ADD_IN

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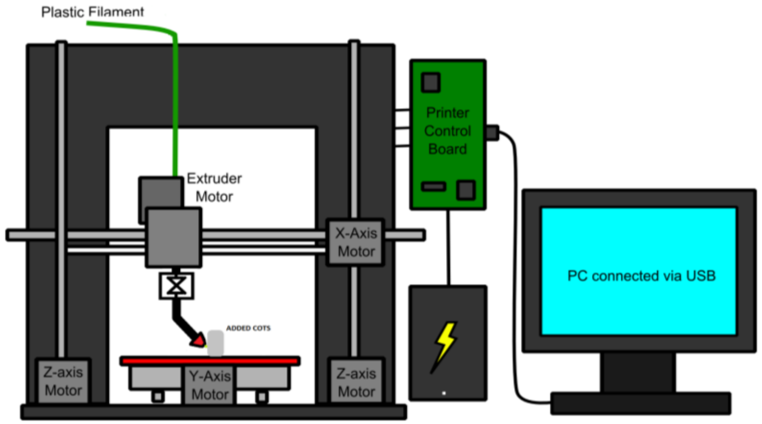


4DOF

OUTLINE

- Project Description
- Use Case
- System Level Requirements
- Functional Architecture
- Cyber physical Architecture
- Subsystem Descriptions and Status
- Project Management

Project Description

“ADD_IN proposes to develop a 3D printer that can enclose COTS items, thus rapidly producing strong, useful and low cost parts.”

Use Cases

3 Primary Use cases

1. Enclose threaded inserts
2. Enclose stiffeners
3. Enclose PCB/Sensor

Enclose Threaded Inserts

Motivation

3D Printed parts are often sufficiently strong, but fail at the interface with other components

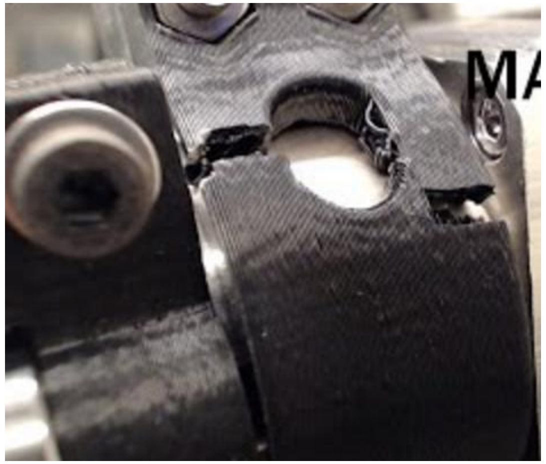
Solution

Enclose threaded inserts to distribute force over larger area and reduce material stress

Enclose Stiffeners

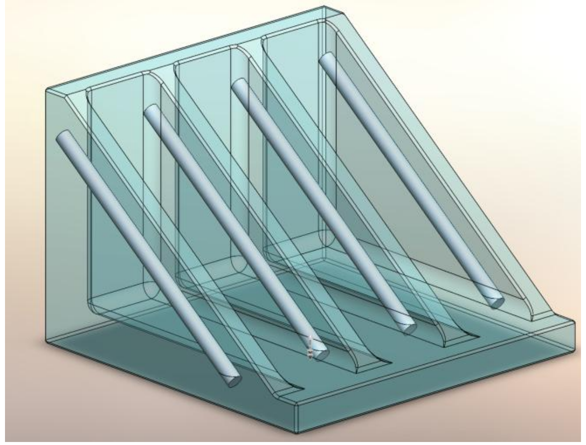
Motivation

3D Print parts often develop cracks and/or delaminate. Part strength is highly directionally dependent



Solution

Enclose wire/rod stiffeners to strength part along loading directions



Integrated Electronics

Motivation

1. Allow designers to develop smaller, more integrated devices
2. Enable in-situ measurement for temperature, strain, acceleration, etc.

Solution

Enable printing surrounding complex shapes such as PCB's and sensor packages

System Level Requirements

Requirement Types

1. Functional (11 Mandatory, 3 Stretch)
2. Nonfunctional (2 Mandatory, 2 Stretch)
3. Performance (Mandatory, 3 Stretch)

Functional Requirements

100	Mandatory	Receive standard 3D part files
101		Prompt user for insertion layer
102		Create Collision free path
103		Generate 4DOF G-Code
104		Rotate nozzle using G-Code
105		Avoid Kinks in Filament
106		Print layers of material
107		Print locating features for COTS items
108		Go to safe configuration during insertion
109		Enclose COTS item with print material
110		Avoid Collisions
400	Stretch	Print between parts
401		Print close to COTS item
402		Automatically Assign insertion layer

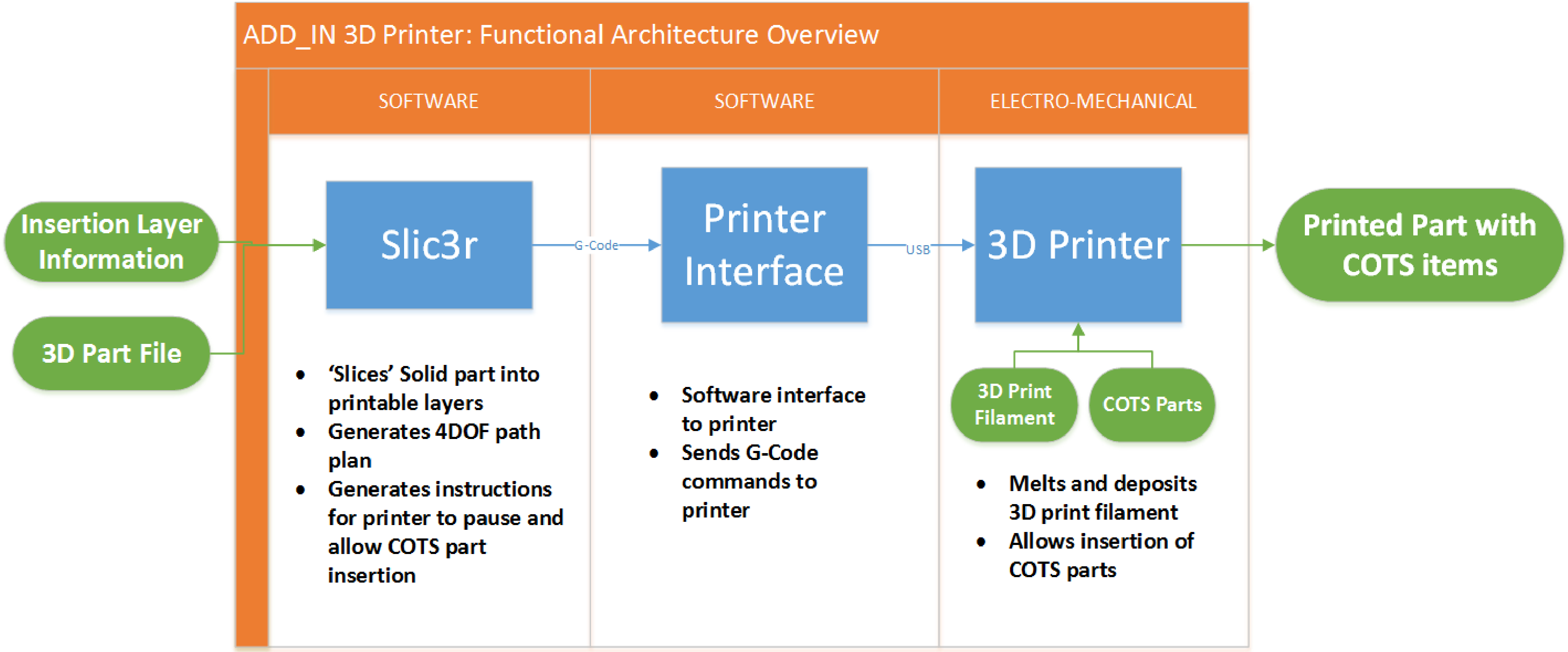
Nonfunctional Requirements

200	Mandatory	Maintain accurate temperature control
201	Mandatory	Provide user feedback during printing
500	Stretch	Maintain print speed
501	Stretch	Easy-to-use interface

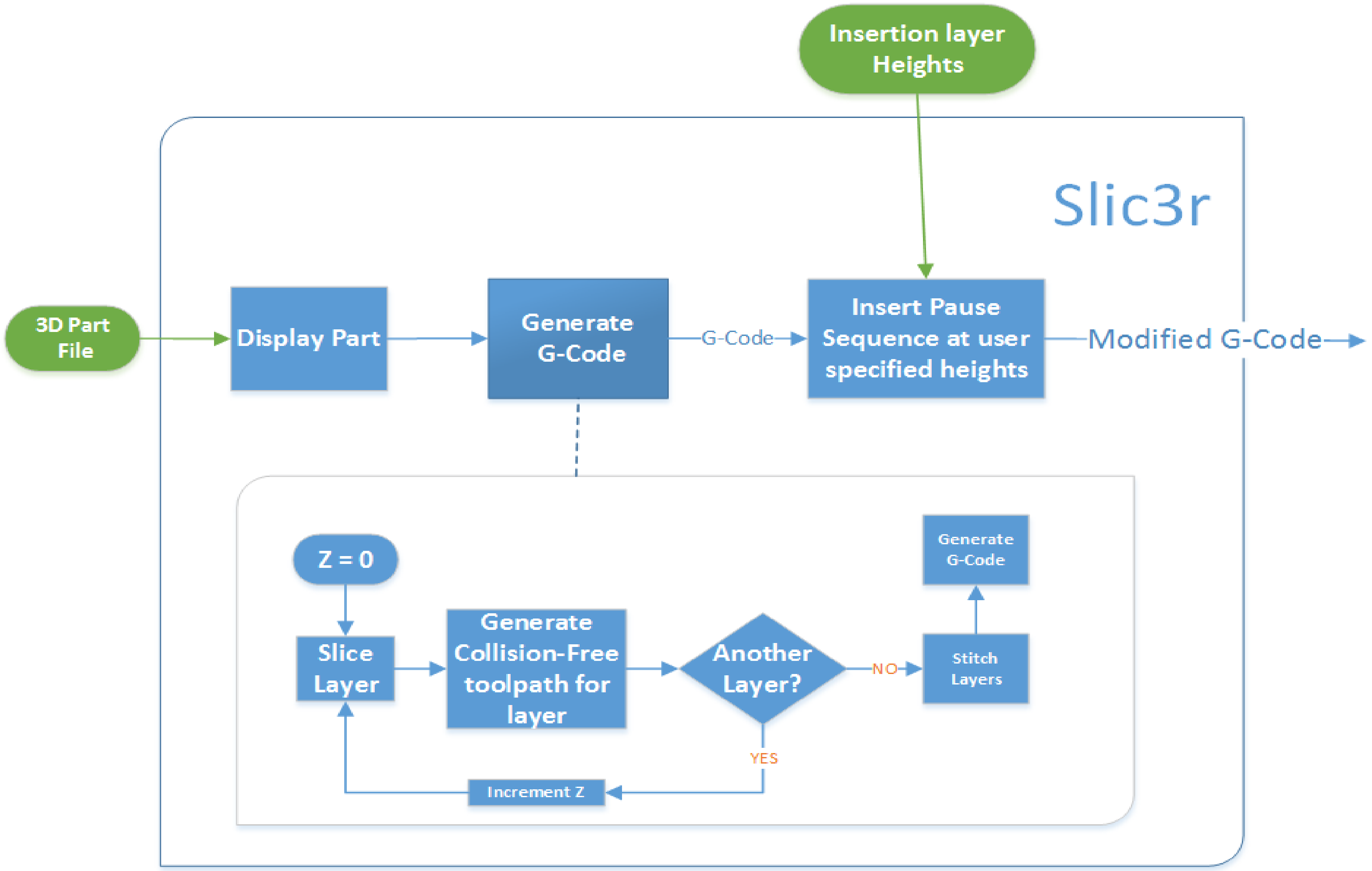
Performance Requirements

300	Mandatory	Incorporate COTS parts of cylindrical and rectangular prism shapes
301		Incorporate COTS parts that are orthogonal to print surface
302		Incorporate COTS parts that have a maximum height of one inch above the print surface
303		Be able to infinitely rotate nozzle
600	Stretch	Print time (excluding insertion time) not to increase more than 5% compared to Makergear M2
601		Print between multiple COTS parts not less than 2 inches apart
602		Position nozzle within 0.1mm of COTS part

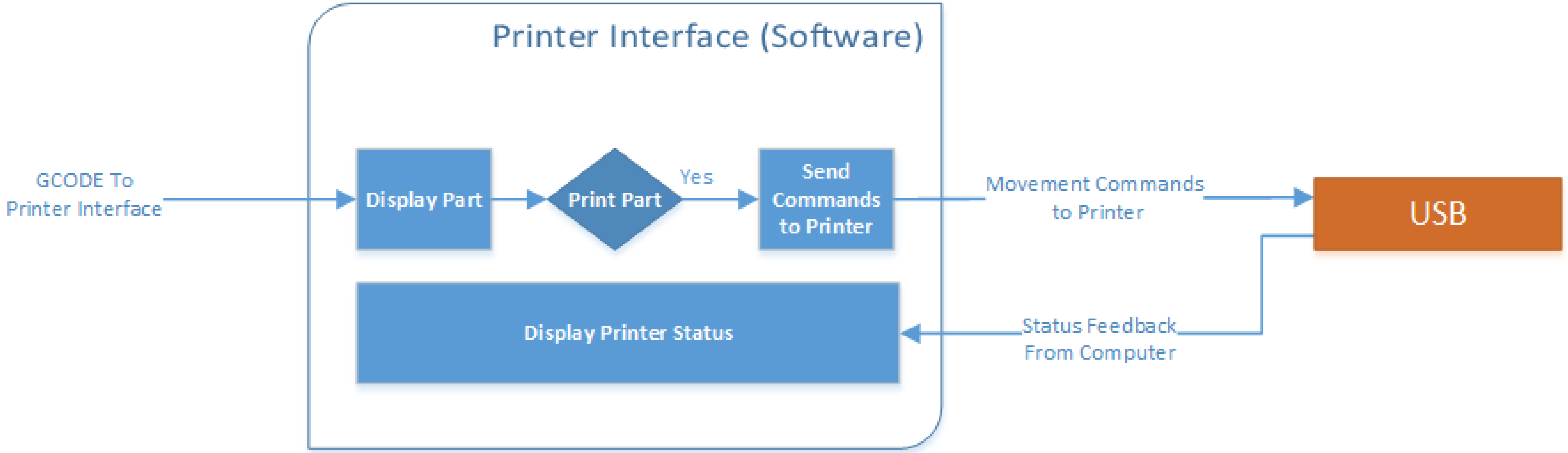
Functional Architecture



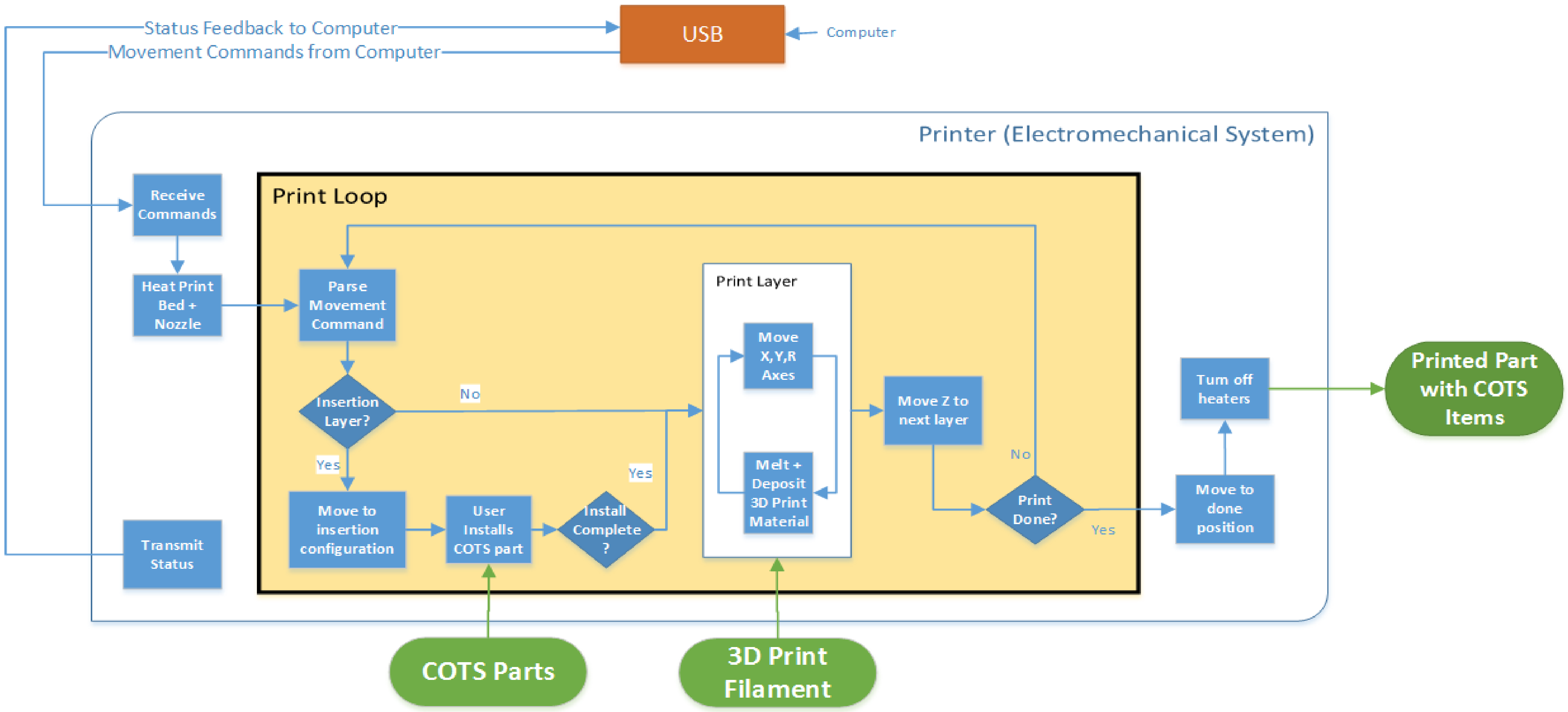
Functional Architecture: Slicer



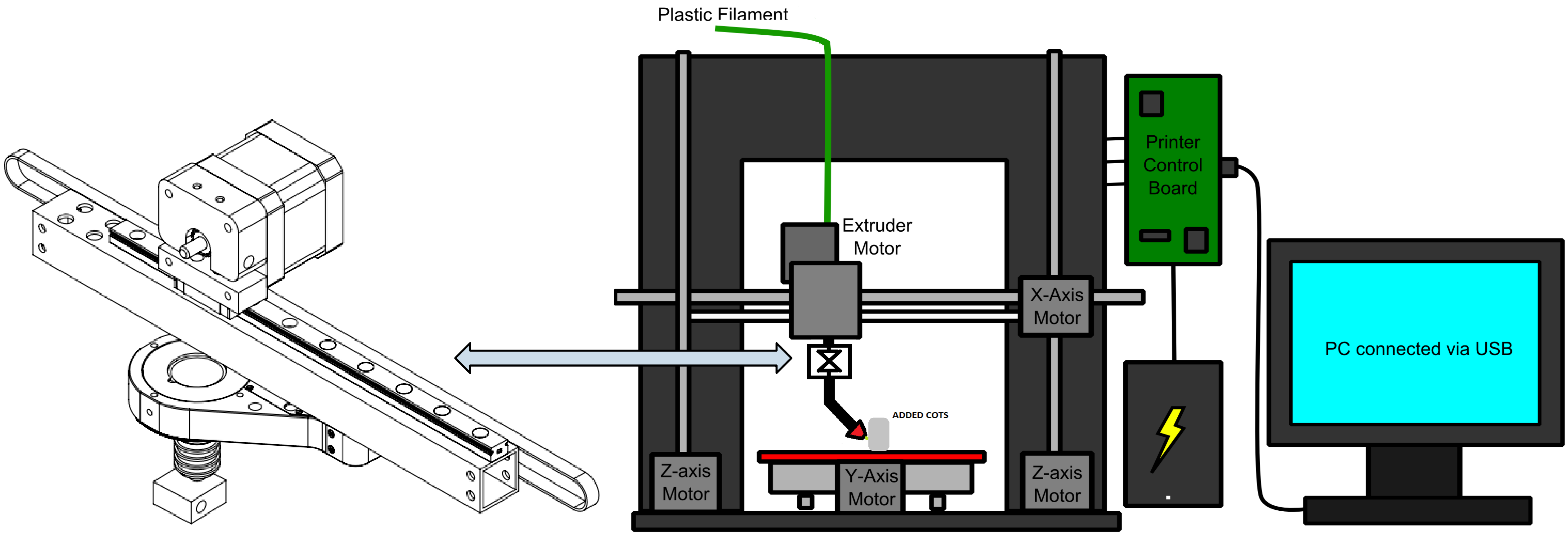
Functional Architecture: Printer Interface



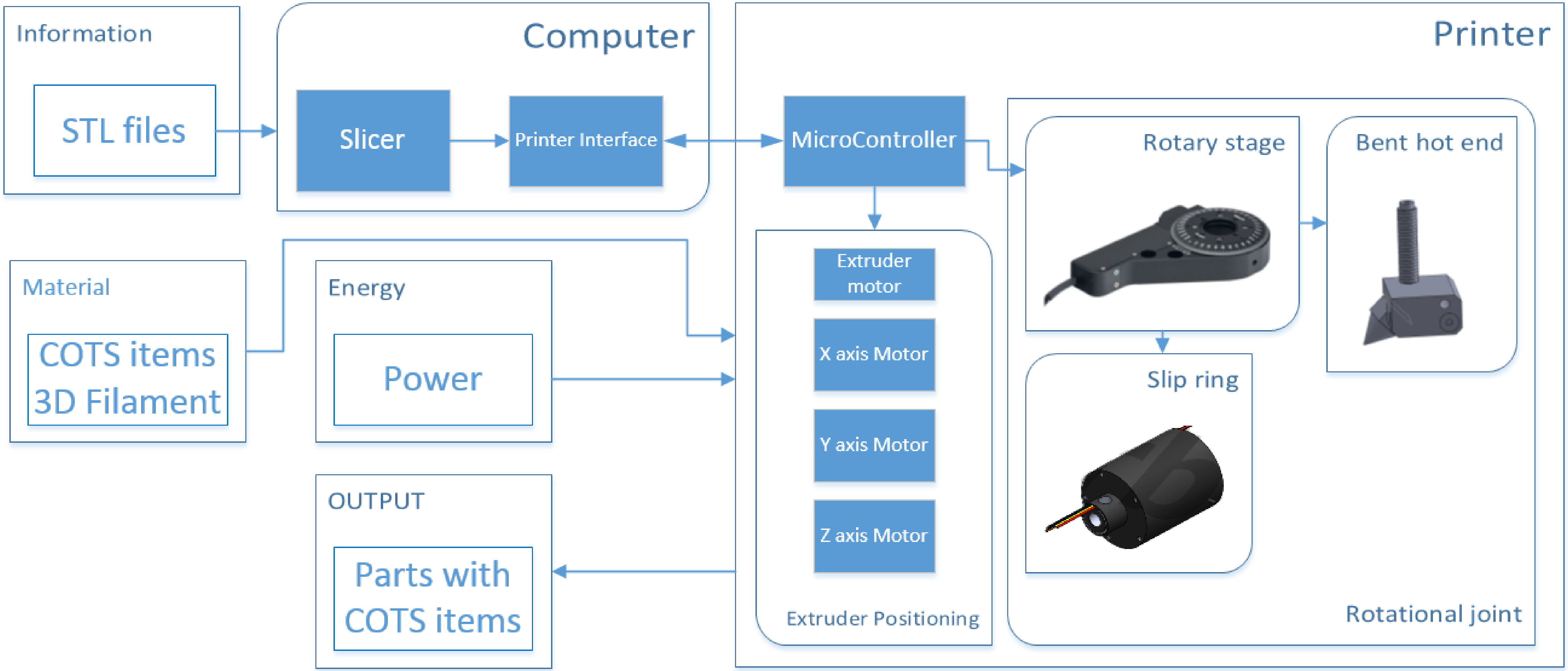
Functional Architecture: Electromechanical



Cyberphysical Architecture



Cyberphysical Architecture



Subsystems (Overview + Current Status)

- **Slicer Software**

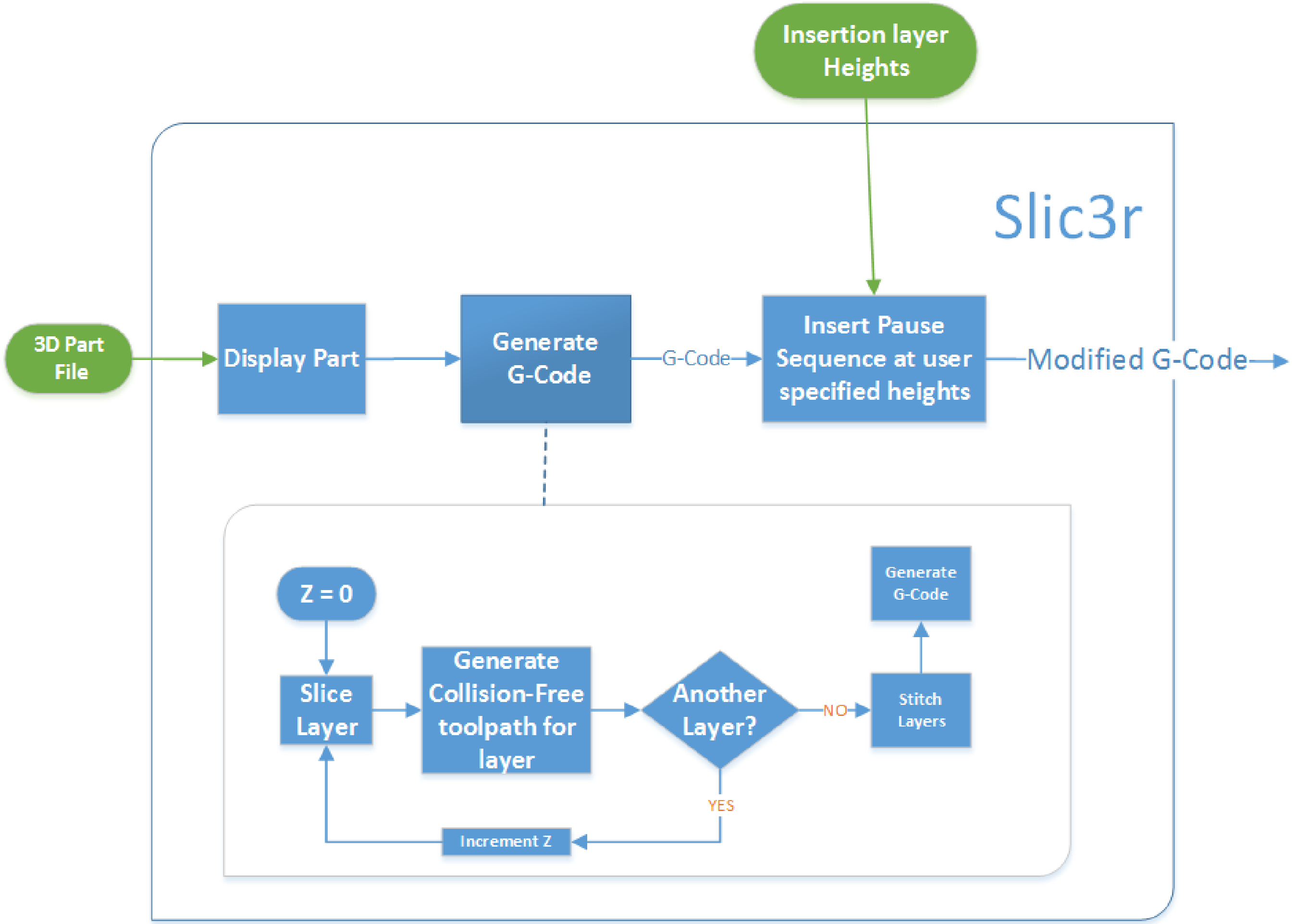
  Receive .stl file; Generate G-Code file
- **RAMBo Controller + Firmware**

  Receive USB Commands; Command axis + heaters
- **Rotary Stage + Slip Ring**

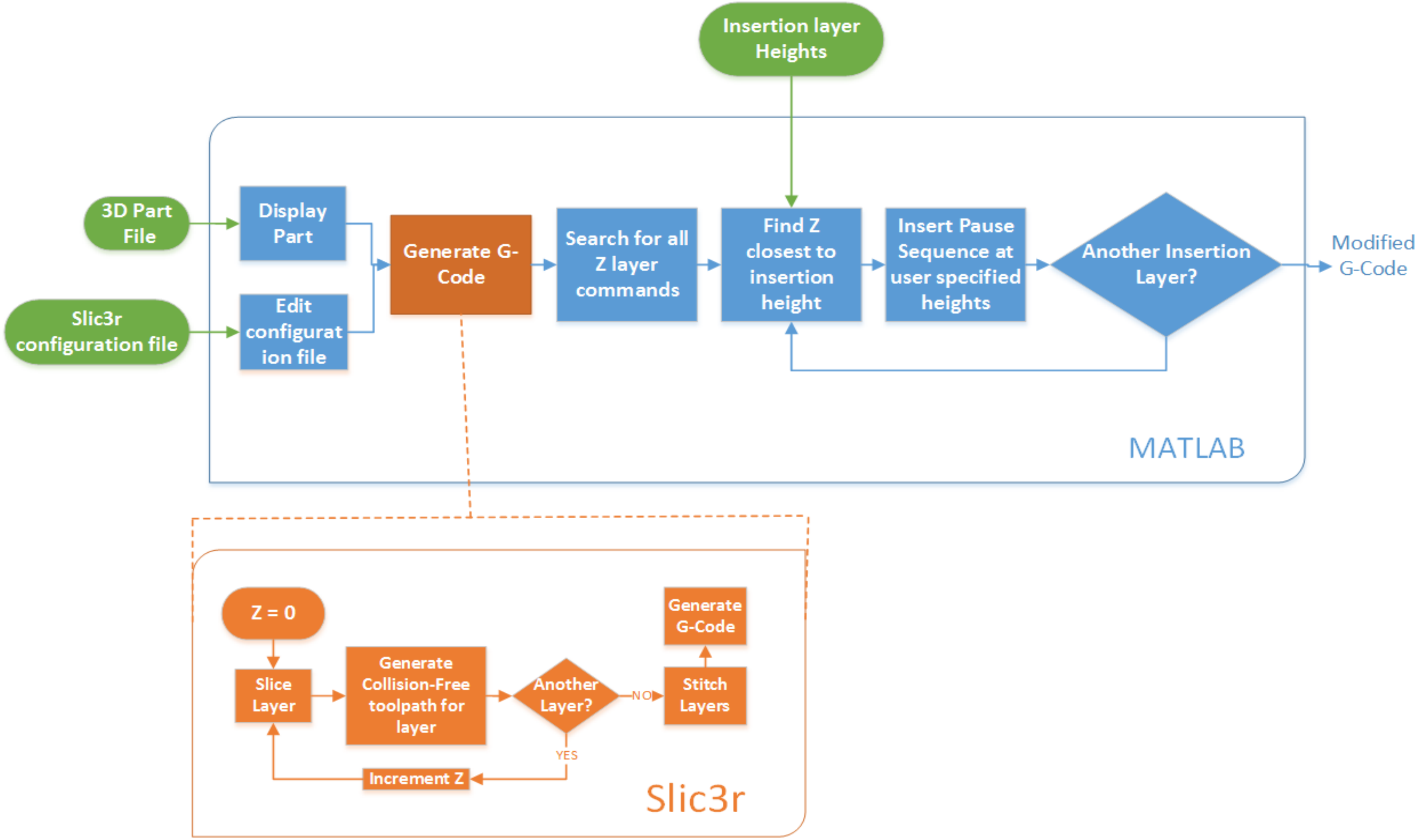
  Infinite nozzle rotation with filament and electrical feed-thru
- **Extruder Nozzle**

  Enclose COTS item in 3D Print material

Slicer Software - Overview



Slicer Software – Current Approach



Slicer Software – Current Status

Recent Tasks:

- Invoke Slic3r from MATLAB
- Implement layer selection algorithm in MATLAB

Upcoming Tasks:

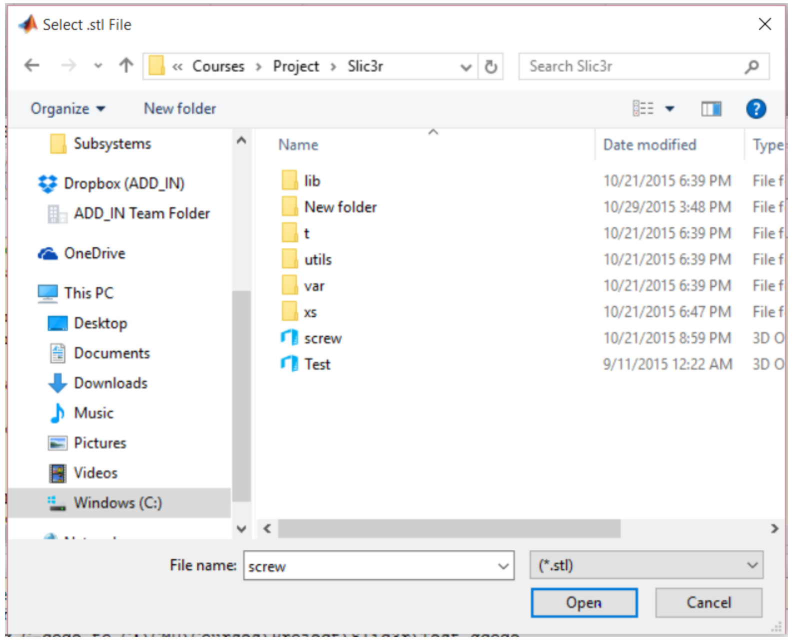
- Design + Implement path planning algorithm
- Generate 4DOF G-Code commands
- Port MATLAB scripts into open source Slic3r software (Spring)

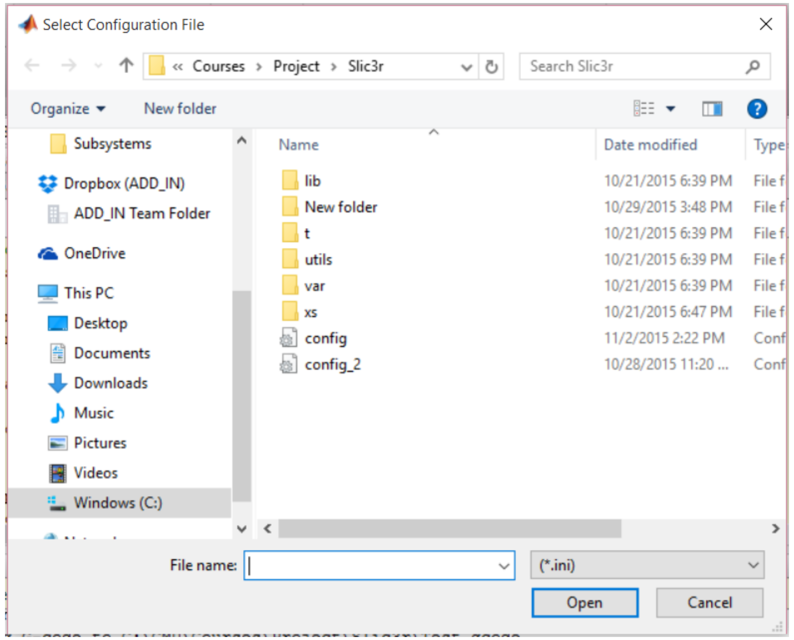
Slic3r/MATLAB integration	Layer Selection Algorithm	Design Path Planning Algorithm	4DOF G-Code Generation	Port MATLAB scripts into Slic3r

Slicer Software – Current Status

USER INTERFACE (MATLAB)

- Slic3r is invoked and resulting G-Code is modified for insertion configuration
- Slic3r settings are loaded through configuration file

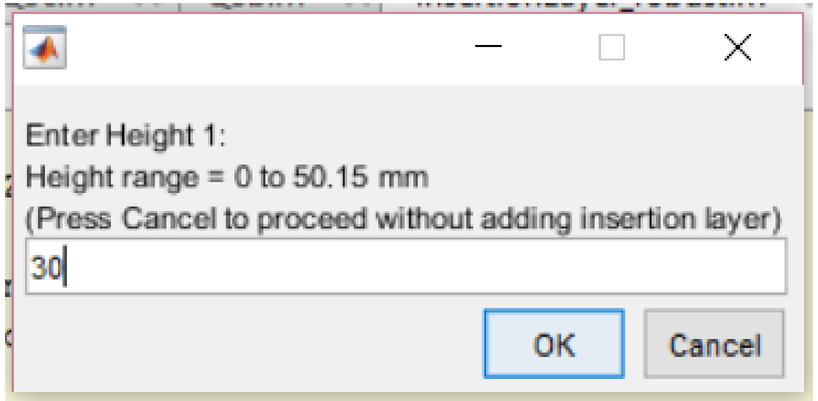




Slicer Software – Current Status

INSERTION LAYER SELECTION

User is prompted for an insertion height



PAUSE SEQUENCE

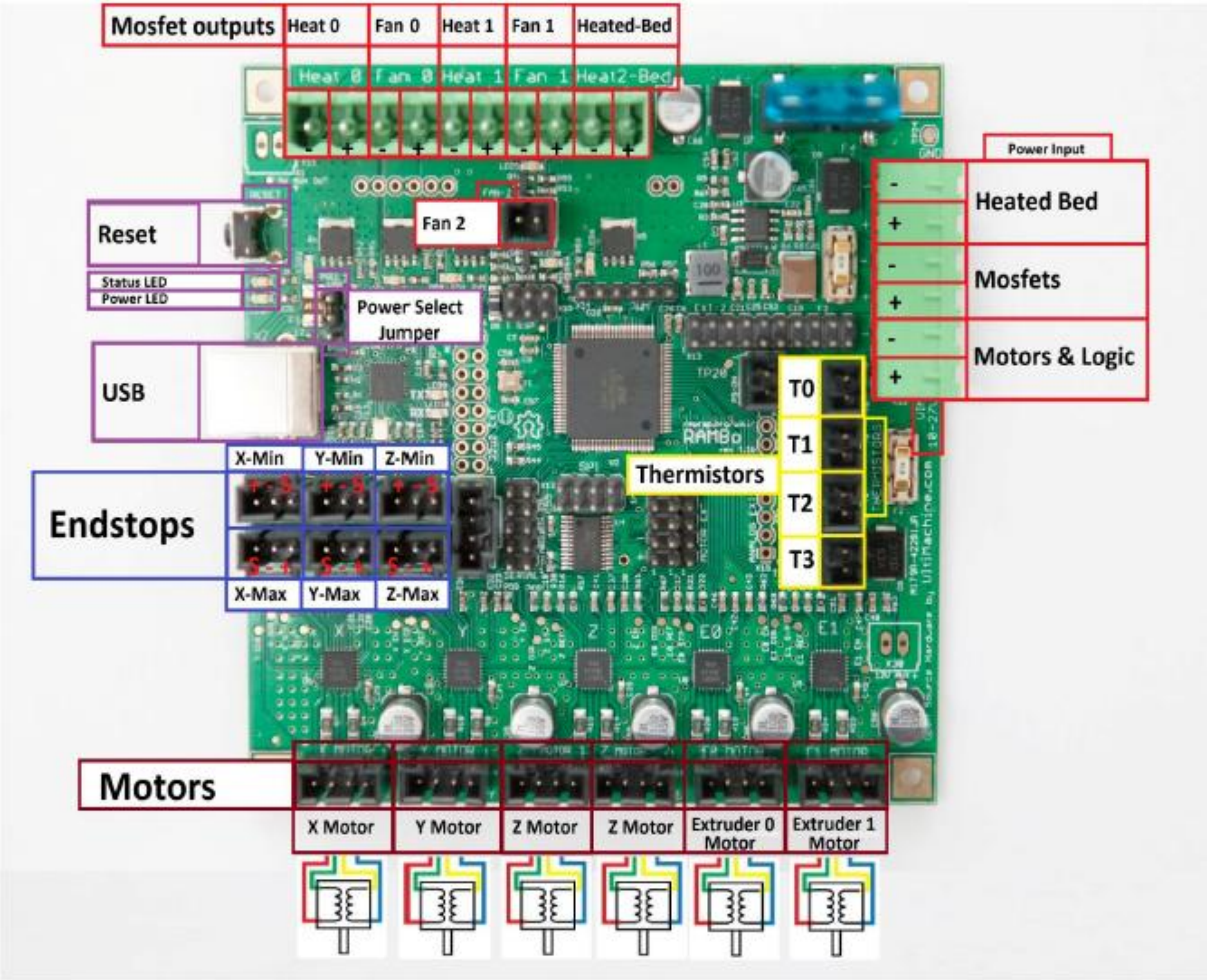
- Pause sequence is inserted before the closest Z command

```
M0                 --Pause
G01 X0 Y200 Z170   --Go to Insertion Position
```

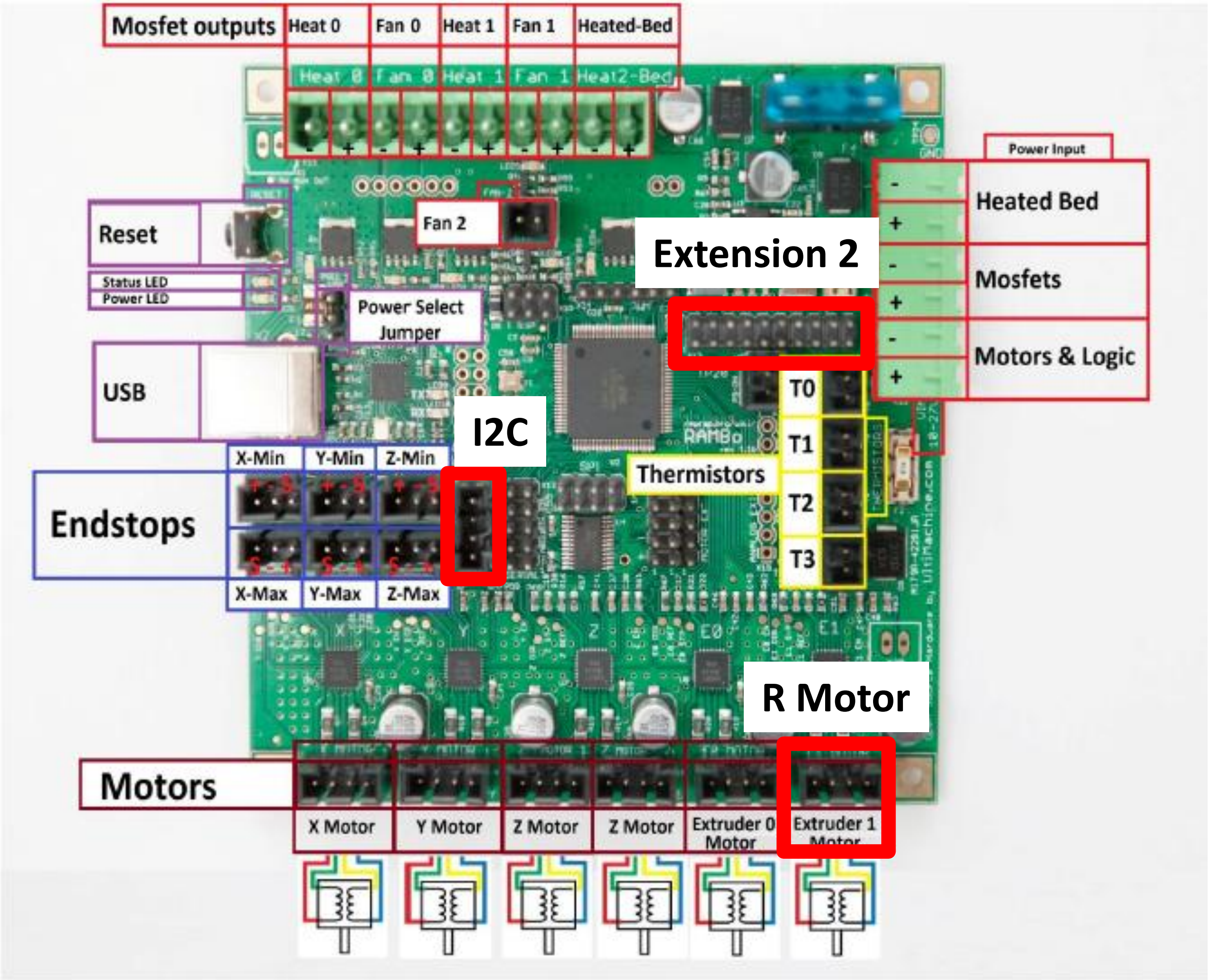
```
G1 X64.854 Y82.992 E75.39678
G1 X63.359 Y84.487 E75.48135
M106 S211.65
M0
G01 X0 Y200 Z170
G1 Z30.150 F7800.000
```

RAMBo Controller - Overview

- Hardware
  - ATMega2560
  - 5 Stepper Outputs
  - 2 Heater outputs
  - Analog Thermistor input
  - I^2C Interface
  - User interface with LCD
- Software
  - Open Source Firmware (Arduino)



RAMBo Controller – Hardware Changes



courtesy Thomas Sanladerer

RAMBo Controller – Firmware Changes

- Control additional stepper motor
- Receive G-codes with 4 degrees of freedom (X-Y-Z-R)
- Modify motor control algorithm to synchronize X-Y-Z-R
- Interface with the thermistor sensing module

RAMBo Controller – Current Status

Recent Tasks:

- Control stepper motor using RAMBo => Done in Task 7
- Thermistor sensor module design => Task 12

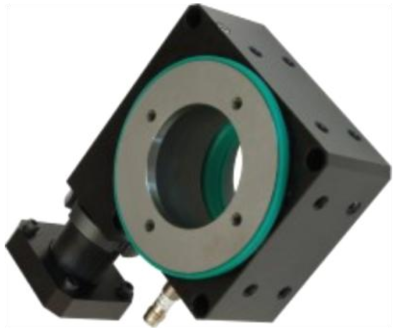
Upcoming Tasks:

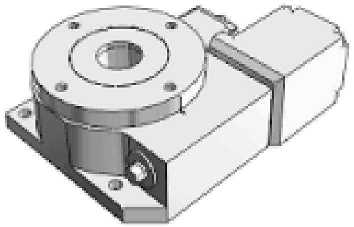
- Modify firmware to for digital nozzle temperature input
- Modify firmware to receive 4DOF G-Code
- Modify firmware to synchronize rotary stage (Spring)

Control stepper with the board	Understand the Merlin Firmware	Write and integrate code for 4th DOF

Rotary Stage + Slip Ring - Overview

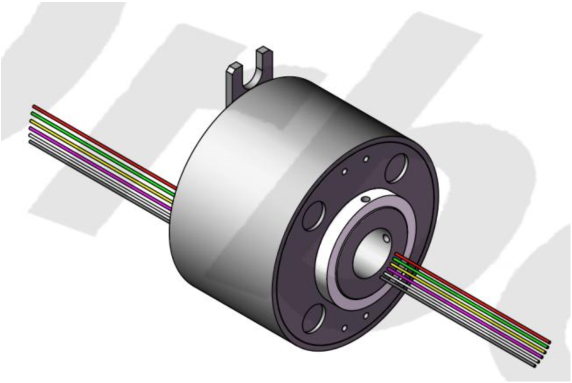
Rotary stage
- Precise nozzle rotation
- Clear aperture for the filament feed + slip ring





Slip ring
- Transmit Heater power + temperature signal
- Clear aperture for the filament feed
- Enables infinite rotation
- Thermistor output will be converted to digital for noise immunity

  => PCB design of task 12



Rotary Stage + Slip Ring – Current Status

Required specification:

Rotary stage

- Speed: ≈ 75°/sec
- Repeatability: ± 1.2°/R *R is the offset of the nozzle tip w.r.t. rotation axis*
- Stepper actuated – control compatible to Rambo board

Slip ring

- Hollow with min aperture of 4mm
- 6 lines
- Compact: length < 25 mm external diameter < 20 mm

Rotary Stage + Slip Ring – Current Status

Recent Tasks:

- Determine required rotary stage speed as function of R
- Research rotary stage suppliers

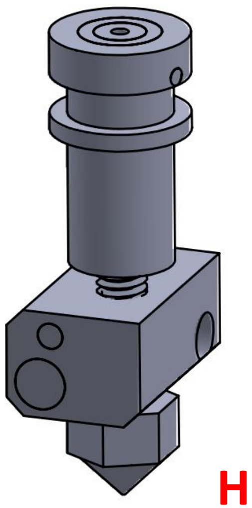
Upcoming Tasks:

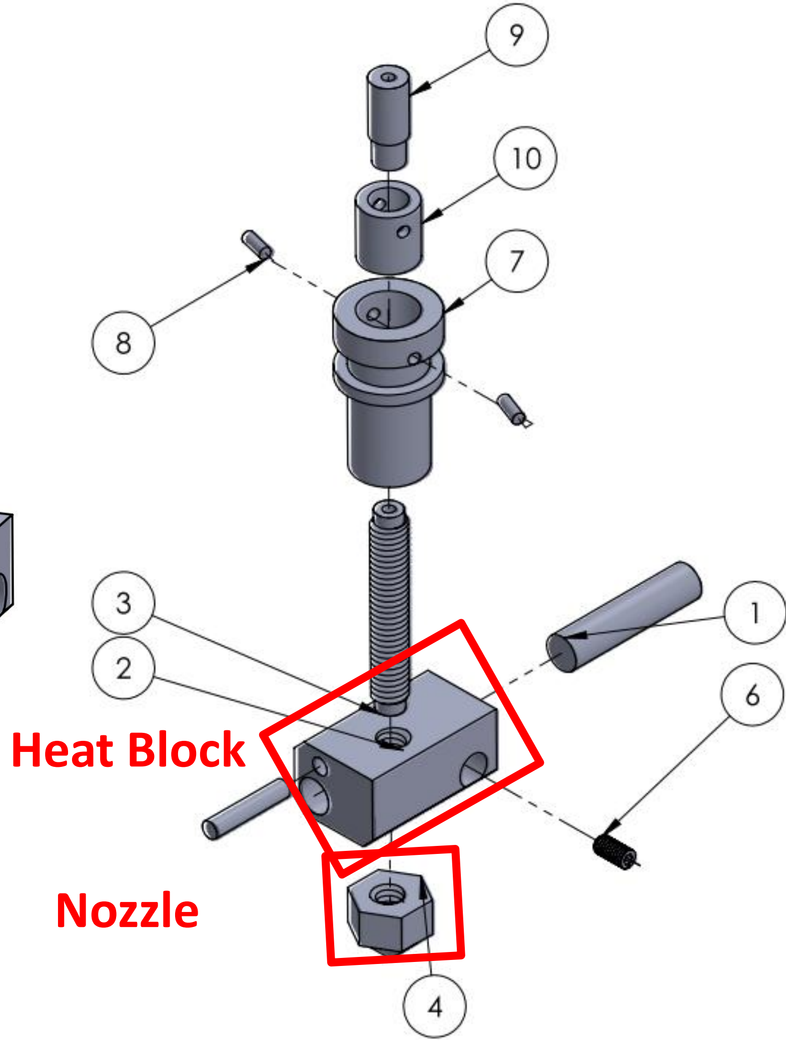
- Select + order rotary stage based on final nozzle dimensions
- Design, manufacture, assemble rotary stage and slip ring mounts
- Modify firmware to synchronize rotary stage (Spring)

Research Rotary Stages	Required Speed Calculations	Select Product	Design mounts	Purchase	Manufacture Mounts	HW + SW Integration

Extruder Nozzle - Overview

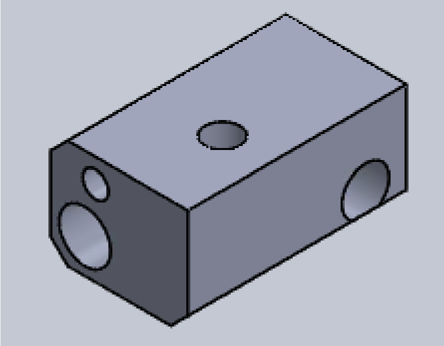
PART NUMBER	DESCRIPTION	ITEM NO.	QTY.
Cartirage Heater	MakerGear M2 Extruder Assembly	1	1
Aluminium Heater Block	MakerGear M2 Extruder Assembly	2	1
M6 Heater Barrel	MakerGear M2 Extruder Assembly	3	1
0.35mm Nozzle	MakerGear M2 Extruder Assembly	4	1
Modular Thermistor	MakerGear M2 Heater Assembly	5	1
M3 screw	MakerGear M2 Heater Assembly	6	1
Groove Mount PEEK	MakerGear M2 Groove Mount Assembly	7	1
Groove Mount Stopper	MakerGear M2 Groove Mount Assembly	8	2
1.75mm PTFE tube	MakerGear M2 Groove Mount Assembly	9	1
Insulator	MakerGear M2 Groove Mount Assembly	10	1

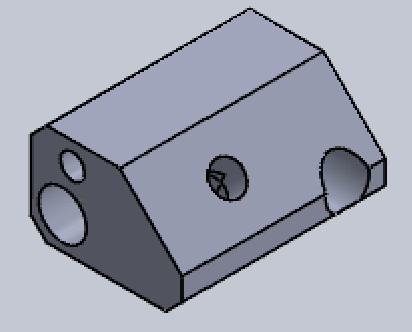




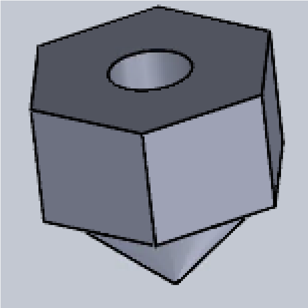
Extruder Nozzle - Overview

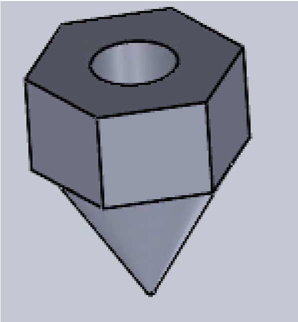
Heat Block



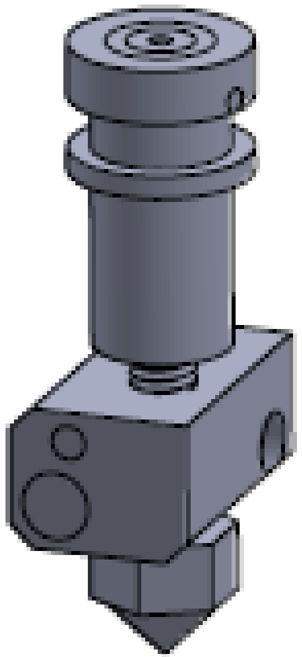


Nozzle

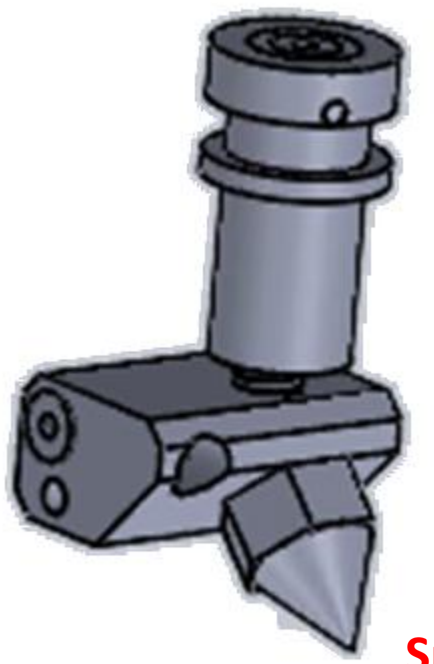




Extruder Nozzle - Overview



Original MakerGear Extruder Nozzle



Angled Nozzle Mount

Small diameter nozzle

4DOF Custom Nozzle

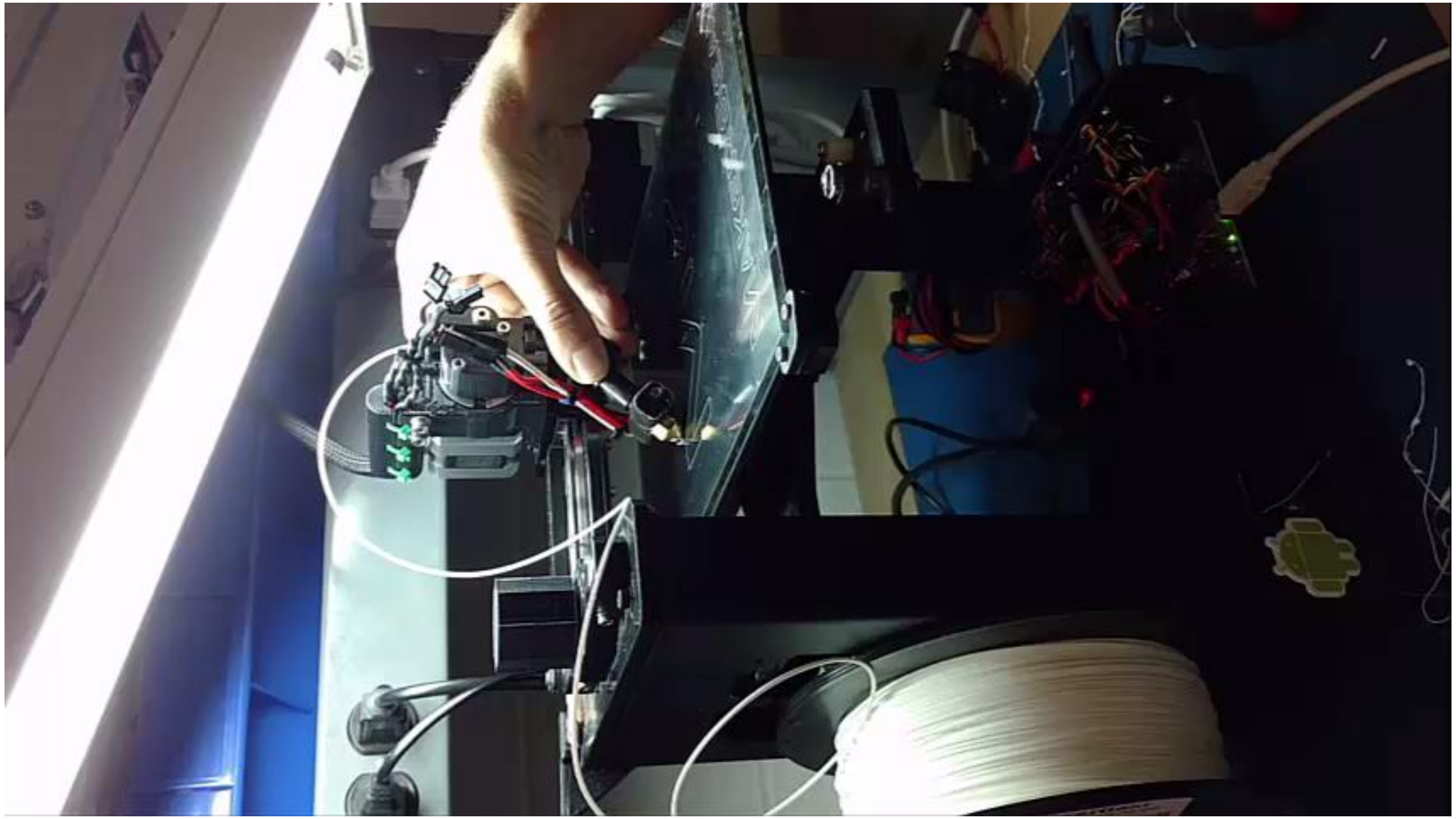
Extruder Nozzle - Overview

Extruder Nozzle Requirements

- Avoid filament kinks
- Similar heat transfer properties as original MakerGear Nozzle
- Uniformly extrude 3D print material

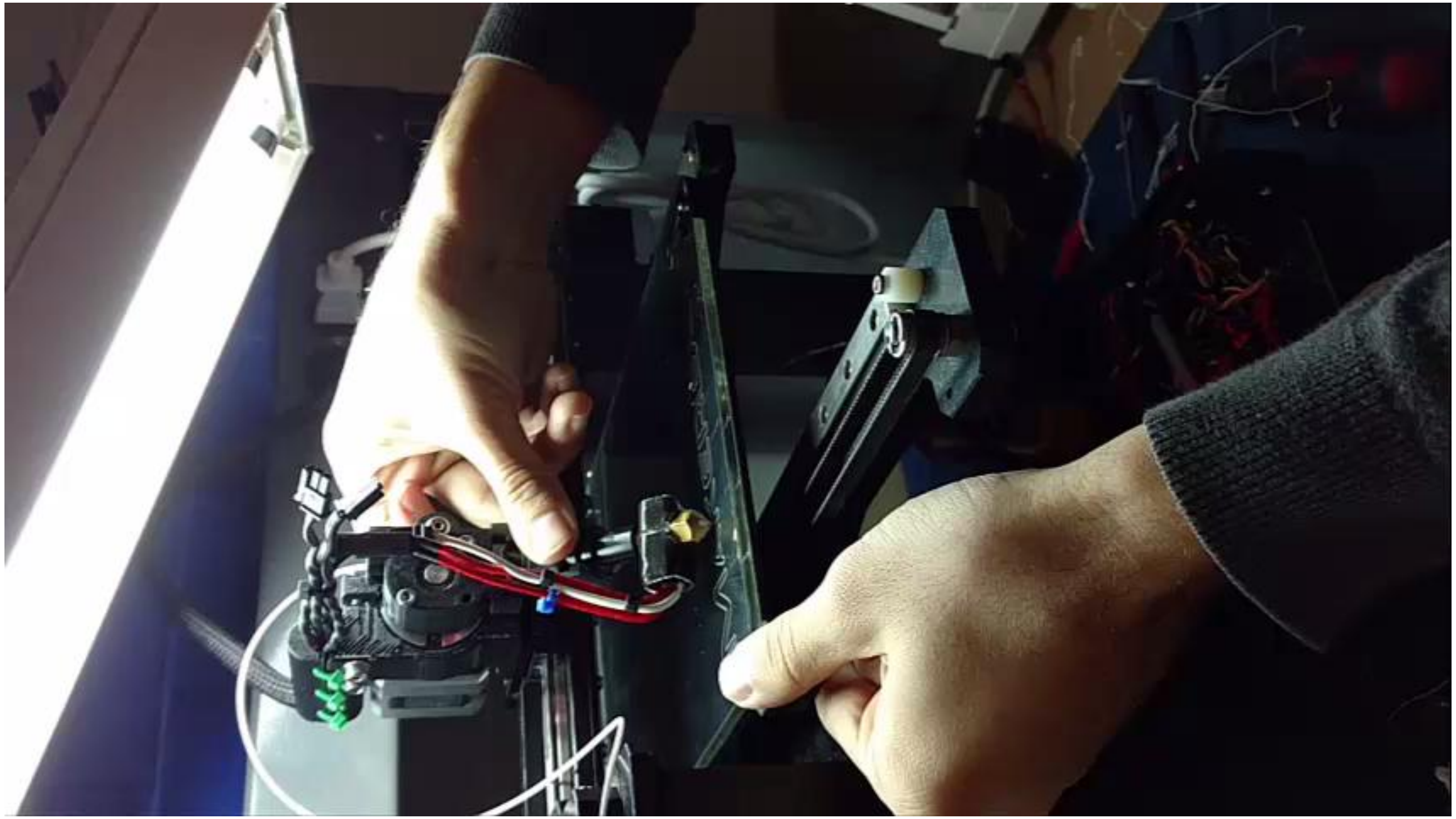
Extruder Nozzle – Current Status

Feeding filament through rotating joint



Extruder Nozzle – Current Status

Uniform extrusion with angled nozzle



Extruder Nozzle – Current Status

Recent Tasks:

- Nozzle Design Research
- Proof of concept testing
  - Filament feed through rotating nozzle
  - Uniform extrusion from angled nozzle
- First iteration nozzle design

Upcoming Tasks:

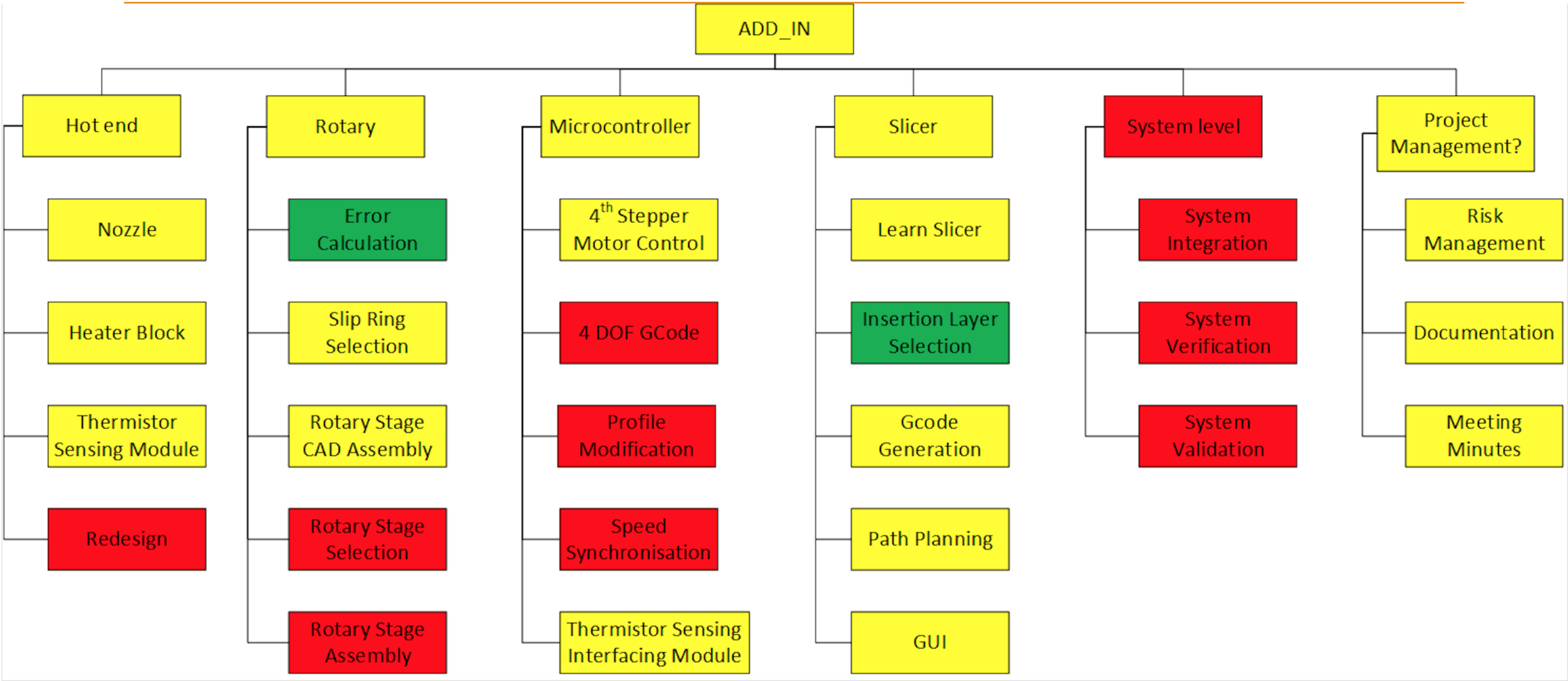
- First iteration nozzle manufacture
- Nozzle design iteration

Research nozzle design	Proof of concept tests	Design first iteration	Machine first iteration	Test + Iterate

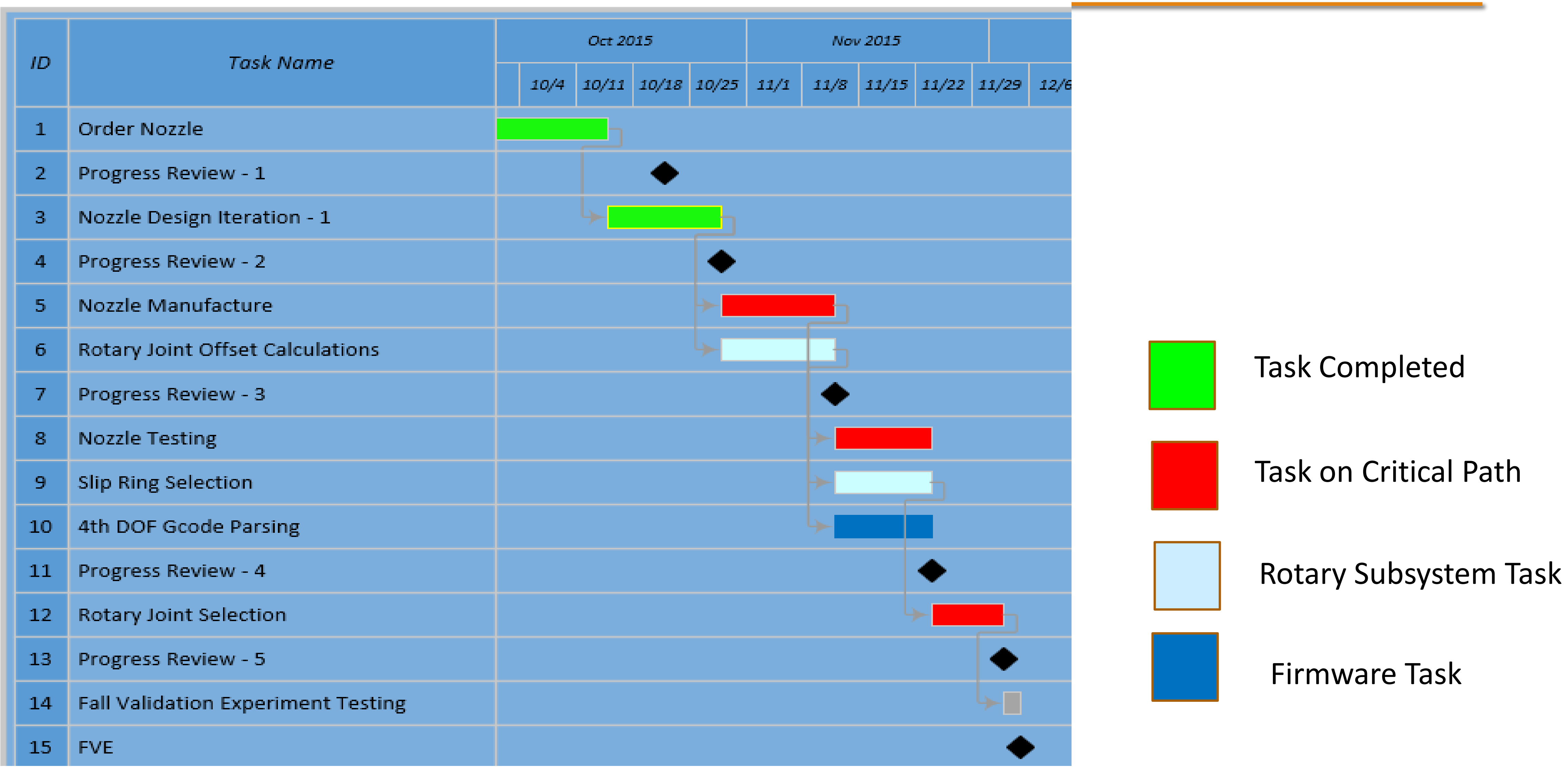
Project Management

- Work Breakdown Structure
- Schedule
- Test Plans
- Budget
- Risk Management

Work Breakdown Structure

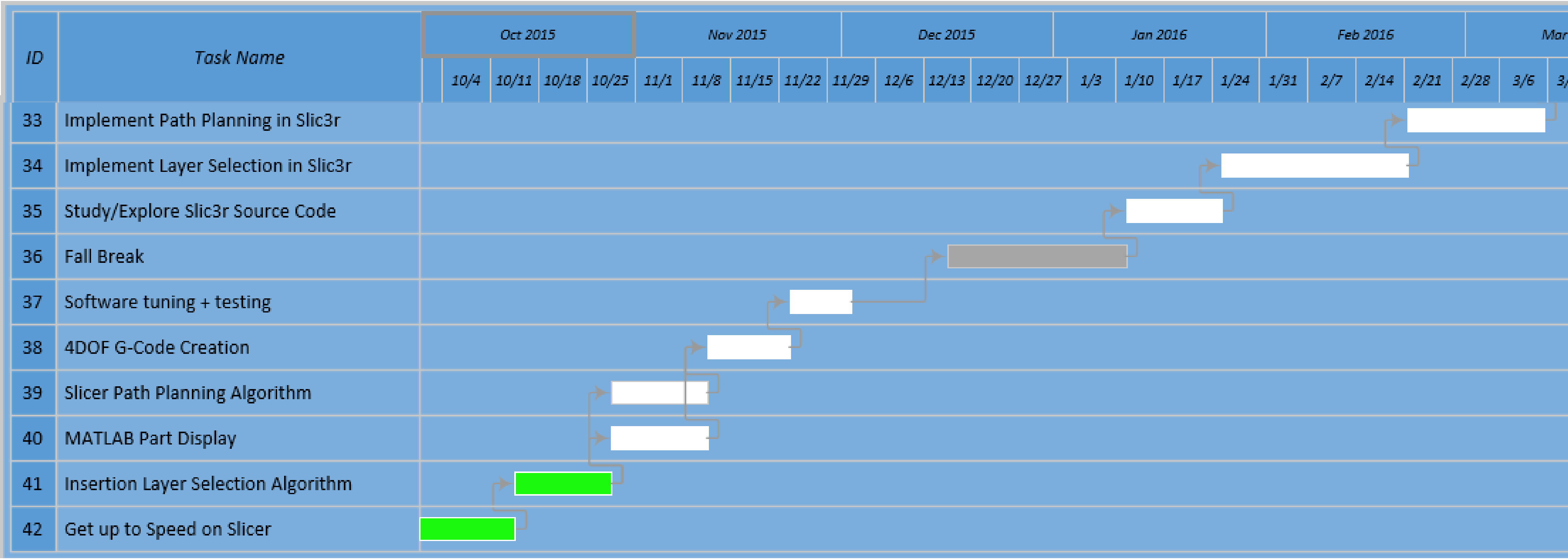


Project Schedule



Project Schedule

Project Schedule



Task Completed

Task Software

Test Plans

- **Fall Validation Experiment**
  - Requirements Mapping
  - Software Verification
  - Hardware Verification
- **Spring Validation Experiment**
  - Requirements Mapping
  - Software Verification
  - Hardware Verification
  - System Validation

FVE – Requirements Verification

	FVE	REQUIREMENTS	Test 1: Nozzle Print Capability	Test 2: Insertion Layer Selection
Mandatory	Functional	Receive standard 3D part files	✓	✓
	Functional	Prompt user for insertion layer		✓
	Functional	Generate 4DOF G-Code		✓
	Functional	Avoid Kinks in Filament	✓	
	Functional	Print layers of material	✓	✓
	Functional	Go to safe configuration during insertion		✓
	Non - Functional	Maintain accurate temparature control	✓	
	Non - Functional	Provide user feedback during printing		✓

FVE – Software Verification

Objective: Demonstrate the ability of a slicer program to allow selection of insertion layers and for the 4DOF printer to ‘pause’ at the selected layers.

Equipment	Sequence	Metric
Physical: 1. 4DOF Printer with standard print nozzle 2. Laptop computer with slicer and printer controller software Electronic: *1. .stl* file for test part	1. Slice part, choosing an insertion layer 2. Send resulting G-Code file to the printer 3. When the printer pauses and enters the insertion configuration, wait 5 minutes, then resume print using hardware printer controller	1. The printer should pause and enter the insertion configuration at the correct height. 2. The printer should resume printing and complete the part without significant defects. Insertion Configuration 

FVE – Hardware Verification

Objective: To evaluate the ability of the custom print nozzle to uniformly extrude 3D print material at different nozzle orientations

Equipment	Sequence	Metric
Physical: 1. 4DOF Printer or equivalent nozzle test fixture 2. 4DOF Custom Nozzle 3. Laptop computer Electronic: 1. Printer controller software 2. G-Code test file which instructs the printer to extrude material	1. If necessary, configure the printer/test fixture with the custom extruder nozzle 2. Power on the system and warm up the print nozzle. 3. Send the test file to the printer 4. After the print, rotate the extruder nozzle angle and reprint the test file	1. Visually inspect all prints to ensure uniform extrusion thickness Pass  Fail 

SVE– Requirements Verification

	SVE	REQUIREMENTS	Part 1: Slicer Capability	Part 2: Printer Capability
Mandatory	Functional	Receive standard 3D part files	✓	
	Functional	Prompt user for insertion layer	✓	
	Functional	Create Collision free path	✓	
	Functional	Generate 4DOF G-Code	✓	
	Functional	Rotate nozzle using G-Code		✓
	Functional	Avoid Kinks in Filament		✓
	Functional	Print layers of material		✓
	Functional	Print locating features for COTS items		✓
	Functional	Go to safe configuration during insertion		✓
	Functional	Enclose COTS item with print material		✓
	Functional	Avoid Collisions		✓
	Non - Functional	Maintain accurate temparature control		✓
	Non - Functional	Provide user feedback during printing	✓	
	Non - Functional	Slicing, Insertion Layer Selection, and Path Planning in single software application	✓	
	Performance	Incorporate COTS parts of cylindrical and rectangular prism shapes		✓
	Performance	Incorporate COTS parts that are orthogonal to print surface		✓
	Performance	Incorporate COTS parts that have a maximum height of one inch above print surface		✓
	Performance	Print volume of 3x3x3 inches		✓
	Performance	Be able to infinitely rotate nozzle		✓

SVE– Part 1: Software Verification

Objective: To evaluate the ability of the slicer software to generate four axis G-Code commands with obstacle avoidance and insertion layer selection capability.

Equipment	Sequence	Metric

Physical:
1. Laptop computer with slicer software and 4DOF G-Code visualization software
 	
Electronic:
1. *.stl* file for test parts:
    1. Part with stiffener rod
    2. Part with threaded insert
    3. Part with sensor/electronics.
	1. Select insertion layer and print configuration
	
	2. Slice the part to generate G-code
	
	3. Visualize resulting G-Code and ensure accuracy
		1. The visualized print path shows the rotation axis being positioned to avoid collisions with the COTS item

SVE– Part 2: Hardware Verification

Objective: To evaluate the ability of the printer to correctly execute 4DOF G-code commands.

Equipment	Sequence	Metric
Physical: 1. Laptop computer with printer interface and slicer software 2. ADD_IN printer with filament 3. COTS Items Electronic: 1. G-code files from part 1	For each of the 3 parts: 1. Send G-Code file to printer 2. Insert COTS item at appropriate layer 3. Resume printing after placement of COTS item	1. The printer successfully finishes the prints

SVE– Part 3: System Validation

Objective: To validate that the parts printed with ADD_IN have indeed superior qualities than standard parts

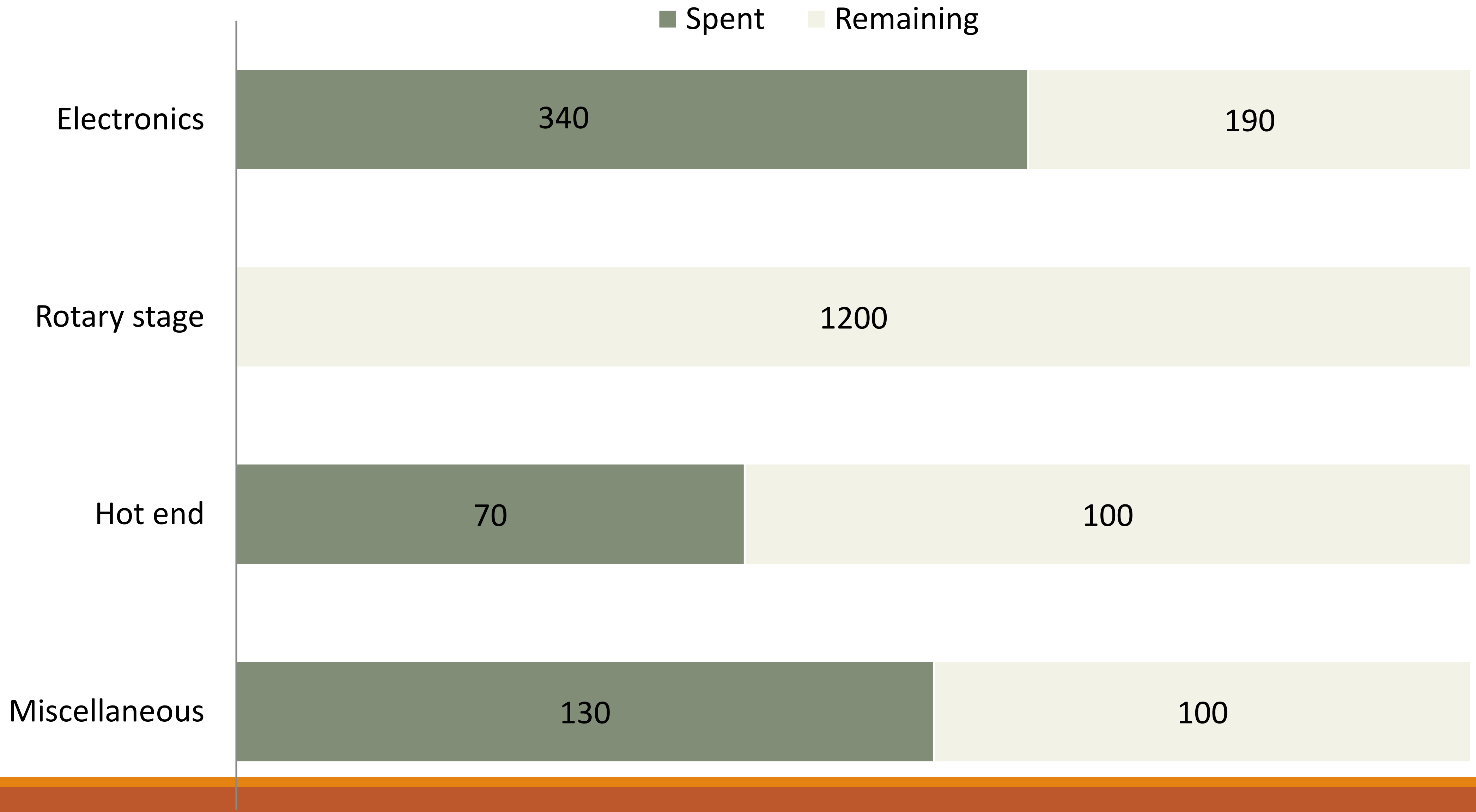
Equipment	Sequence	Metric

Physical:
1. 3D printed parts
2. Test setup for each printed part
    1. Bending stiffness tester
    2. Pull out strength tester
    3. Electronics operation tester
	Perform adequate testing:
	1. Pullout strength test for part with screw insert.
	2. Bending stiffness test for part with stiffener
	3. Electronics/sensor functionality check
		1. Pullout strength should be more than similar part with glued screw insert
		2. Stiffness should be more than similar part without stiffener
		3. Electronics/sensor works and was not damaged during the print

Budget

Category	Details	Cost
Electronics	Backup Rambo Board	$190
	Slip Ring	$140
	Spare Parts: Motor – Extruder	$200
Rotary stage	Rotary Stage	$1200
Hot end	Materials/parts	$150
	Heater/Thermistor	$20
Miscellaneous	Market research: Makerfaire tickets	$80
	Experimental Filaments/others	$150
Total		**$2130**

Current budget status



Risk Management

LIKELYHOOD

5					
4		ID3			ID5
3			ID2		
2			ID4	ID1	
1					
	1	2	3	4	5

SEVERITY

High Priority Risks

<table>
<tr><th>Risk ID</th><th>Risk Title</th><th>Risk Owner</th><th>Date submit</th><th>Date updated</th></tr>
<tr><td>1</td><td>Nozzle not extruding uniformly</td><td>Ihsane</td><td>10/24/2015</td><td>11/2/2015</td></tr>
<tr><th colspan="5">Description</th></tr>
<tr><td colspan="5">Custom nozzle design does not extrude filament of uniform shape and thickness while moving</td></tr>
<tr><th colspan="3">Consequences</th><th>Risk Type</th><th>Risk Level</th></tr>
<tr><td colspan="3">Low print quality</td><td>Technical, Schedule</td><td>20</td></tr>
<tr><th colspan="2">Risk Reduction Plan</th><th>Date</th><th>Expected Outcomes</th><th>Comments</th></tr>
<tr><td colspan="2">1. Test early and often to identify potential sources of extrusion non-uniformity</td><td>11/5/2015</td><td>Identify and minimize sources of non-uniformity</td><td></td></tr>
<tr><td colspan="2">2. Planned iteratation on nozzle design using lessons learned from nozzle testing and research</td><td>11/12/2015</td><td>Produce final nozzle design with similar quality to original MakerGear Nozzle</td><td></td></tr>
</table>

High Priority Risks

<table>
<tr><th>Risk ID</th><th>Risk Title</th><th>Risk Owner</th><th>Date submit</th><th>Date updated</th></tr>
<tr><td>2</td><td>Rotary Joint Accuracy</td><td>Ihsane</td><td>10/24/2015</td><td>11/2/2015</td></tr>
<tr><th colspan="5">Description</th></tr>
<tr><td colspan="5">The offset of extruder nozzle from the axis of rotation is greater than 20mm</td></tr>
<tr><th colspan="3">Consequences</th><th>Risk Type</th><th>Risk Level</th></tr>
<tr><td colspan="3">Achieving print accuracy requires non-standard, high cost rotary stage</td><td>Technical, Cost</td><td>16</td></tr>
<tr><th colspan="2">Risk Reduction Plan</th><th>Date</th><th>Expected Outcomes</th><th>Comments</th></tr>
<tr><td colspan="2">1. Custom designed extruder with small nozzle to minimize offset</td><td>1/12/2016</td><td>Nozzle offset can be kept below 20 mm</td><td></td></tr>
<tr><td colspan="2">2. Planned iteration on nozzle design</td><td>1/30/2016</td><td>Low offset will not cost print quality</td><td></td></tr>
</table>

High Priority Risks

Risk ID	Risk Title		Risk Owner	Date submit	Date updated
3	Weight of the X movement assembly		Nikhil	10/24/2015	11/2/2015
Description					
The increased weight from the rotary stage will decrease the accuracy of the X axis assembly					
Consequences				**Risk Type**	**Risk Level**
Lower Print Quality				Technical	8
Risk Reduction Plan		**Date**		**Expected Outcomes**	**Comments**
1. Perform early testing of weight affects to evaluate sensitivity to increased weight		10/30/2015		Determine risk liklihood early, provide time for redesign.	**Solved**
2. Redesign/modify X-axis assembly		11/5/2015		With time investment, X-axis can be modified to accommodate increased weight without sacrificing speed	
2. Reduce printing speeds to reduce acceleration forces		11/15/2015		Less weight sensitivity but printer usefulness is reduced	

High Priority Risks

Risk ID	Risk Title		Risk Owner	Date submit	Date updated
4	Path Planning Algorithm		Dan	11/1/15	11/2/15
Description					
Preliminary path algorithm has been designed, but their may be unforeseen failure cases					
Consequences				**Risk Type**	**Risk Level**
Schedule delay				Technical, Schedule	6
Risk Reduction Plan			**Date**	**Expected Outcomes**	**Comments**
Review algorithm with sponsor/experts			11/4/15	Get feedback and insight on algorithm design	
Perform MATLAB Test/simulation Path Planning Algorithm			11/6/15	Early identification of potential pitfalls	

High Priority Risks

<table>
<tr><th>Risk ID</th><th>Risk Title</th><th>Risk Owner</th><th>Date submit</th><th colspan="2">Date updated</th></tr>
<tr><td>5</td><td>Slic3r cannot be modified</td><td>Dan</td><td>10/28/15</td><td colspan="2">11/2/15</td></tr>
<tr><th colspan="6">Description</th></tr>
<tr><td colspan="6">Not possible to port layer selection + 4DOF path planning into Slic3r code</td></tr>
<tr><th colspan="3">Consequences</th><th colspan="2">Risk Type</th><th>Risk Level</th></tr>
<tr><td colspan="3">Increases dependency of project on MATLAB</td><td colspan="2">Failure to meet requirements</td><td>20</td></tr>
<tr><th colspan="2">Risk Reduction Plan</th><th>Date</th><th colspan="2">Expected Outcomes</th><th>Comments</th></tr>
<tr><td colspan="2">1. Contact Developer</td><td>10/28/15</td><td colspan="2">Documentation and Recommendations</td><td>No reply as of 11/2/15. Will try other contact methods</td></tr>
<tr><td colspan="2">2. Identify local Perl programming resources</td><td>11/15/15</td><td colspan="2">Guidance for current and future Perl programming difficulties</td><td></td></tr>
<tr><td colspan="2">3. Use different software</td><td>Spring</td><td colspan="2">Delay in systems integration</td><td>Major overhead required for familiarization with new software</td></tr>
</table>

QUESTIONS?