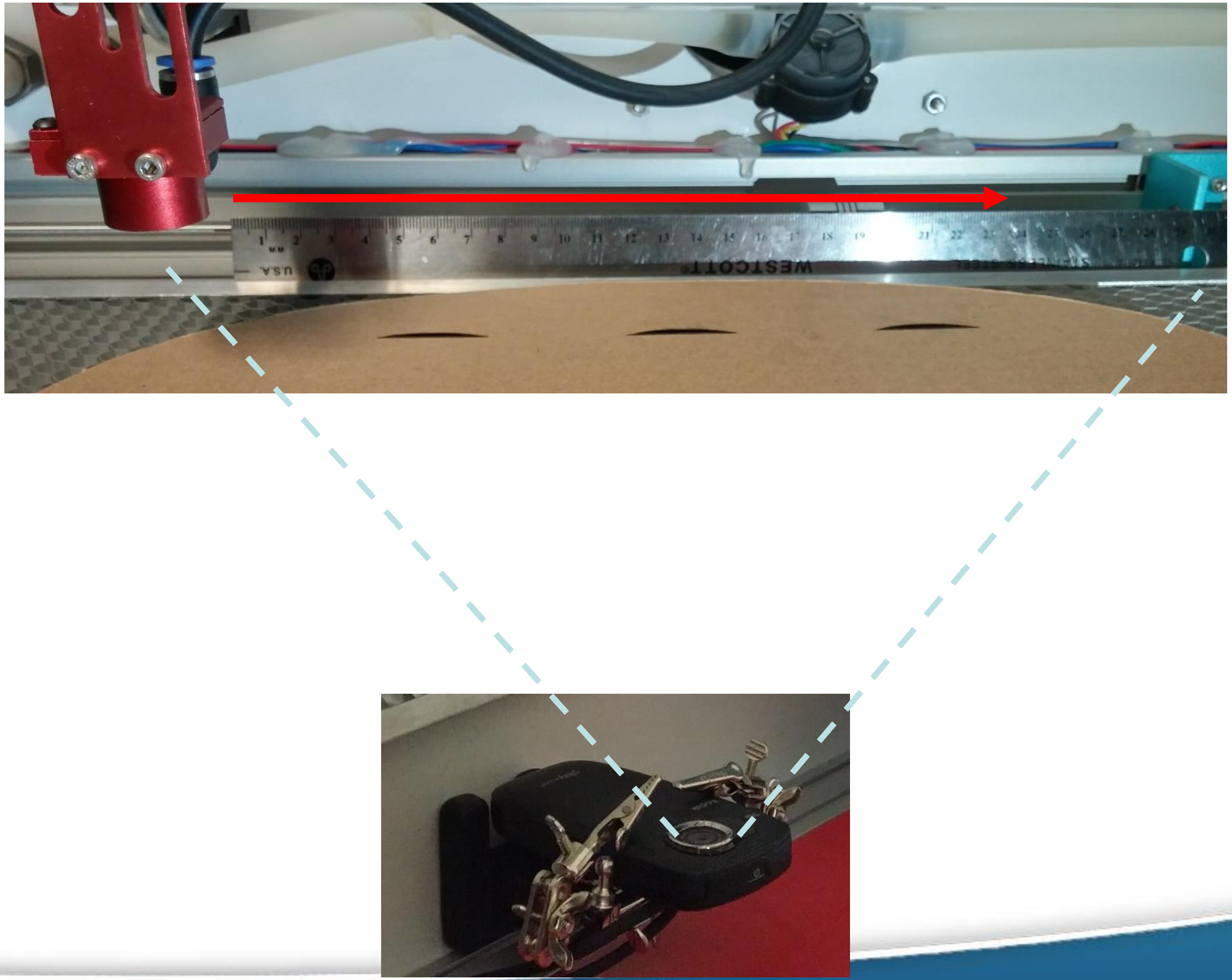
Laser System – Slew Rate Characterization

- Objectives:
  - Correlate Slew Rate control values (%) to linear speeds (mm/s)
- Progress: 100% Complete
  - Experiment Conducted on 1/28 (Ahead of Schedule)
  - Videos Analyzed in Logger Pro
  - Trend Constructed (See Following Slides)

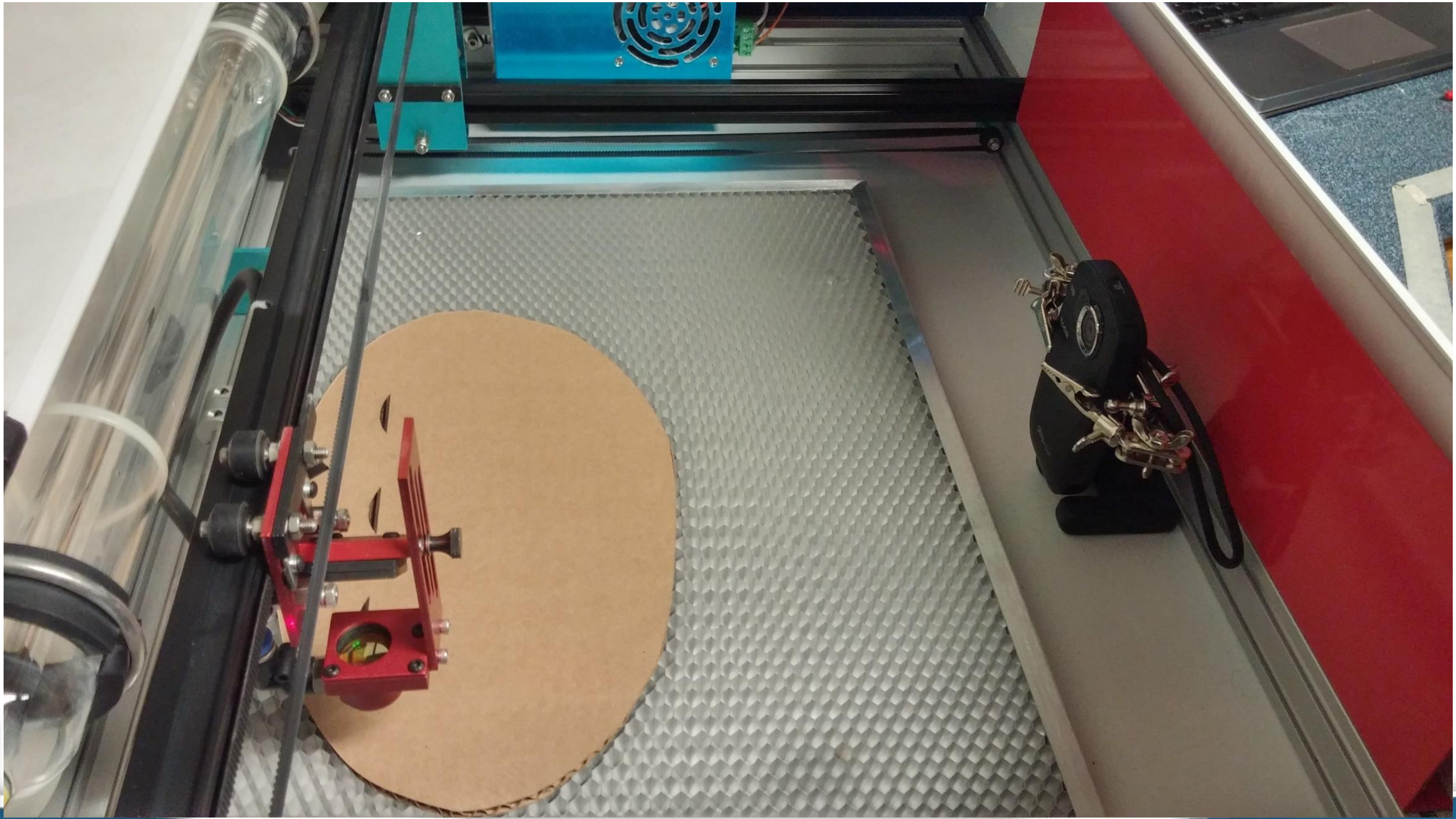
Requirement I.D.	Description
4.3.1	Laser Control Parameters shall be determined for proper sintering

Laser System – Slew Rate Characterization

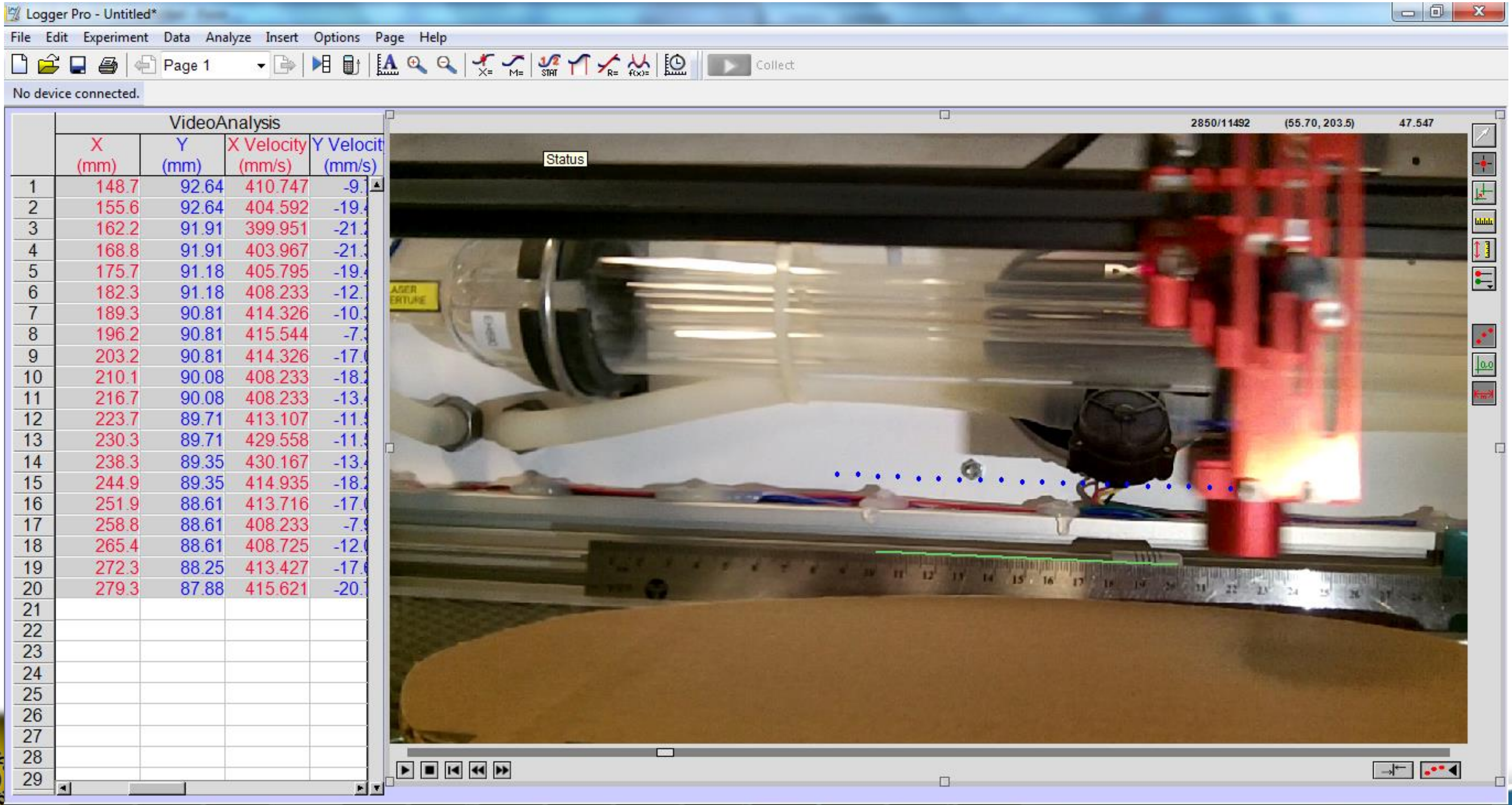
- Procedure:
  - Place ruler behind optics carriage. Start video.
  - Move optics carriage using software at designated slew rate. Stop video.
  - Adjust Slew rate setting in software. Repeat measurement.
  - Analyze videos in LoggerPro to retrieve speed measurements.
  - Use data to construct a trend. We expect a linear relationship.



Laser System – Slew Rate Characterization



Laser System – Slew Rate Characterization



	VideoAnalysis			
	X (mm)	Y (mm)	X Velocity (mm/s)	Y Velocit (mm/s)
1	148.7	92.64	410.747	-9.
2	155.6	92.64	404.592	-19.
3	162.2	91.91	399.951	-21.
4	168.8	91.91	403.967	-21.
5	175.7	91.18	405.795	-19.
6	182.3	91.18	408.233	-12.
7	189.3	90.81	414.326	-10.
8	196.2	90.81	415.544	-7.
9	203.2	90.81	414.326	-17.
10	210.1	90.08	408.233	-18.
11	216.7	90.08	408.233	-13.
12	223.7	89.71	413.107	-11.
13	230.3	89.71	429.558	-11.
14	238.3	89.35	430.167	-13.
15	244.9	89.35	414.935	-18.
16	251.9	88.61	413.716	-17.
17	258.8	88.61	408.233	-7.
18	265.4	88.61	408.725	-12.
19	272.3	88.25	413.427	-17.
20	279.3	87.88	415.621	-20.
21				
22				
23				
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27				
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Laser System – Slew Rate Characterization