

# **MANUFACTURING TECHNOLOGY FOR METALS IN A MICROGRAVITY ENVIRONMENT**

## **PROJECT COMPLETION AND EVALUATION**

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# Team Members

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# **Vision**

Leaders in Space Printing Innovations

# **Mission**

Use current 3D printing, satellite systems and space capabilities to develop a technology where we design on Earth while printing in Space.

# Purpose

Develop a technology that improves current 3D printing capabilities to allow low-powered space metal manufacturing, **staying ahead of TIME.**

*“From Earth to Space”*



# Existing Technology

Direct Metal Laser Sintering (DMLS)

Electron Beam Melting (EBM)

Selective Laser Melting (SLM)

Selective Laser Sintering (SLS)

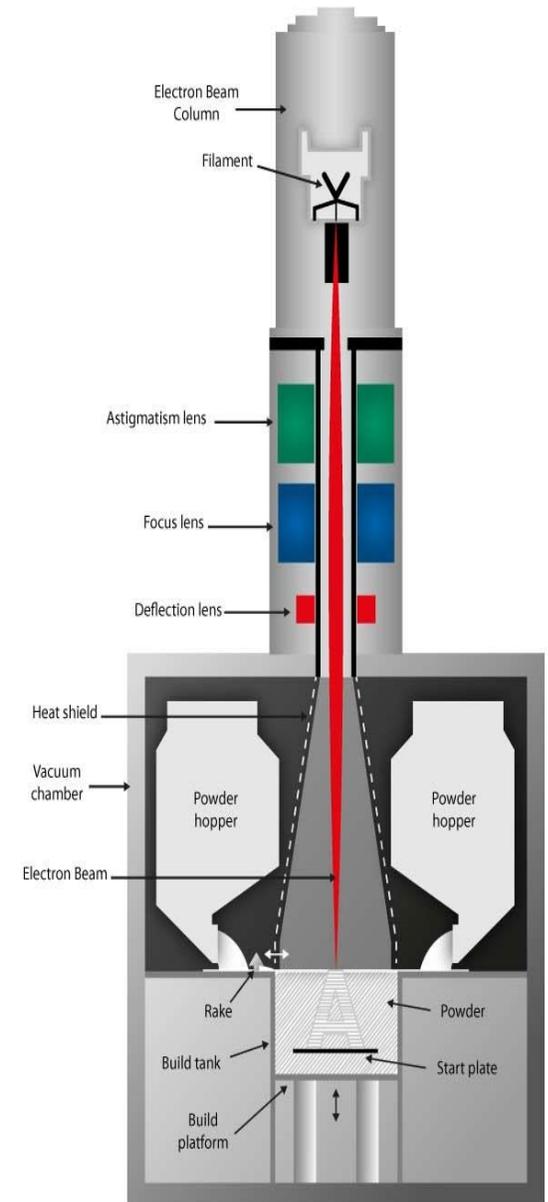
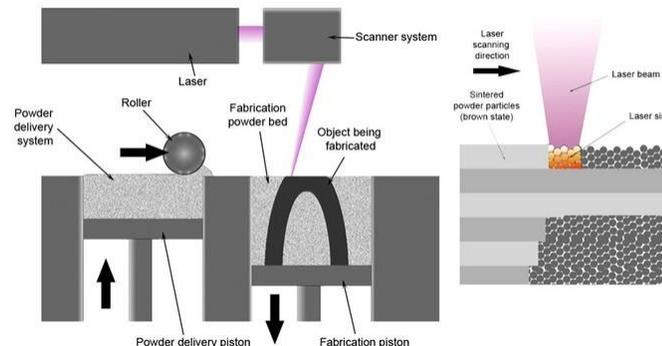
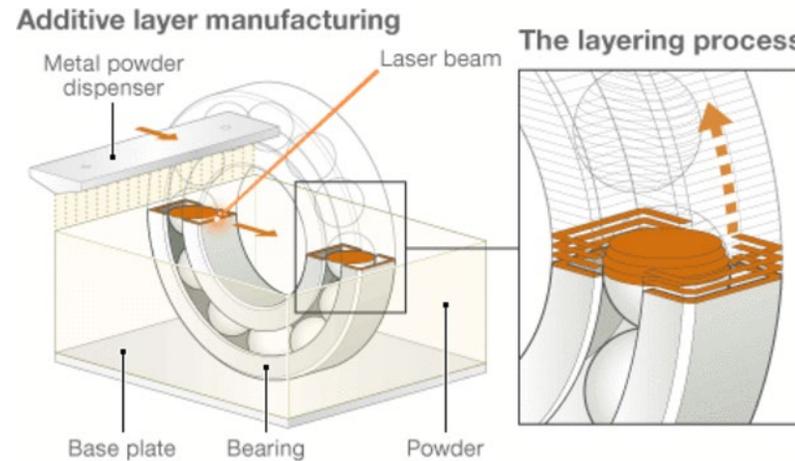
Liquid Metal Jet Printing (LMJP)

Laser Metal Deposition Manufacturing (LMD)

Electron Beam Fabrication (EBF)

Metal Injection Modeling (MIM)

Metal Filled ABS Filaments



# Potential Applications

## On-orbit repairs

Tools, components, and structures

## Additive manufacturing

Coupled with printed electronics, could produce satellites and other large structures

## Additive Construction

Settlement Infrastructure for Lunar or Martian Habitat

Metal additive manufacturing offers greater strength requirements than nonmetallic or composites!



# Project Timeline



MILESTONE	Completion Date
✓ NASA Kick-off Meeting	September 3, 2015
✓ Mission Concept Review (MCR)	September 9, 2015
✓ System Requirements Review (SRR)/ System Definition Review (SDR)	October 15, 2015
✓ Preliminary Design Review (PDR)	November 17, 2015
✓ Critical Design Review (CDR)	March 9, 2016
✓ Process Checkpoint Review (PCR)	April 6, 2016
Project Completion and Evaluation by NASA	August 30 2016

# Systems Definition

- Project Plans
- System WBS
- Project Management Plan
- Development Plans
- Systems Concepts and Architecture
- Risk Analysis

# Review of System Requirements

1. System shall manufacture metal in microgravity environment
  - 1A. System shall process raw material into solid part
    - 1A-1. System shall implement minimal loss of raw material
      - 1A-1A. System shall have up to a minimum of 10%
    - 1A-2. Auto-feed mechanism shall transport raw material
      - 1A-2A. System shall have a minimum printing speed of  $7\text{cm}^3/\text{min}$ .
    - 1A-3. System shall contain material throughout entire process
    - 1A-4. System and product shall be aerospace-grade metal

# Review of System Requirements

1B. System shall control heat dissipation

1B-1. System shall maintain constant temperature levels

1B-1A. Heat bed shall be able to output and maintain a temperature range of 570-600°C.

1B-1B. Extruder heater shall maintain a constant temperature of 600°C.

1B-1C. Relays shall control current flow to allow heat bed meet functionality requirements.

1B-2. Insulator shall control heat dissipation to ensure component safety.

1B-2A. System insulation shall allow a maximum of 40°C of temperature exposure to relevant components.

# Review of System Requirements

1B-3. Temperature sensors will be implemented.

1B-3A. Temperature sensors shall have an operating precision of  $\pm 3^{\circ}\text{C}$ .

1B-3B. Conditioning circuits shall allow relevant components to meet functionality requirements.

1C. System shall manufacture high-complexity part

1C-1. Prints produced shall have high precision

1C-1A. Motor shall require  $1.8^{\circ}$  angle change per 200 motor steps.

1C-1B. System shall maintain printing repeatability tolerance of  $\pm 0.1\text{mm}$  for printed parts.

1C-1C. System shall maintain a difference in dimensions of printed part of up to 1% when compared to CAD.

# Review of System Requirements

- 1C-2. Demo model shall test geometric complexity
- 1C-3. Surface finish processes shall be minimized
- 1C-4. Motors shall provide precision movements to all relevant loaded components.
- 1C-5. System shall use computer code generation to allow manufacturing of complex parts.

# Review of System Requirements

2. System shall operate with low power consumption within the volumetric restraints

2A. Power shall be drawn from the MSG to the system

2A-1. Power consumption shall not pass 1000W

2A-2. 12V standard power shall be supplied for low power components

2B. Minimum number of components shall be used in order to minimize volume and weight

# Review of System Requirements

2C. System shall fit inside the MSG volume parameters

2C-1. System shall meet volumetric constraints and exclusion zones of 736mmx638mmx373mm as stated in MSFC-RQMT-2888, Appendix G

2C-2. MSFC-RQMT-2888 shall be used as a guideline for restraints

# Risk

Risk Management and Mitigation have been identified throughout our design.

## Risk Identification:

The identified risks will be analyzed once the following parts are tested:

- Extruding System - deterioration, malfunction, clogging, discharge control, overheating and precision loss
- XYZ Axis Actuator - motion, motor and its precision
- Heat Bed - overheating, deterioration, clogging, fluid pump and suction malfunction
- Feedstock Storage - precision and delivery jamming
- Electrical Hardware - power supply, motor malfunction and overheating
- Electrical Components - heat dissipation, wiring, short circuits, component overheating and failure
- General - equipment maintenance and replacements

## Risk Mitigation

Throughout testing and the analysis, necessary precautions will be employed to avoid risks. Proper mitigation are established to ensure the **safety**, **reliability**, **repeatability**, and **quality** of the final design in the event a risk occurs.

# Preliminary Design

- Systems Requirements Level 3
- Traceability of Requirements
- Verification Matrix
- Performance Specifications
- Initial Concept of Ideas
- Trade Studies
- Design to Specifications
- Concept of Operations

# Requirements Verification Matrix

## Verification Method Definitions

### **Analysis (A)**

Verification of the system by simulating with models and abstract calculations of intended operation

### **Demonstration (D)**

System will be manipulated as intended to prove that results are as expected

### **Inspection (I)**

Nondestructive examination during operation to ensure functionality

### **Test (T)**

Controlled and predetermined series of inputs to ensure system will act according to its design

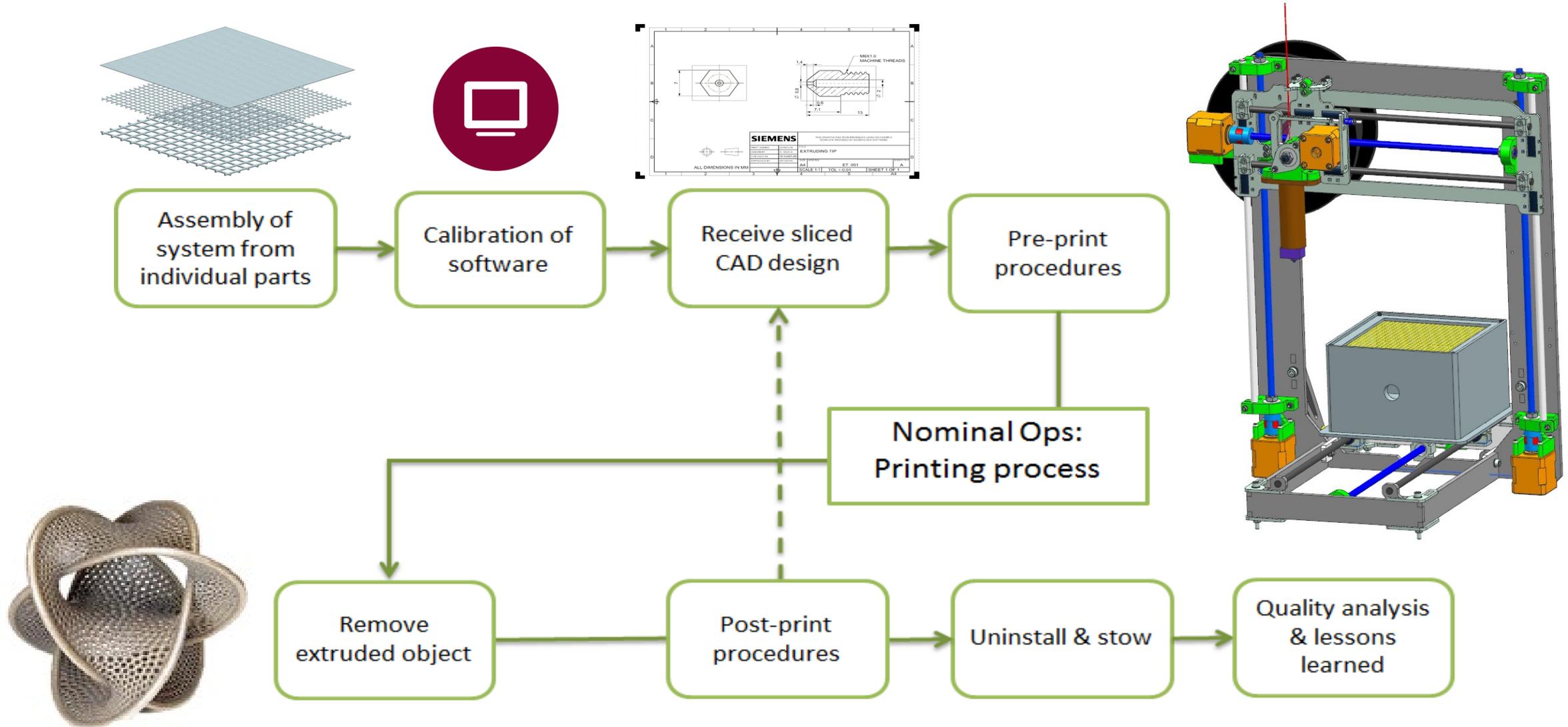
# Level III Requirements Verification Matrix

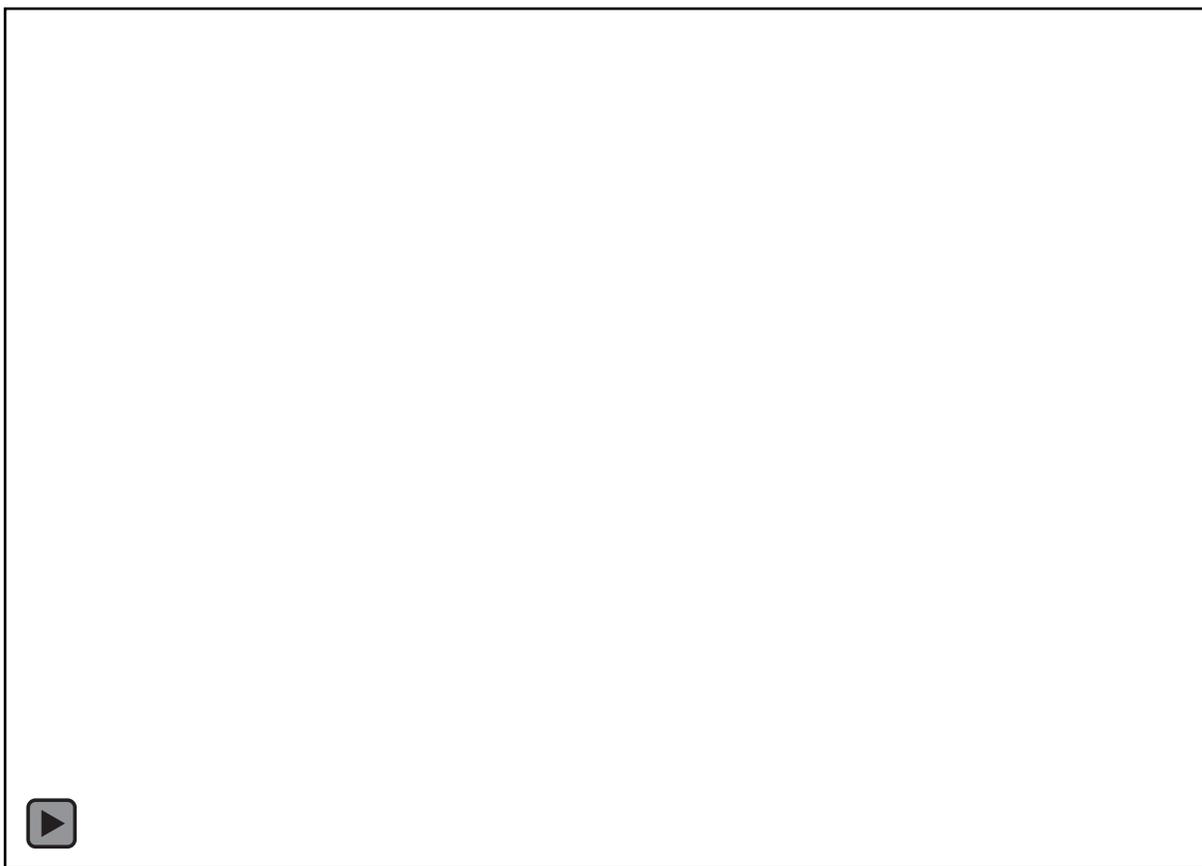
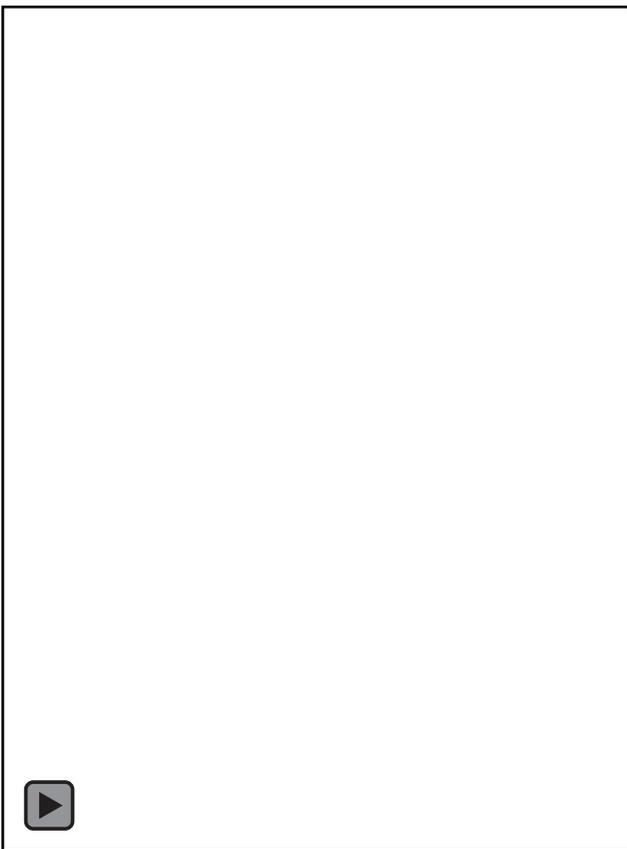
Level 3 Requirement	Rationale	Verification Activity	Verification Method				Verification Responsibility	Met Requirements
			A	D	I	T		
System shall implement minimal loss of net material use	Full net-material use in space is important, since supply is very limited due to launch dependency.	Once prototype is assembled, calculation of theoretical mass from estimated filament length to be used in a print will be compared to its experimental mass value.		X	X		XTIME	-
Auto-feed mechanism shall transport raw material	Automated material handling puts astronauts out of danger from contamination, protects material from impurities.	Once prototype is assembled, auto-feed mechanism will be visually inspected to assure optimum functionality.			X		XTIME	The design of an auto-feed mechanism which would feed metal filament from a spool to the printer.
System shall contain material throughout entire process	Protects astronauts from danger of contamination, protects material from impurities.	Before initial testing phase, a fluid analysis will be executed to observe material conduct and verify that material is contained properly.	X				XTIME	-
End product shall be aerospace grade metal	System shall process aerospace grade metals, due to their properties and value in use for space exploration.	By not using a manufacture method that affects the molecular composition of feedstock, aerospace properties can be maintained.			X		XTIME	-
System shall maintain a constant temperature level	Temperature should be maintained at a constant level to avoid warping during the extrusion process and maintain controlled environment throughout the	During system operation, temperature levels on the thermocouples will be monitored. These real-time readings will be collected in a graph and compared to established set-point.				X	XTIME	During Testing phase Heating and temperature control were tested and maintained steady
Insulator shall control heat disipation in order to protect sensitive componets	Electrical systems are fragile to extreme temperature changes, and must be protected.	External temperature sensors will measure thermal bleed from the extruding mechanism and heat bed. These readings will be monitored during initial testing phase to to assure that		X			XTIME	A copper mesh heat shield was implemented in the prototyping phase to protect sensitive electronics and
Temperature sensors shall be implemented for relevant components	Monitor the heating componets for temperature control	The use of a thermometer will serve as a reference in order to verify temperature readings are within the desired range. To ensure the measurements from temerature sensors are		X			XTIME	A MAX6675 Thermcouple was installed on the printer hardware and relevant firmware was adapted to its

# Level III Requirements Verification Matrix

Level 3 Requirement	Rationale	Verification Activity	Verification Method				Verification Responsibility	Met Requirements
			A	D	I	T		
Prints produced will have a high precision, when compared to original model	Objects manufactured need to have a certain precision in order to achieve maximum use potential.	The system will print different objects and compare them to their original models to measure precision. Dimensions will be measured and dimensional variance compared to CAD model.			X		XTIME	-
Demo model shall test geometric complexity	Geometric complexity shall test system capabilities and its ability to manufacture specific parts.	A demonstration piece with test geometries will be extruded to test the system's geometric complexity capabilities.		X		X	XTIME	-
Surface finish procedures shall be minimized	Post processing for objects in space is harshly limited, and should be kept to a minimum to keep print integrity at maximum.	Evaluation of test coupons produced by a functional prototype shall confirm the quality of the extruded surface.			X		XTIME	-
Power consumption shall be below 1000W	Power supplied by the MSG is limited to 960 W	Specifications of electrical components will verify that the sum of all power consumption remains below max. consumption. A wattmeter will measure voltage and current during system operation.		X		X	XTIME	While testing, printer power consumption was no more than 400W
12V standard power shall be supplied for low power components	Limit number of power sources	Electric components that need less than or 12V of power will be chosen for assembly.	X				XTIME	By using electrical components that need a relatively low voltage, the power requirements have been met.
System shall meet dimensional constraints and exclusion zones 766mm x 638mm x 373mm as stated in MSFC-RQMT-2888, Appendix G	Space for experimentation is limited, and must be constrained to the MSG.	Once system is assembled and tested, its dimensional features will be measured and compared to MSG restraints.			X		XTIME	By making a CAD design with specific dimensional constraints, the physical limits within the MSG have been met.
MSFC-RQMT-2888 shall be used as guideline for MSG dimensions constraints	Due to physical constraints, the MSFC-RQMT-2888 grants specific restraints.	When testing for MSG constraints, the MSFC-RQMT-2888 document shall be used as a guideline.			X		XTIME	MSFC-RQMT-2888 was used as reference for inspecting that the dimensions of the CAD model are within standards/

# Concept of Operations Overview





# Critical Design

- Finalized Design
- Engineering Drawings
- Manufacturing Plan
- Materials and Process Control Plan
- Integration and Assembly Plan
- Testing Plan

# Extruder

## **Extruder Tip**

Enables the precision needed to print high complexity objects

## **Heater Block**

Heats the tip to the desired temperature

## **Tungsten Block**

Heats the heating chamber and the filament

## **Ceramic Insulator**

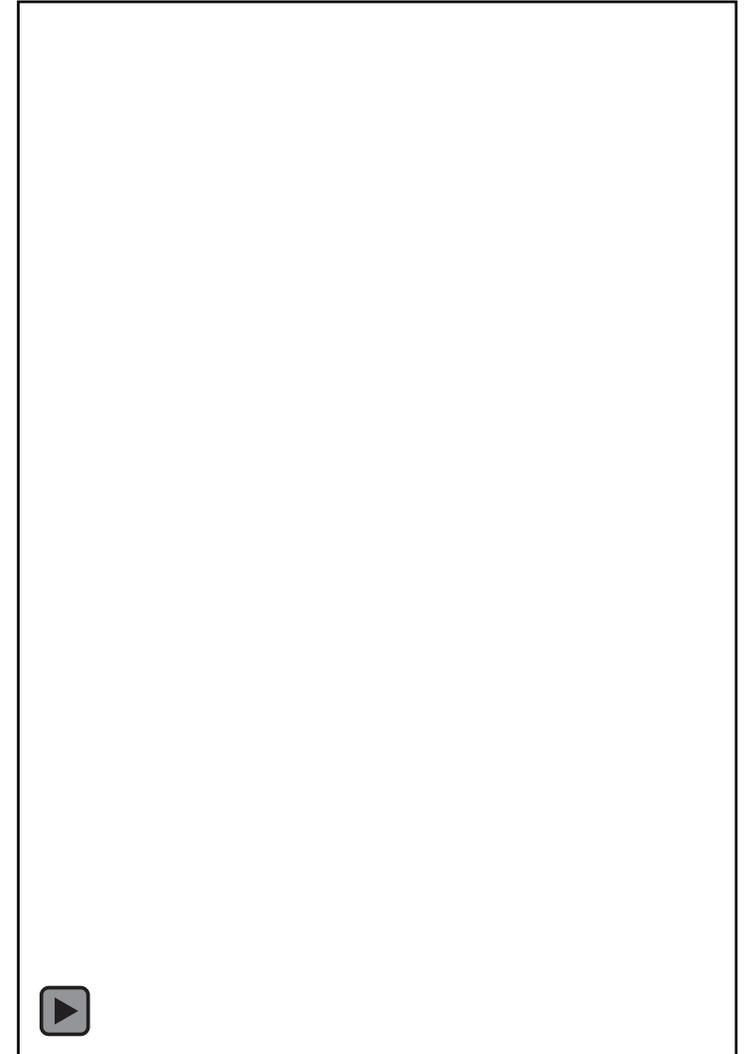
Covers the heating chamber and coils which insulate any heating dissipation for constant process operation and safety

## **Heating Chamber**

Covers and heats the aluminum filament

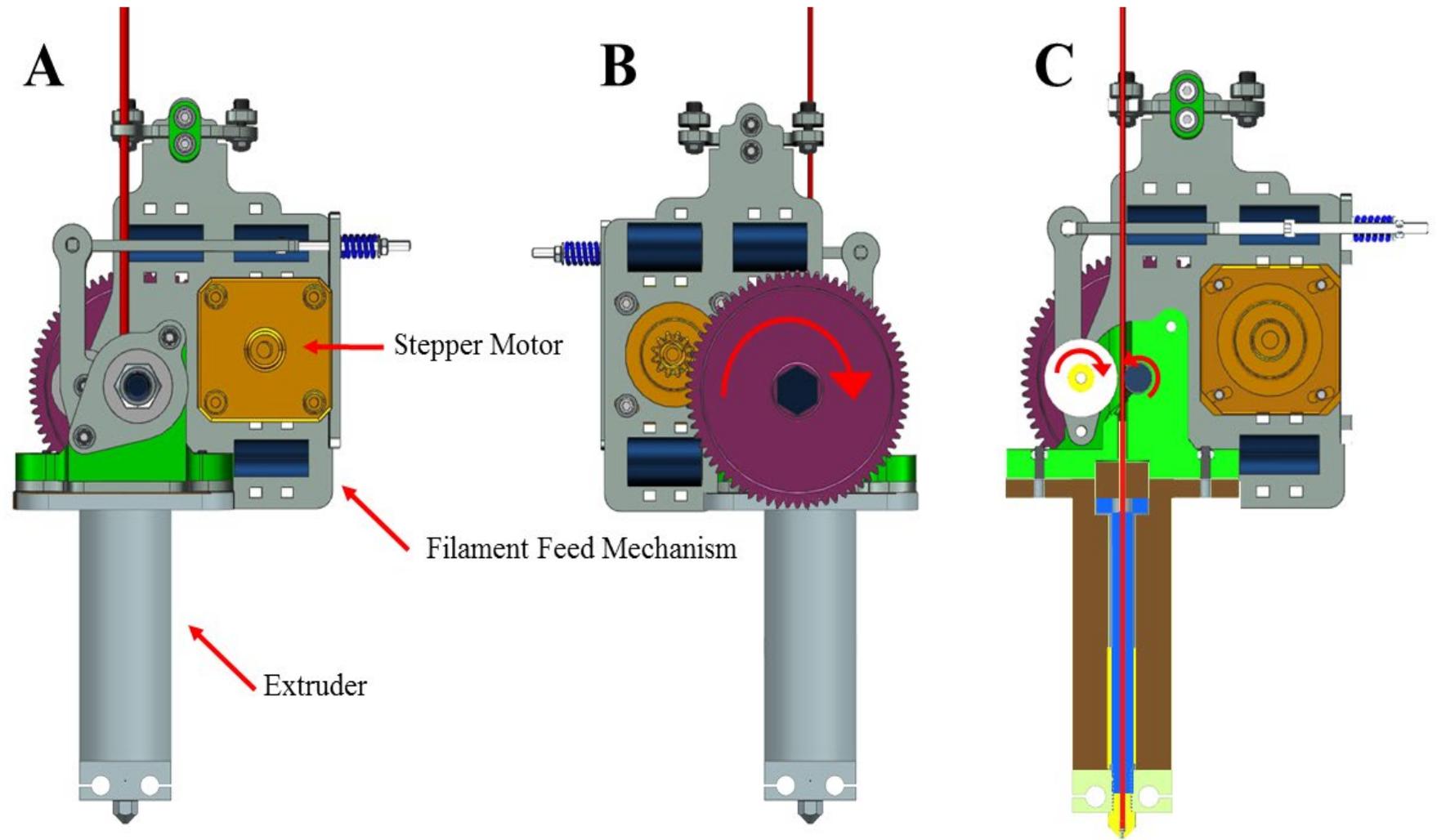
## **Ceramic Block**

Prevents any heat dissipation from the heating chamber to the system

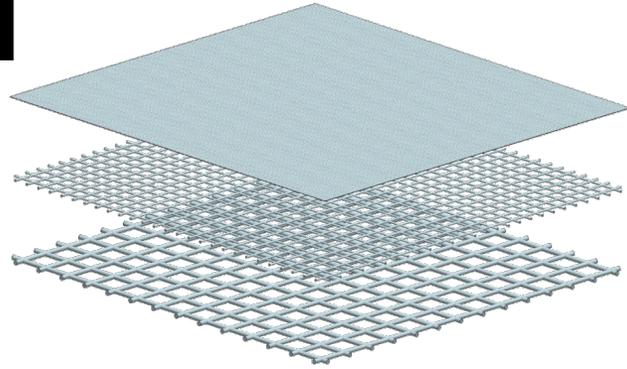


# Auto-Feed Mechanism

Filament feed and confinement during extrusion process.



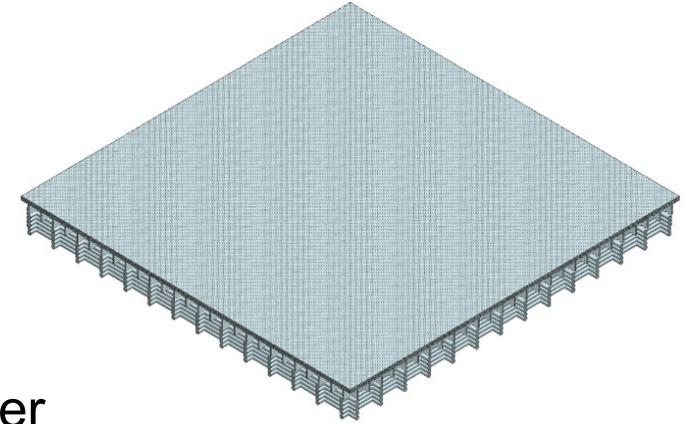
# Heat Bed



## Mesh

Material: Copper

Three different sizes will be placed layer by layer. Bottom and mid-layer will provide strength and stability. Top layer will be in contact with extruded material.



## Heat bed

Material: Copper

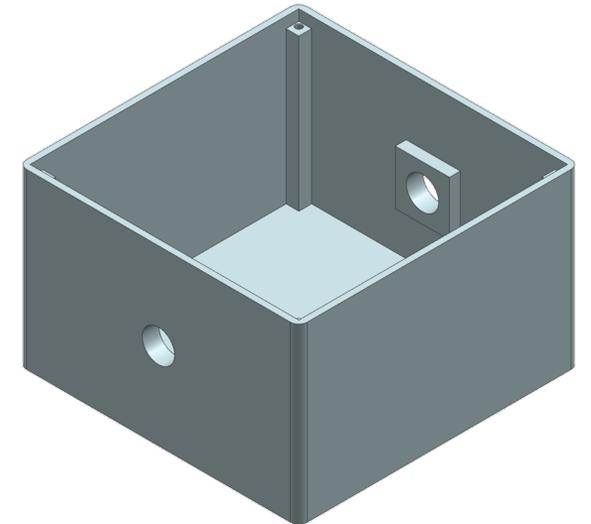
Its properties allow efficient high temperature use. Mesh will allow inert gas to flow through, as suction, to maintain extruded object in place.

## Heat bed case

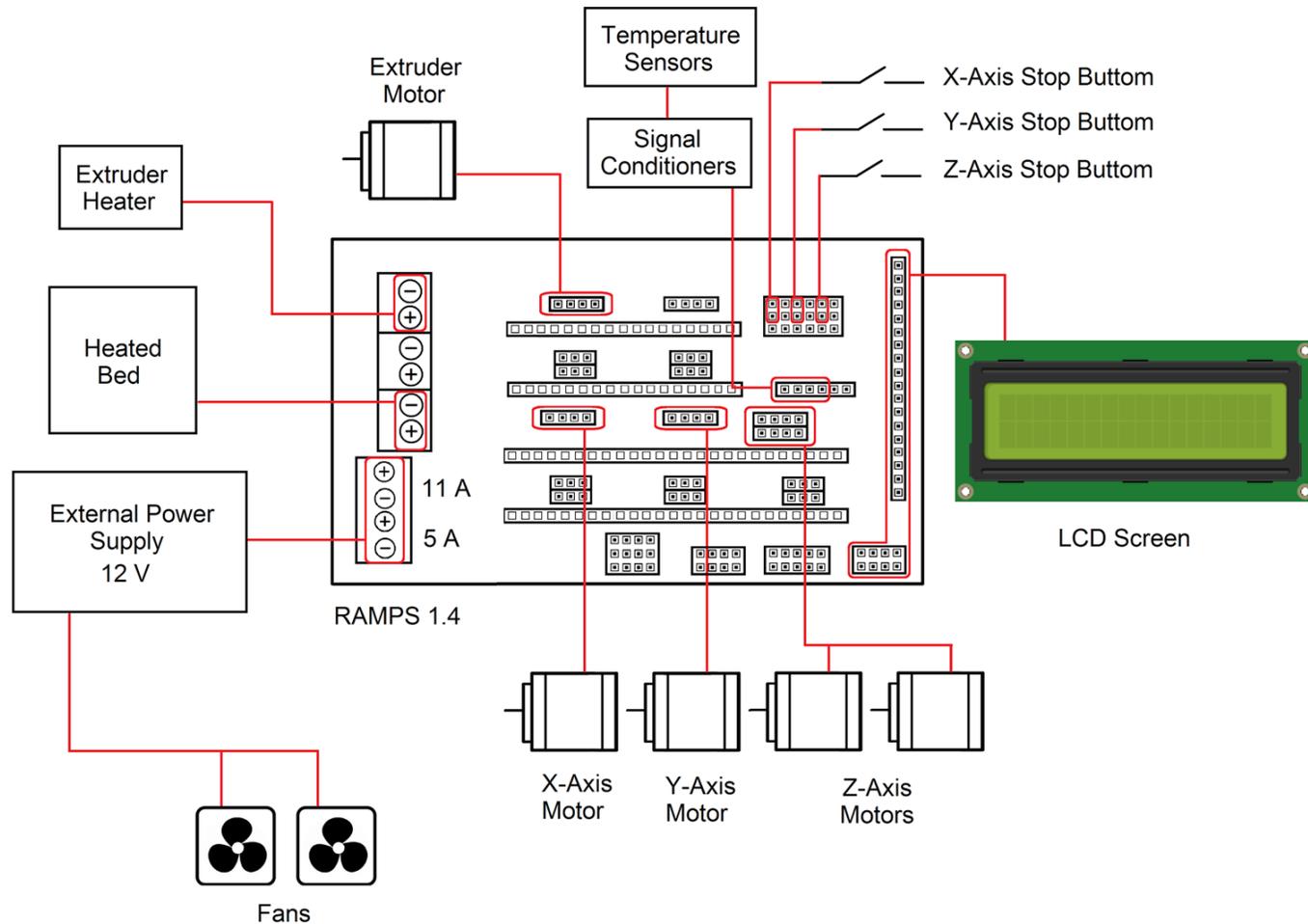
Material: Stainless steel

Will hold heat bed in place. Heating element placed inside will heat the bed.

Two pipes will be connected, at lateral sides, in order to create suction and holds material in place with the use of an air pump.



# Electrical Design Overview



## Microcontroller

- Arduino MEGA
- RAMPS 1.4 (Shield)

## Stepper Motors + Drivers (x5)

- Nema 17 Bipolar
- Hold Torque 60Ncm
- Rated current 0.64A
- 12V
- DRV8825 Stepper Motor Driver

## Thermocouple (x2)

- Sensor Temperature Range: 200 to 1250°C
- Relevant Temperature Range: 0 to 700°C

## Power Supply

- DC/DC 120/12V (480W)
- Max Current 40

## Heat Bed

- 120 V ( less than 600W)

## Extruder Heater (x2)

- 12V (40W)

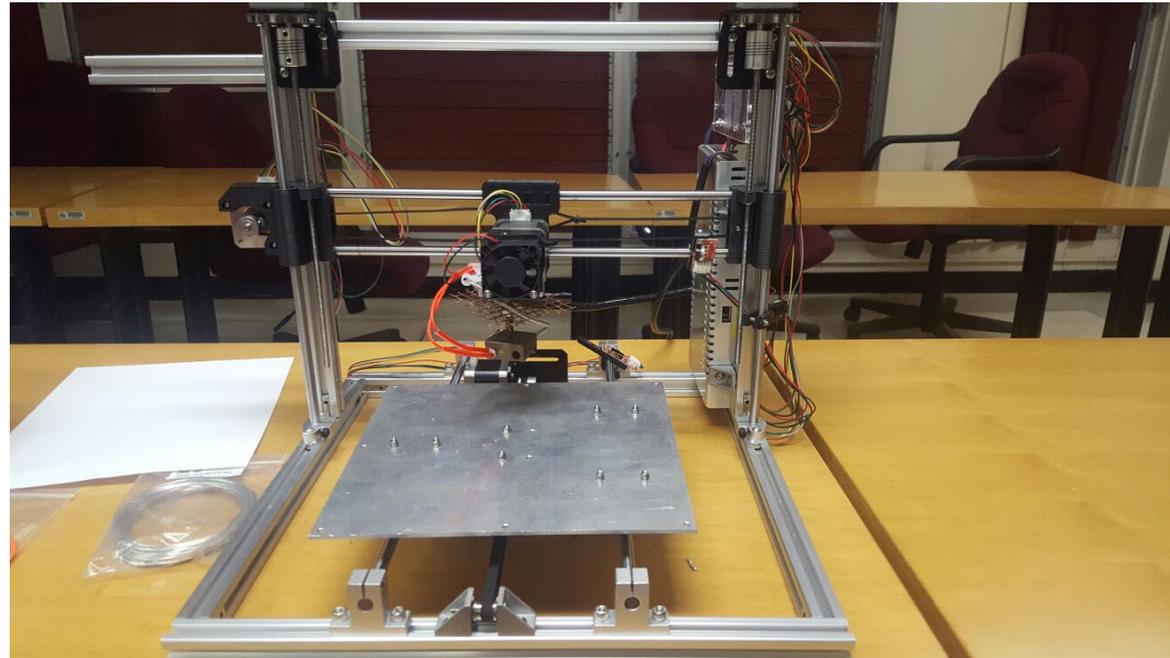
## LCD screen

- User interface

# Software

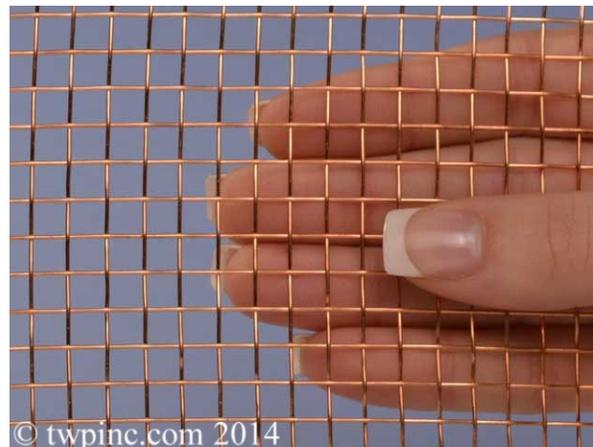
- The open source firmware implemented to the microcontroller was a modified version of Marlin
- Software team added new functionality to the following:
  - New maximum temperature threshold
  - Temperature Manager altered to compensate delayed heating
  - Marlin modified to operate with a MAX6675 Thermocouple

# Assembly and Testing



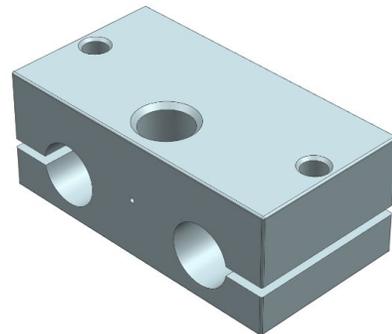
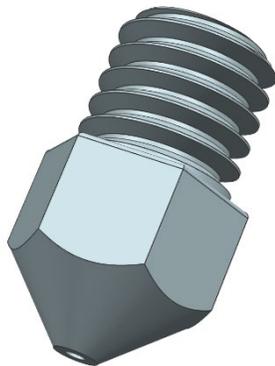
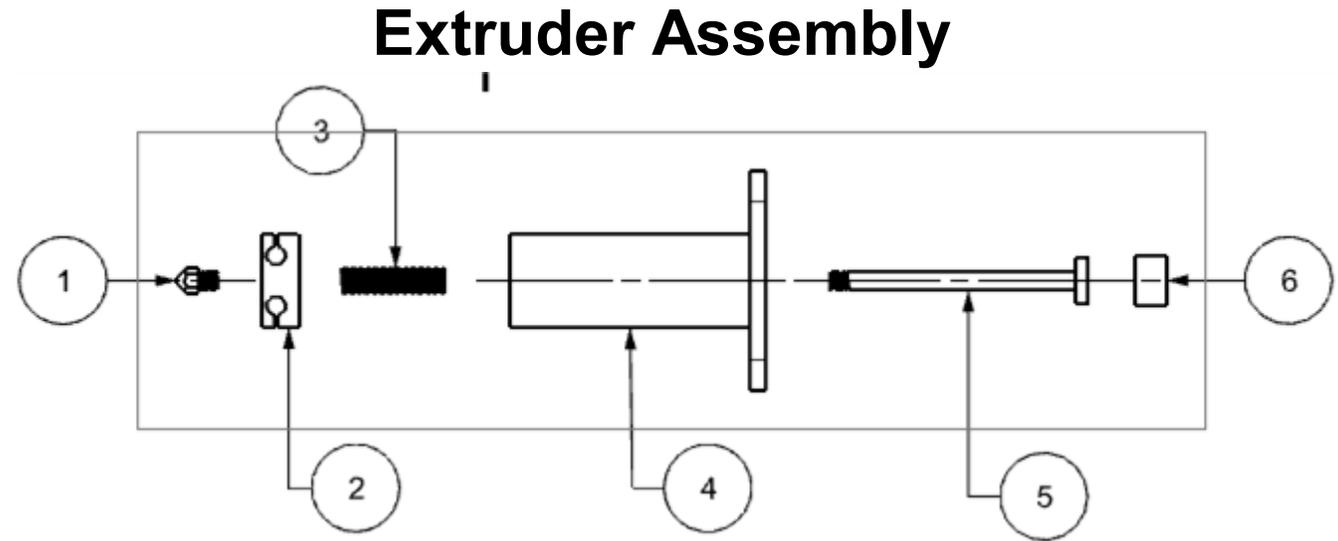
# Procured Hardware for Heat Bed

Heat Bed	
Part Number	Part
2	Membrane Mesh
N/A	Air Pump
N/A	Air Hose
N/A	Air Hose T-Connector
N/A	Air Hose Mouthpiece



# Parts Manufactured

Extruder	
Part Number	Part
5	Heating Chamber
1	Extruding Tip
2	Heating Block

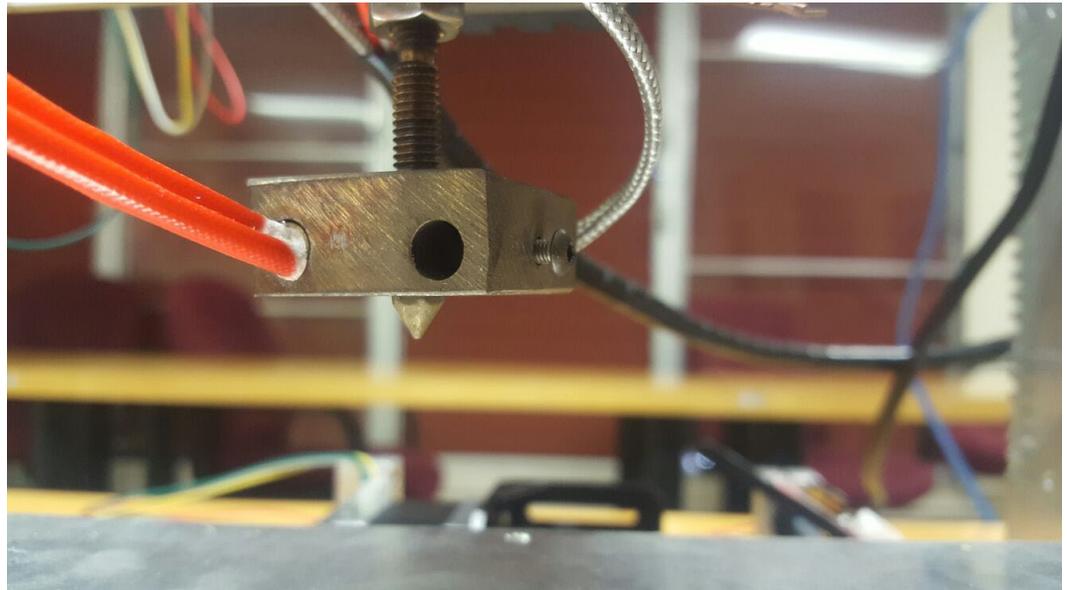


These parts were manufactured in-house from raw material.

# Prototype Extruder

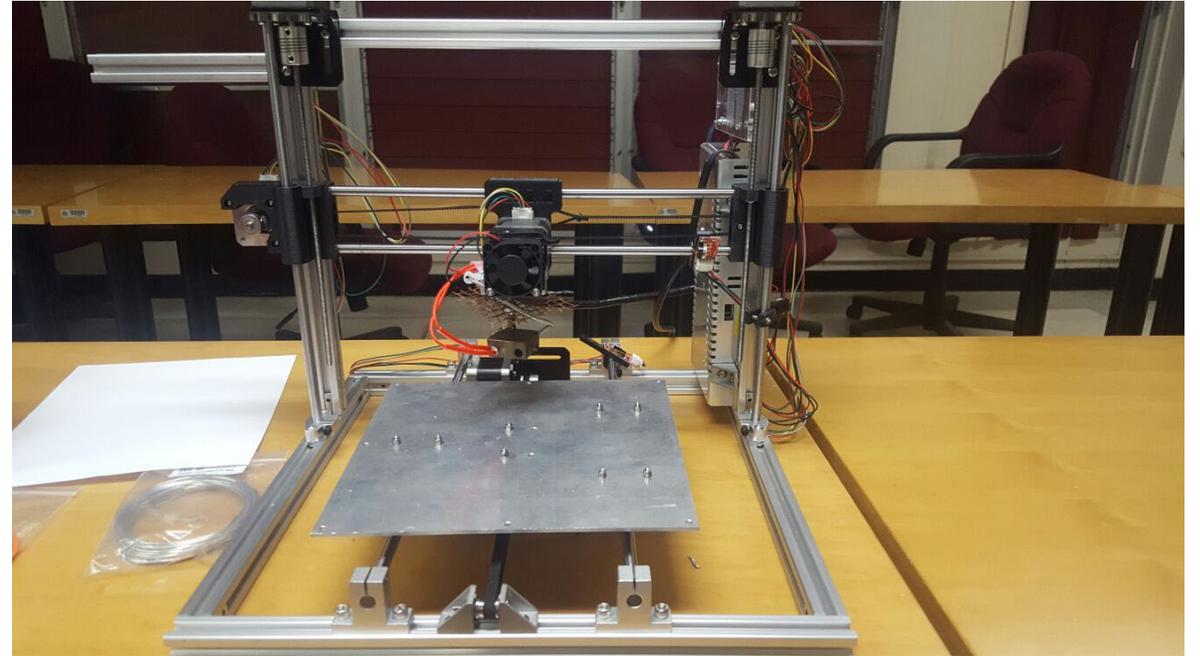
Differences from Design:

- Lack of ceramic coating to prevent heat dissipation.
- Addition of a copper mesh Heat Shield to protect electronics from high temperatures.



# Assembled Prototype

Using the framework of the acquired Prusa i3 FDM printer, we modified the extrusion mechanism and electronic circuitry to be compatible with a MAX6675 thermocouple and added a higher capacity heater cartridge.



# Test Results



## Phase I:

### **Mechanical (A)**

During tests, the axis and temperature controls of the prototype were calibrated to optimum functionality. Initial tests resulted in the Aluminum filament not melting. Subsequent tests show that the heating chamber and extruder tip dissipate heat too quickly for the aluminum to change phases. Attempts to compensate the dissipation effect by bringing the extruder temperature to 800 degrees Celsius (1,472 Degrees Fahrenheit) were not effective.

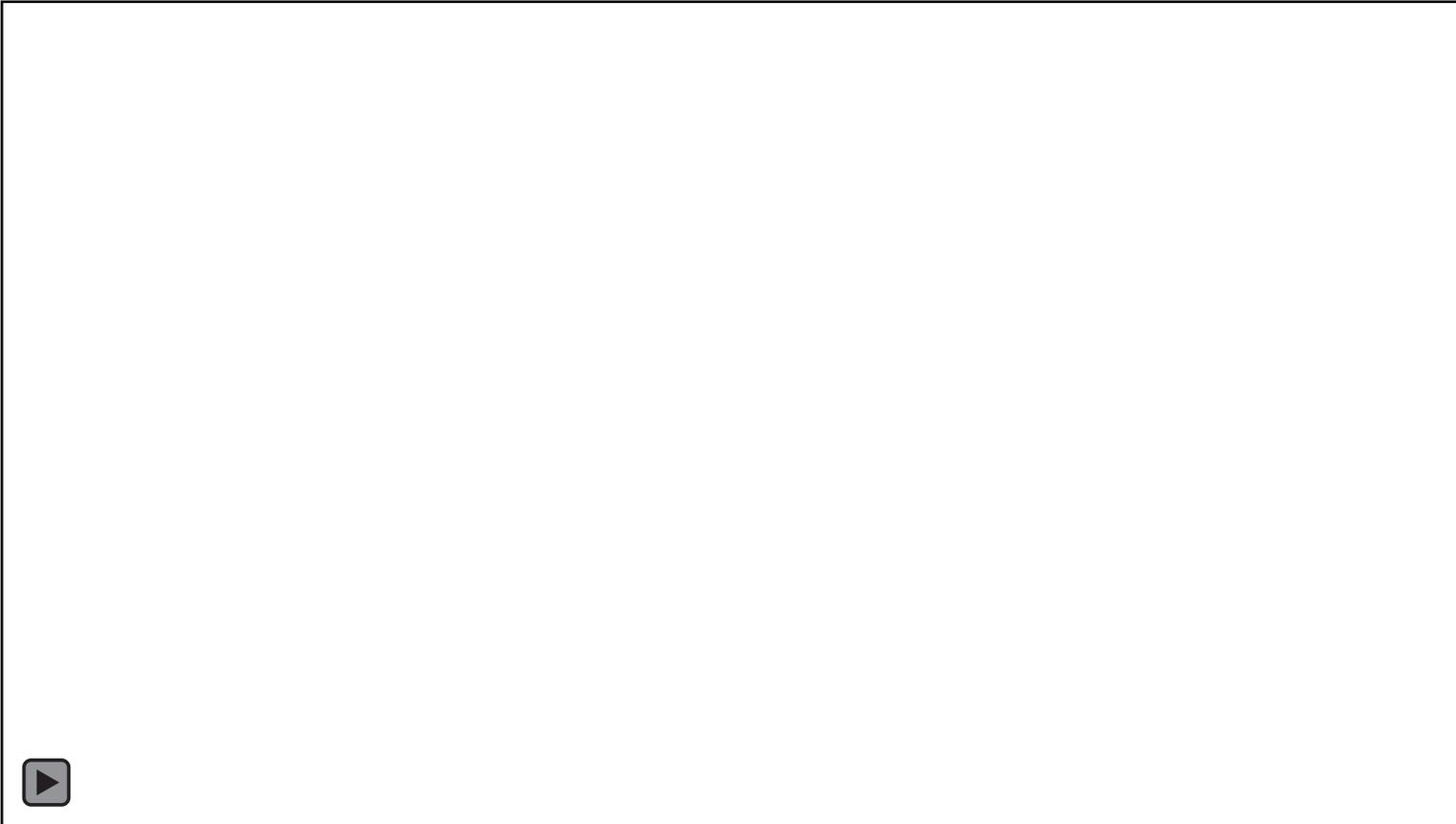
### **Software (B)**

After calibrating and modifying Marlin firmware, motion controls and temperature readings were tested with positive results.

### **Electrical (C)**

Electrical circuits were wired and connected. Power supply was able to provide necessary power without exceeding 1000 Watts (power consumed by hour was around 100 Watts). Extruder heater lagged in providing heat but reached target temperature (first 600C, then 800C) with only a small delay.

# Axis Control Tests



# Challenges

**Challenge 1:** Accelerated Heat Dissipation- As heat travels from the heater cartridge across the heat block, and into the extruder tip it dissipates into the air mainly from the extruder tip as it exposed to open atmosphere.

**Solution:** Modification to extruder tip design to minimize contact with open atmosphere and the addition of ceramic insulation.

**Action taken:** Due to time constraints and the unavailability of a ceramic insulator, thermal complementation was implemented in the form of heating the extruder an extra 200 degrees Celsius.

# Challenges

**Challenge 2 :** Delay in Heater reaching target temperature- Limitations by the power distribution of the RAMPS board lead to insufficient power to be effectively delivered to heater cartridge.

**Solution:** Rewire Power supply and RAMPS configuration.

**Action taken:** Added an external heater cartridge powered by secondary power supply, code modified to prevent execution of security measures implemented by Marlin firmware in order to proceed testing in a limited timetable.

# Acknowledgement

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# Questions and Answers

