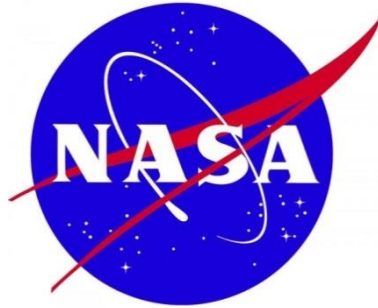




Badger COMET

Compartmentalized Onboard Material Extrusion Technology

Final Design Report

X-Hab 2014

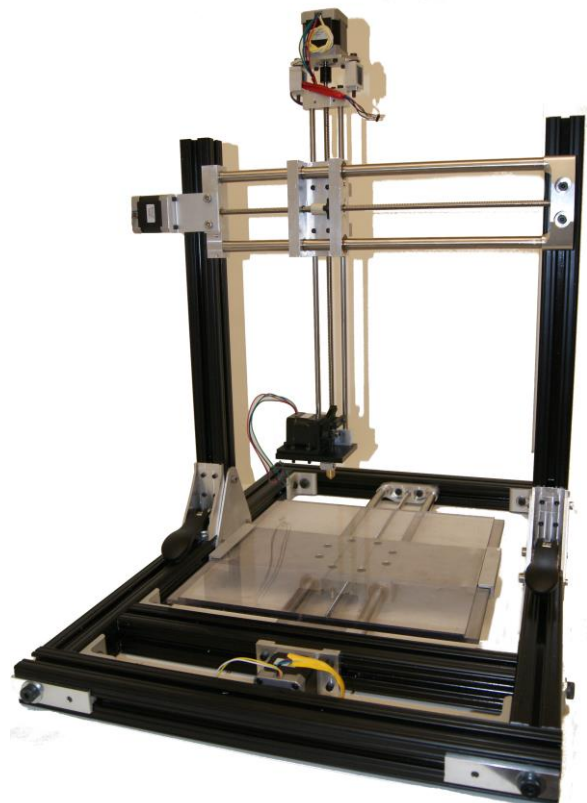
5/22/2014

Faculty Advisor

Dr. Frederick T. Elder

Graduate Teaching Assistant

Ryan Knippel



Executive Summary

In response to the 2014 NASA Academic Innovation Challenge, the University of Wisconsin – Madison team presents the design of a collapsible Fused Deposition Modeling (FDM) system for *in situ* manufacturing in a space habitat environment, the Badger Compartmentalized Onboard Material Extrusion Technology (COMET).

The proposed mechanism incorporates one year of design and testing on an array of current additive manufacturing techniques, with the goal of providing a reliable and maintainable manufacturing solution. Seven Level 1 requirements were employed to guide the design process, based on information in the challenge, communications with NASA, and the evolving systems feedback of project work groups. These requirements provided a baseline for the development of the System Requirements Document (SRD, Appendix I), which framed the design of the system. The design requirements deemed critical to the success of the systems are as follows:

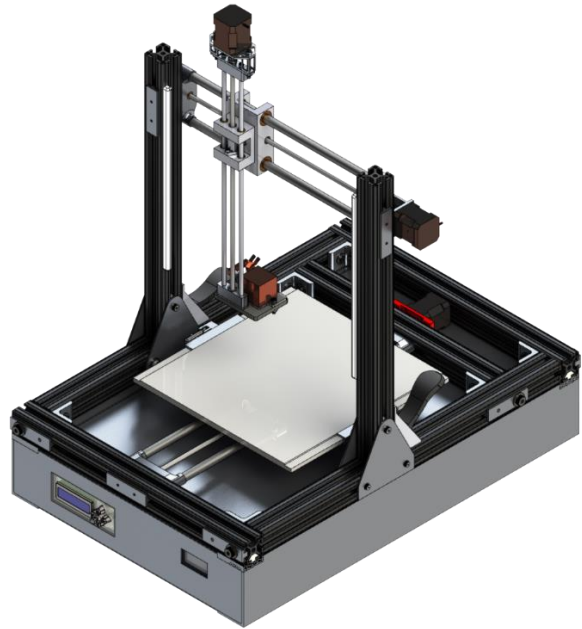


Figure 1: Badger COMET Top Level Design

- **The system shall compose an FDM workstation capable of producing parts within industry standard tolerances.**
- **The system shall reduce to a minimum of 50 percent or less of its deployed volume when not in use, and must collapse without the need for disassembly.**
- **The system shall meet all relevant NASA safety and functional standards.**

The final design for the Badger COMET was selected from multiple design iterations, which balanced the critical design requirements listed above with system reliability, with the final goal of providing a minimal system weight.

The system collapses in the vertical direction, allowing for a maximum reduction in volume. Guide rods and precision, anti-backlash lead screws provide all linear movement in the device. Stepper motors were chosen to actuate each system axis, due to their high precision and repeatable accuracy. The system is controlled through an on-board computer system and embedded electronics package.

Team Members

Sara Beyer – Senior
B.S Electrical Engineering

Tyler Bream – Graduate
B.S Electrical Engineering
B.S Computer Science
B.S Mathematics

Reid Carlson – Graduate
B.S. Engineering Mechanics & Astronautics
B.S. Economics

Skylar Dhaese – Junior
B.S Engineering Mechanics & Astronautics

Sean Kelly – Graduate Student
B.S. Engineering Mechanics & Astronautics

Benjamin Lange – Graduate
B.S Engineering Mechanics & Astronautics

Jake Ptaszynski – Junior
B.S Engineering Mechanics & Astronautics

Alex Schwartz – Graduate Student
B.S. Engineering Mechanics
B.S. Computer Science

Casey Sennott – Graduate
B.S Engineering Mechanics & Astronautics

Erik VanderSanden – Senior
B.S Engineering Mechanics & Astronautics

Steve Wishau – Graduate
B.S. Engineering Mechanics & Astronautics

Andrew Witzmann – Junior
B.S Engineering Mechanics & Astronautics

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System Level Trade Study

A comprehensive investigation and literature review of the current state-of-the-art in additive manufacturing was performed by the Badger COMET team. The goal of this system level trade study was to identify an additive manufacturing methodology suited to the applications discussed above.

Current additive manufacturing systems consist of a mechanism for depositing or curing material in a build area, thereby constructing a desired component. Conventional systems use a solid model, or computer generated image of a component, to generate a mechanical actuation sequence for the printing mechanism. This allows the system to function in a very similar fashion to a CNC machine tool.

Specialized additive manufacturing systems are capable of manufacturing exotic materials, such as artificial human tissue (Maxey, 2012). The majority of current systems, however, produce components from conventional engineering materials, include an array of plastic polymers and metals. The advantage of additive manufacturing is its ability to produce structures that are almost impossible to manufacture using traditional techniques (Waldo, 2012). This versatility makes additive manufacturing an attractive platform for *in situ* manufacturing during future space exploration missions.

Comparison of Polymer and Metallic Additive Manufacturing Systems

Typically, in metallic manufacturing systems, metallic powder is used to build up the part by raising the temperature of the base print materials in order to melt it. Most metals require temperatures greater than 1000°C for processing. This requires significant heat shielding, insulation, temperature, and atmospheric control compared to polymer systems (Gibson, 2010). Materials can range from low density titanium powders to high density steels, requiring the powder storage and positioning to be capable of handling large masses.

Polymer and metallic additive manufacturing systems are typically capable of similar component accuracy (Gibson, 2010). However, metallic systems can leave grainy surface finishes (Gibson, 2010). Metallic manufacturing systems must both heat the material to a high temperature and move the heavier metal, and thus require more energy when compared to polymers. These characteristics also result in metallic systems being slower than polymer based printing systems when building parts of equivalent size. Laser-based systems have high initial cost and upkeep. The lifetime of lasers used in additive manufacturing can be as low as 4000 operating hours (Gibson, 2010), which would require repair parts to be launched and then stored on station for long-term use.

Polymer based additive manufacturing systems have benefits over metal based systems for the *in situ* application of the Badger COMET. Polymers have a substantially lower processing temperature than metal, thus allowing for a reduction in system size, complexity, and weight.

Additive Manufacturing System Classifications

Additive manufacturing systems can be classified by the printing material or the method of material deposition. The use of a single material source that is moved across the surface of an object to build up the layers is referred to as a *1D Channel*. Multiple 1D Channels can be included to improve printing performance and are referred to as *N x 1D Channels* or an *Array of 1D Channels*. Furthermore, *2D Channels* can print over a surface with each pass. Materials used in additive manufacturing can be categorized in many ways due to their wide range, but an accurate way to categorize them includes four classes: liquid polymer, discrete particles, molten material, and laminated sheets.

Using these printing methods and materials as selection categories, Figure 2 summarizes current additive manufacturing technologies.

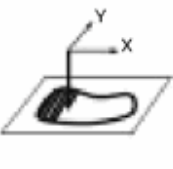
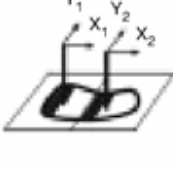
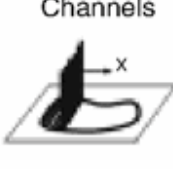
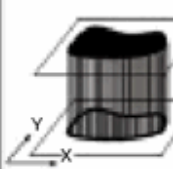
	1D Channel	2x1D Channels	Array of 1D Channels	2D Channel
Liquid Polymer	 SLA (3D Sys)	 Dual beam SLA (3D Sys)	 Objet	 Envisiontech MicroTEC
Discrete Particles	SLS (3D Sys), LST (EOS), LENS Phenix, SDM	LST (EOS)	3D Printing	DPS
Molten Mat.	FDM, Solidscape		ThermoJet	
Solid Sheets	Solido PLT (KIRA)			

Figure 2: Additive Manufacturing Technologies categorized by printing method and material. Source: Additive Manufacturing Technologies (pg. 28) by Ian Gibson.

Some of the most common additive manufacturing methods referenced in Figure 2 are described in detail below:

- **Stereolithography (SLA)**

Stereolithography utilizes photo-polymerisation of liquid resin to lay down a layer of material. Once each layer has cured, an additional layer is added to build up a three dimensional part. To accomplish this, light is projected onto a layer of resin, curing the material. The thickness of each layer is determined by the energy of the light to which it is being exposed. After the part has been created, the part must have excess resin washed off. Post-curing with ultraviolet light finishes the converting (Melchels, Feijen, & Grijpma, 2010). Materials that work well in SLA are able to cure quickly upon exposure to light. Materials that are available for stereolithography are typically glassy, rigid, and brittle with few having elastic characteristics (Melchels, Feijen, & Grijpma, 2010).

- **Selective Laser Sintering (SLS)**

SLS “fuses thin layers of powder that have been spread across the build area” (Gibson, 2010). Typically, the layers of powder are spread across the print area by a leveling roller. The process must take place inside a chamber of nitrogen gas to prevent oxidation of the powder material. The powder is also kept just below its melting point and/or its glass transition temperature to minimize laser power requirements and prevent warping due to temperature gradient (Gibson, 2010). The surrounding, un-fused powder is kept around the built up product to serve as support. Once the part is built, it is allowed to cool for safe handling and removed for any other finishing operations or use.

- **Paper Lamination Technology (PLT)**

PLT uses paper as the build material along with a laser printer to apply a resin powder where bonding is desired (Gibson, 2010).

- **Fused Deposition Modeling (FDM)**

FDM heats a polymer filament and places the polymer across the surface of the part with an extruder head. FDM machines can be scaled up or down in size to fit the printing needs of the customer. Additionally, machines can be made to handle only one or many types of materials. FDM machines work well with polymers that are amorphous, meaning they have no specific melting point, but rather increase in softness and viscosity as heated (Gibson, 2010). Many FDM machines use ABS materials that have tensile strengths ranging from 22 MPa to 27 MPa (Gibson, 2010). Higher tensile properties can be achieved with PC-based materials (Gibson, 2010). Limitations in FDM technology include the inability to draw sharp internal or external corners due to the round nozzle head. Additionally, the final product exhibits anisotropic material properties, with the direction perpendicular to each printing surface having lower strength.

Among these options, the Badger COMET team chose FDM as the reliable manufacturing methodology that met the requirements of NASA’s mission. A detailed description of the Badger COMET FDM system is included below.

Material Choices for Fused Deposition Modeling

FDM provides several manufacturing material options. Commonly used materials and their mechanical properties are summarized in Table 1 below.

Table 1: FDM Manufacturing Material Properties

Material	Elastic Modulus [ksi]	Tensile Strength [ksi]	Specific Gravity	Processing Temp [F]	Percent Strength of 6061-T6
ULTEM 9085	322	10.4	1.34	600+	24.76%
ABS	329	5.2	1.04	350	12.38%
PLA	330	9.8	1.2	250	23.33%

The Badger COMET team selected PLA as the primary printing material, due to its low processing temperature and ubiquity in the desktop additive manufacturing industry. Additional information on manufacturing material properties has been included in Appendix V.

System Architecture

System Overview

Badger COMET supplies NASA's space habitat with an additive manufacturing device capable of accurately producing necessary parts for sustainable living onboard the habitat. When not in use, Badger COMET stows in a compact configuration. The design includes component storage containers, launch restraint systems, detailed system maintenance instructions, and replacement components. Badger COMET provides NASA with the option of printing replacements for failed parts. This method saves space, mass, and cost when compared to departing earth with replacement parts for all components.

Electrical and Programming Subsystems

A fully-integrated, embedded electronics system operates and controls the entire device. All aspects of motion are controlled through a central microprocessor, converting standard G-code into operational controls for the motors, extruder head, and fans, as well as monitoring system temperature and maintaining safety functions. The user interface consists of a simple Liquid-Crystal Display (LCD) panel.

The user controls the interface with a 4-direction interaction pad and two selection buttons to facilitate USB interaction for uploading G-code files, seen in Figure 3. This interface facilitates operation of the machine, selects files and parts to create, recalls previous projects through embedded memory, and manages error handling procedures.

Compartmentalization Design Subsystem

The base structure and axes subsystems manage the subsystem folding mechanisms, as well as system storage. Badger COMET in its collapsed configuration is shown in Figure 4. Badger COMET is a free-standing additive manufacturing system that collapses to approximately 35 percent of full volume when not in use.

Extruder Design Subsystem

The Extruder Module subsystem encompasses all mechanical components directly related to the heating and extrusion of the print material onto the print surface. This includes the heating element, extrusion nozzle, temperature sensors, and filament feed system.

Extruder Actuation Subsystem

The extruder actuation subsystem includes all aspects of the mechanical system related to movement of the extruder module during operation. This includes actuation of the extruder module in three axes, as seen in Figure 3.

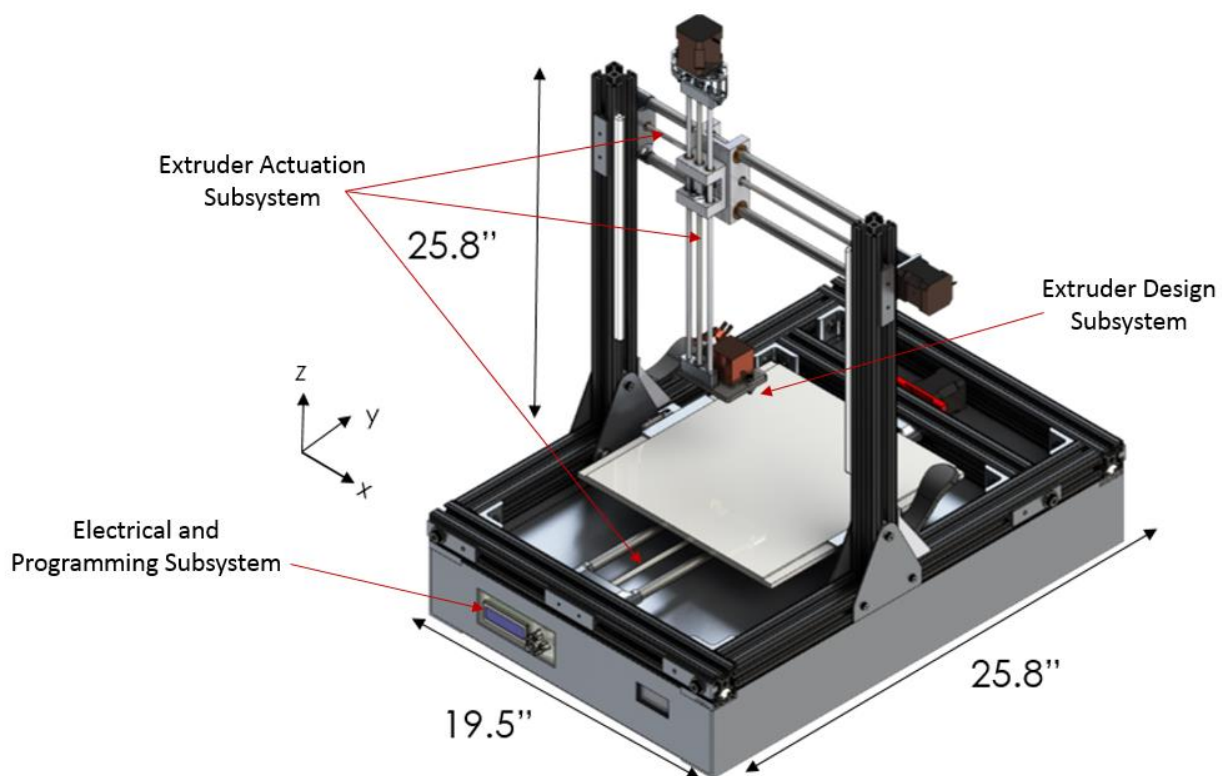


Figure 3: Deployed Badger COMET

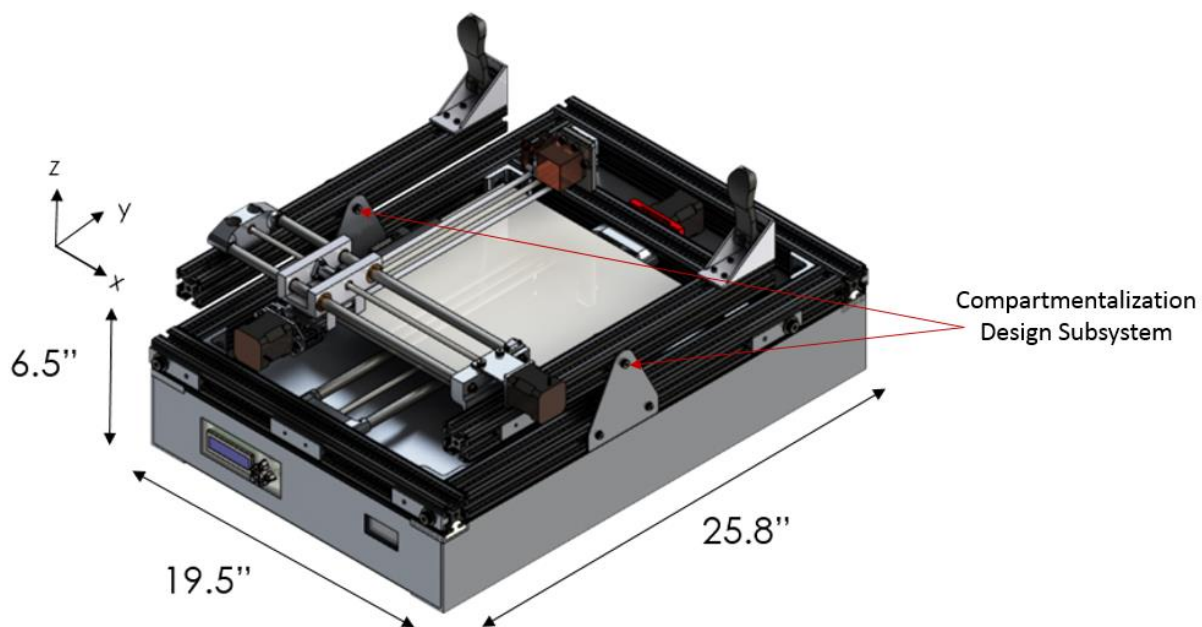


Figure 4: Collapsed Badger COMET

Level 1 Requirements

The following Level 1 requirements have been identified through NASA project requirements and manufacturing feasibility studies.

Requirement 1

Description:

Provide a functional 3D printer with a print volume of 11 in x 12 in x 11 in.

COMET:

System design produces a print volume meeting this requirement.

Requirement 2

Description:

Printer should produce components with an average dimensional tolerance less than 250 microns.

COMET:

System design and extruder actuation produces a print resolution meeting this requirement.

Requirement 3

Description:

The deployed printer has the ability to reduce its volume by at least 50 percent when collapsed.

COMET:

Design produces a 65 percent reduction in volume when stowed.

Requirement 4

Description:

The printer shall deploy and stow safely.

COMET:

Mechanical design includes manual deployment, mechanical locks, and stowage with limited complexity, meeting this requirement.

Requirement 5

Description:

The system will have a maximum mass not exceeding 27 kg.

COMET:

Design has a total system mass of 14 kg.

Requirement 6

Description:

NASA safety standards, outlined in NASA-STD-3001, have been prioritized and assessed to limit associated risk.

COMET:

A database of relevant NASA safety standards has been compiled and cross referenced with related design subsystems in Appendix I: System Requirements Document. The primary safety standards in consideration are NASA-STD-3001 Volumes 1 & 2 and NASA-STD JSC2058-4 and are met with regard to system design.

Requirement 7

Description:

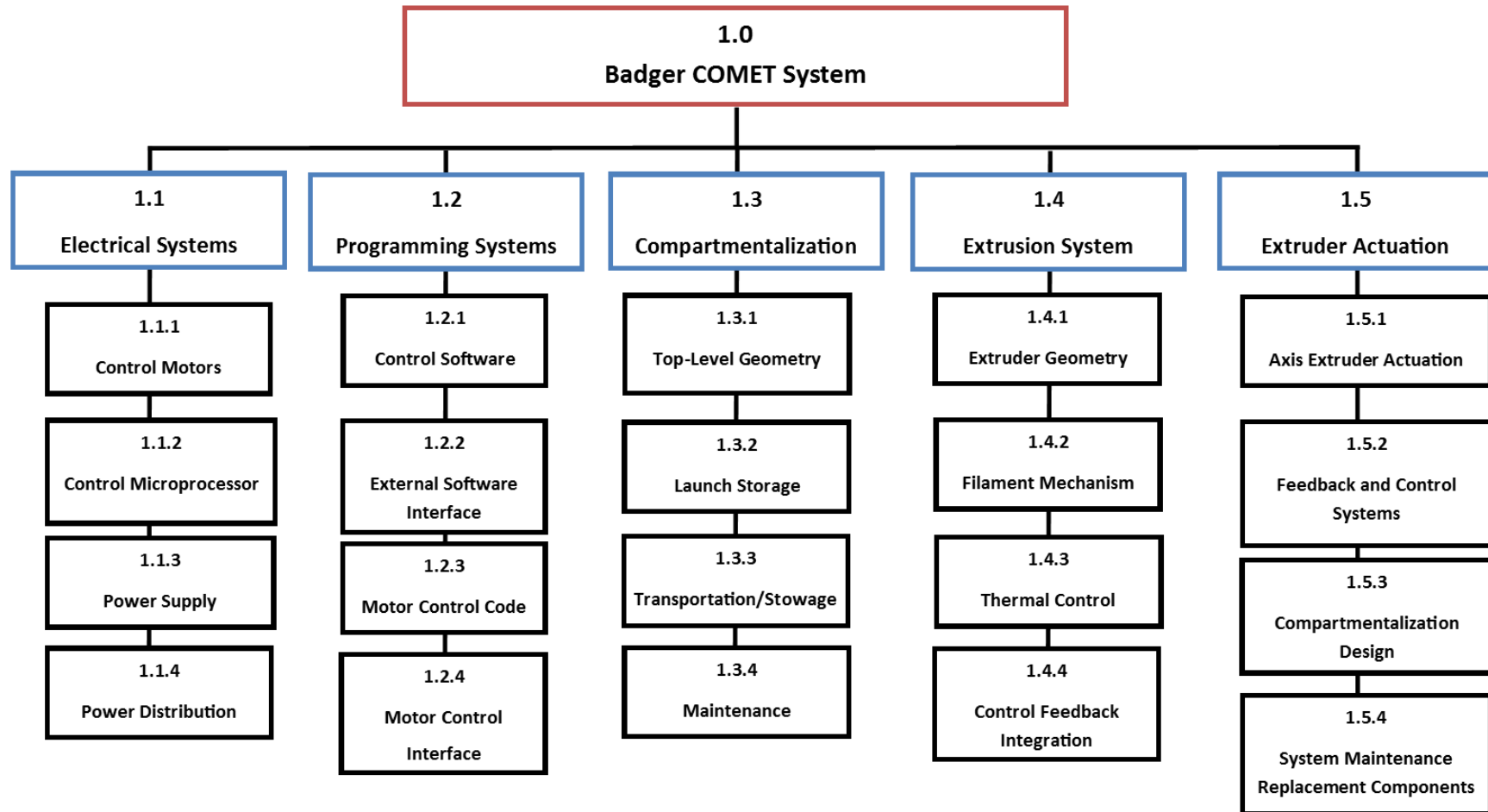
Provide on-system storage for printer feedstock.

COMET:

Design allows for on-system storage of printer feedstock.

Work Breakdown Structure

Figure 5 illustrates the Badger COMET work breakdown structure.

*Figure 5: Work Breakdown Structure*

System Functional Baseline

Figure 6 describes the system functional baseline. This chart illustrates each major subsystem and its individual components, as well as the top-level interconnectivity of the system.

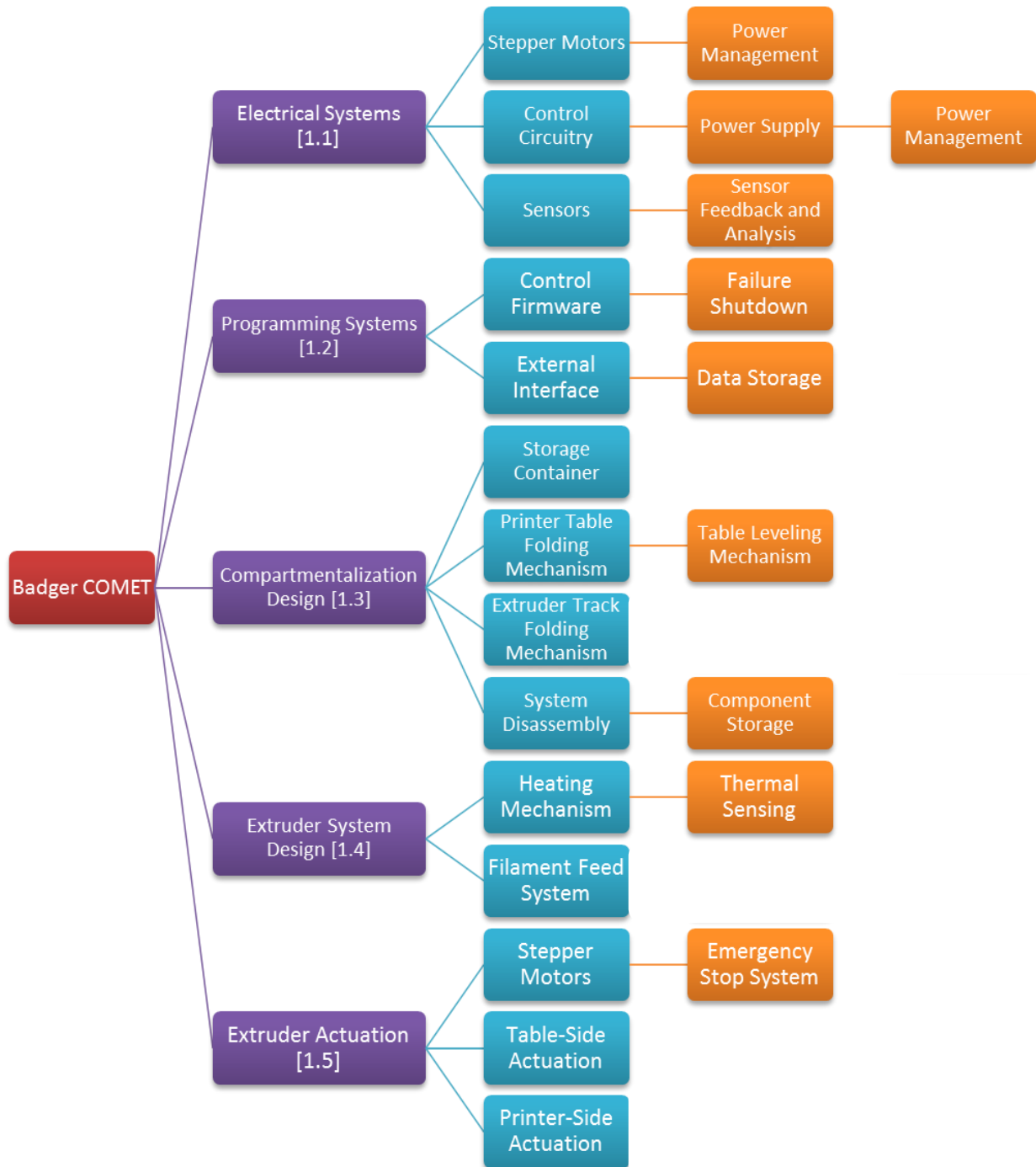


Figure 6: System Functional Baseline

Concept of Operations

The Badger COMET operational life cycle includes launching from Earth, deployment from its collapsed configuration, printing of parts, and returning into its stowed configuration. Figure 7 displays the order and relationship between these states.

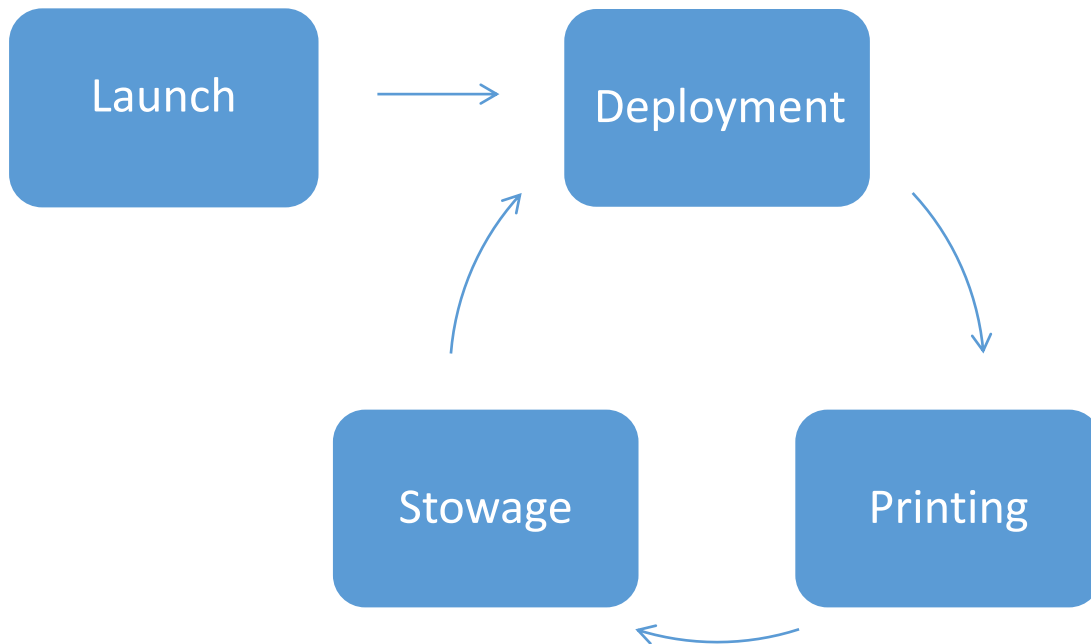


Figure 7: Operational Life Cycle

Launch

During transport from Earth to orbit, Badger COMET maintains its collapsed state and stores inside a transport case that protects all components.

Deployment

To deploy the printer, the user moves the upright frame forward from its stowed position to the base-frame hinges. The user then rotates the upright frame ninety degrees so that it is perpendicular to the base-frame. The upright frame affixes to the base using quick release hinges located on both sides of the base-frame. Once the printer locks into position, the filament feeds to the printer and the user can begin printing.

Printing Activity

To begin printing, the user inserts the STL file through the Universal Serial Bus (USB) and initiates printing through the LCD and buttons. The firmware system validates the print file and checks all connections are secured properly. Once printing completes, the user removes the part from the printer surface.

Stowing

When the print is complete, Badger COMET stows by reversing the procedure for deployment. After detaching the filament feed, the upright frame unlocks from the base-frame via the quick-release hinges. The user rotates the upright frame downwards, creating a parallel position with the base-frame.

Base Structure

The base structure provides a rigid bottom assembly for maintaining stiffness for the entire system. The primary structural components (hollow aluminum 15-series profile T-slotted 80/20[®]) fasten through the use of corner brackets, T-slot blocks, and shoulder bolts, as seen in Figure 8.

Several features assist in the attachment and protection of other subsystems. The y-axis precisely fits within the internal structure of the base, with a notch providing the exact location for the linear actuator and an enclosed area for the attached motor. The x- and z- axis vertical beams hinge on the brackets attached to the sides of the base. Between the hinge brackets, notches machined into the 80/20[®] provide an indexing location for the vertical beams, seen in Figure 9.

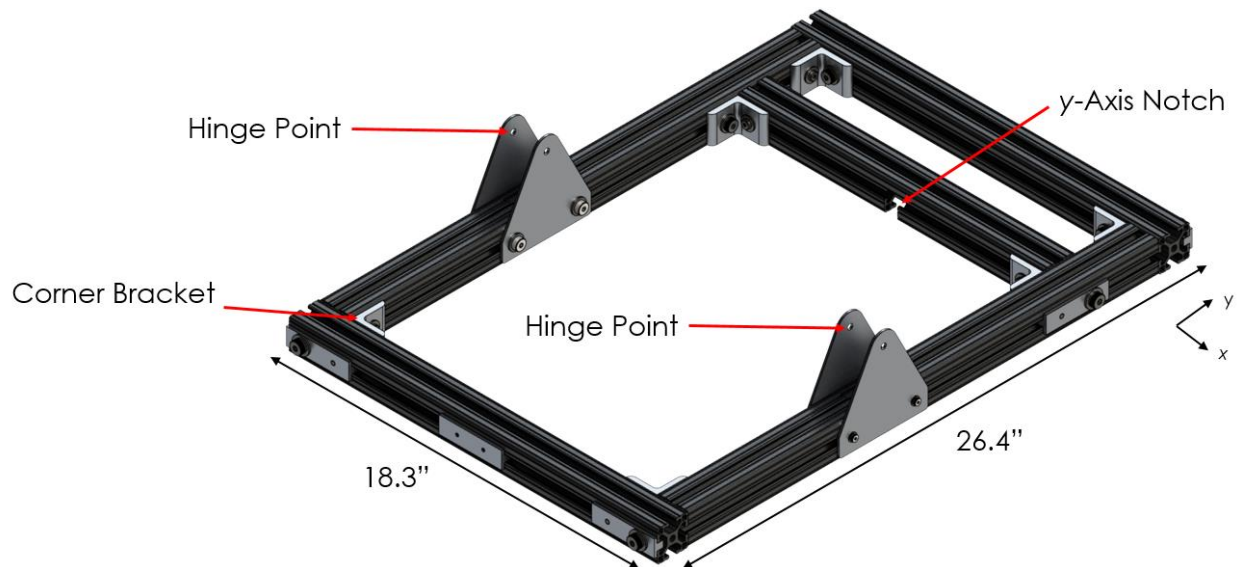


Figure 8: Base Structure Assembly



Figure 9: Vertical Beam Notch

y-Axis

The y-axis governs all motion of the print surface. A NEMA 17 stepper motor, shown in Figure 10, attaches to the base structure through a mounting plate. This motor controls the actuation of the y-axis subsystem through a lead screw linear actuator. Traced back to the base structure, the 80/20[®] piece shown in the figure contains the notch through which the lead screw travels.

Linear motion guides the print surface carriage through an attached underlying lead screw bracket, shown in Figure 11. Two linear guide rods, also seen in Figure 10, maintain parallel and near-frictionless carriage movement with oil-impregnated bushings inserted in the carriage. End stops prohibit the carriage from contacting the base structure and causing damage to the print surface.

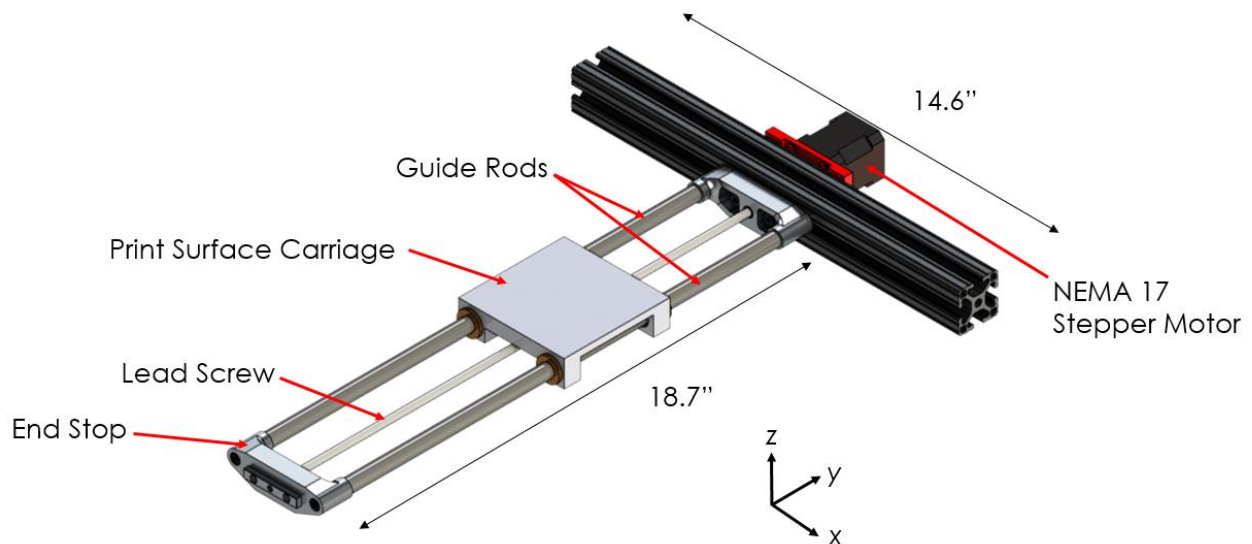


Figure 10: y-Axis Assembly

Lead Screw Bracket

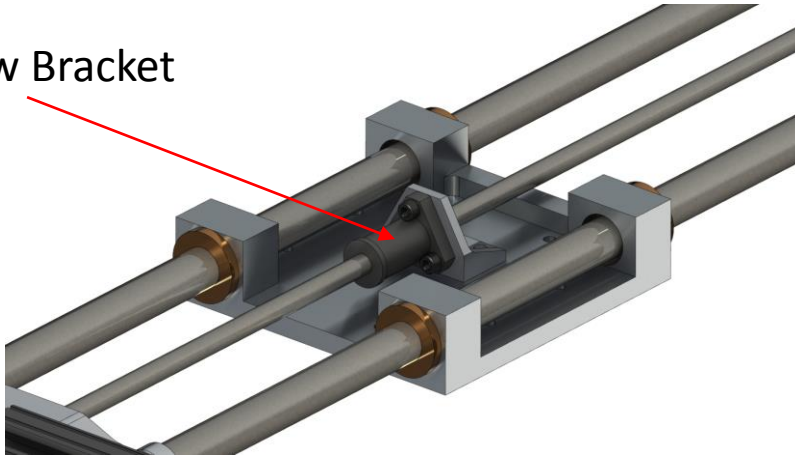


Figure 11: Lead Screw Bracket

Print Surface

Extensions from the y-Axis carriage in Figure 12 provide an attachment method for the print surface. The print table, Figure 13, slides into the print surface extensions until the indexed location is reached. To ensure the print table remains in the same location for every print, grooves on the table flanges lock into the upper portion of the extension slot. The encircled red area in Figure 13, the print surface clamping method, is detailed in Figure 14.

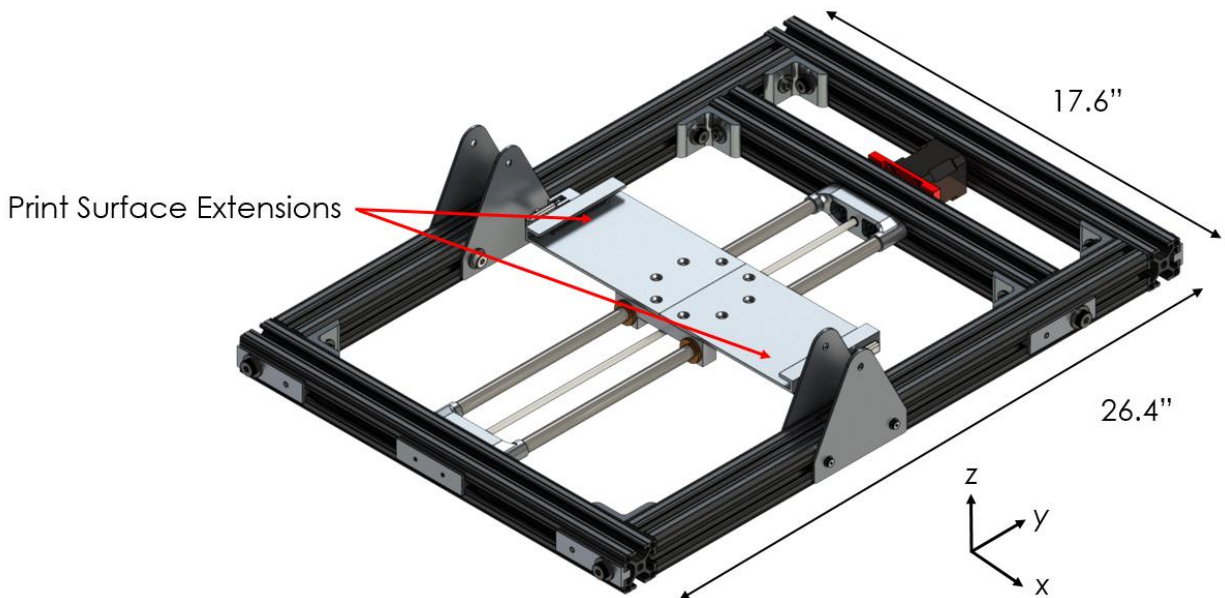


Figure 12: Print Surface Attachment

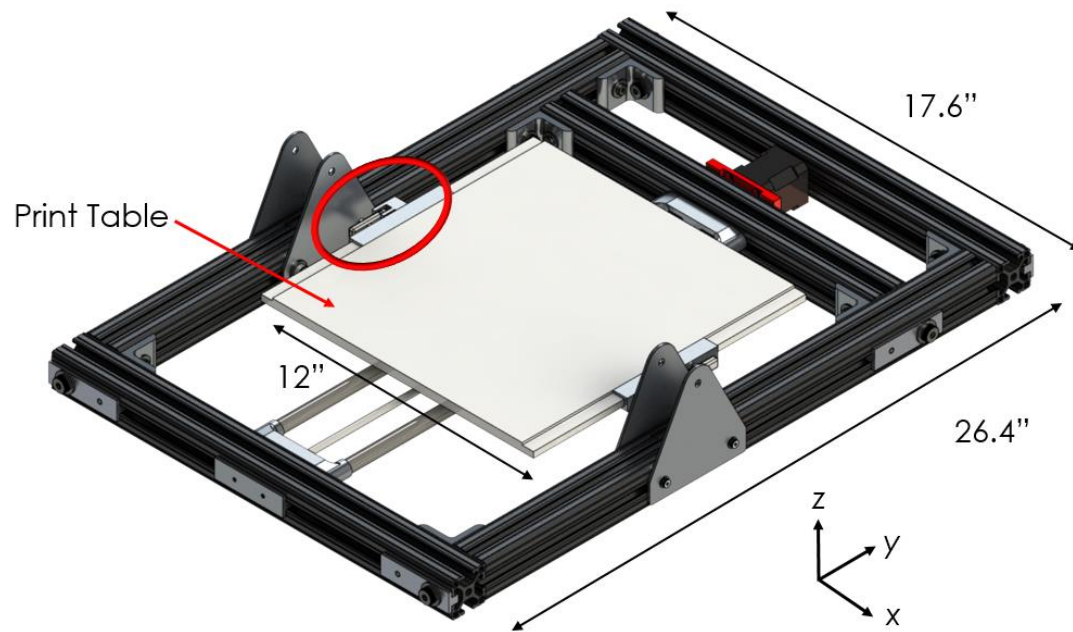


Figure 13: Print Table

Each print surface extension contains a rigidly attached clamp for locking the print table into place. In addition to the localized grooves on the print table matching the extrusion profile, noted in Figure 15, the clamps provide an upward force to lock the table in precisely the same location for each deployment. As the clamps maintain geometric symmetry and apply equal forces on each side of the table, leveling the surface is not required.

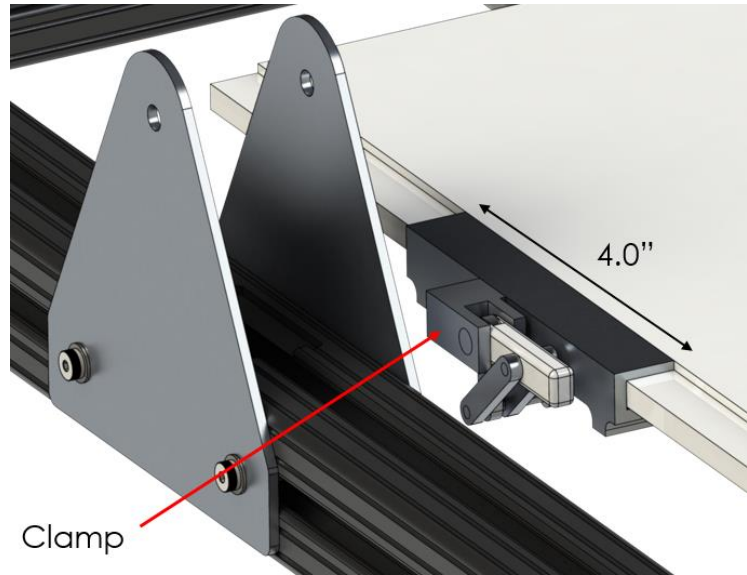


Figure 14: Print Surface Clamp

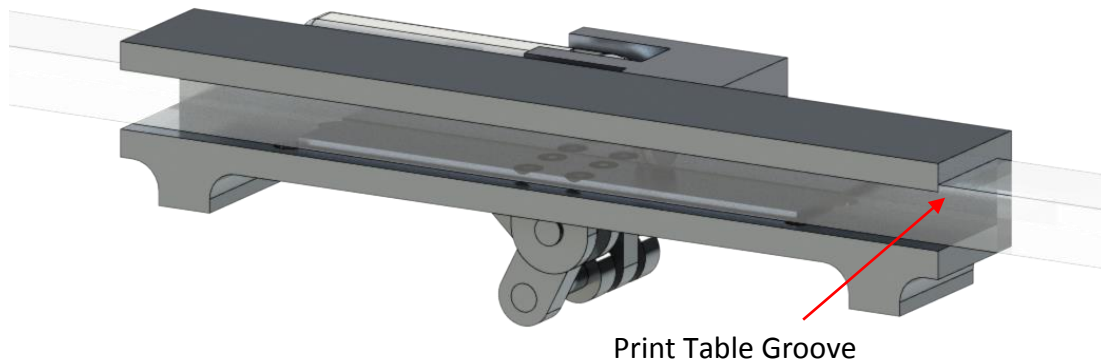


Figure 15: Print Table Grooves

x-Axis

The x-axis translates motion of the extruder module across the print surface. Similar to the other axes, an anti-backlash lead screw drives the axis with linear guide rods, seen in Figure 16. Lead screws with guide rods, proven technology that holds high tolerances, allows for a high tolerance print resolution. The rod holders and end-stops maintain uniform distance between the rods over the span of the x-axis. The motor-to-lead screw shaft alignment must remain perfectly axial, otherwise torque from the motor and lead screws causes failure and jamming of the subsystem; this is prevented via a custom motor mount.

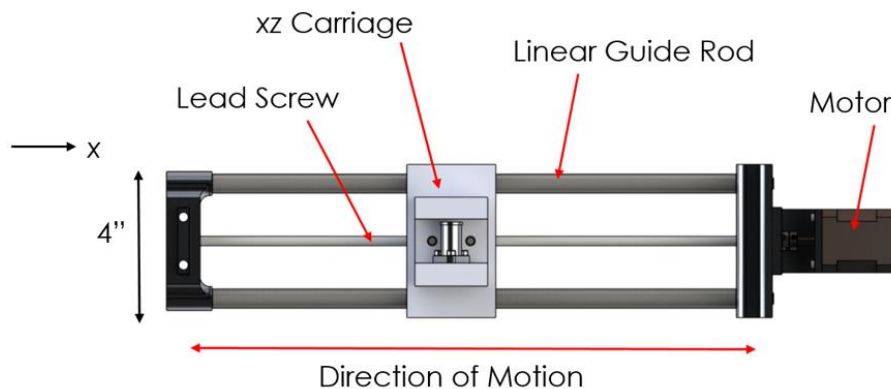


Figure 16: x-Axis

Quick release hinges, comprised of custom cam shafts and t-nuts, lock the vertical supports found in Figure 17 in place. The hinge handles run parallel to the bottom frame section to avoid catching on anything in the exterior environment and potentially opening by mistake. The x-axis sub-assembly mounts to the vertical beams through indexing shoulder screws and locking t-blocks. The enclosed shaft couplers allow for some deflection, but maintain flexibility to isolate vibration and unintended outside forces.

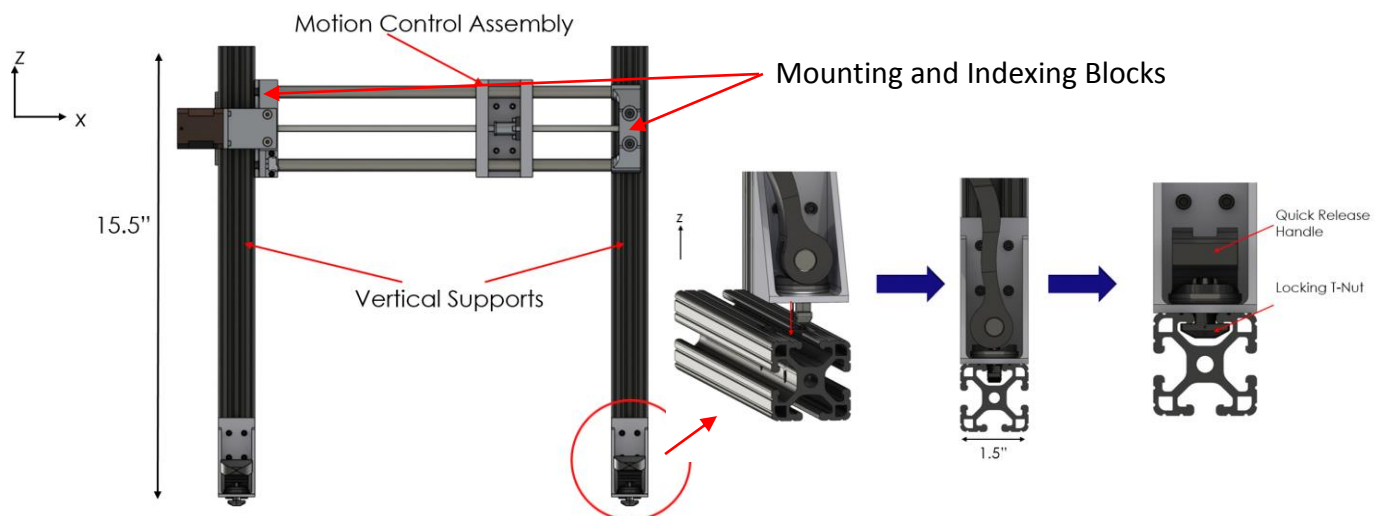


Figure 17: Vertical Supports

z-Axis

The Badger COMET vertical axis closely resembles the x- and y- axes. The z-axis assembly actuates through a NEMA 17 stepper motor coupled to a precision lead screw. A connection bracket, shown in Figure 18, rigidly affixes the z-axis assembly to the lead screw driving the x-axis. This allows complete control of the extruder module location in two axes during printing.

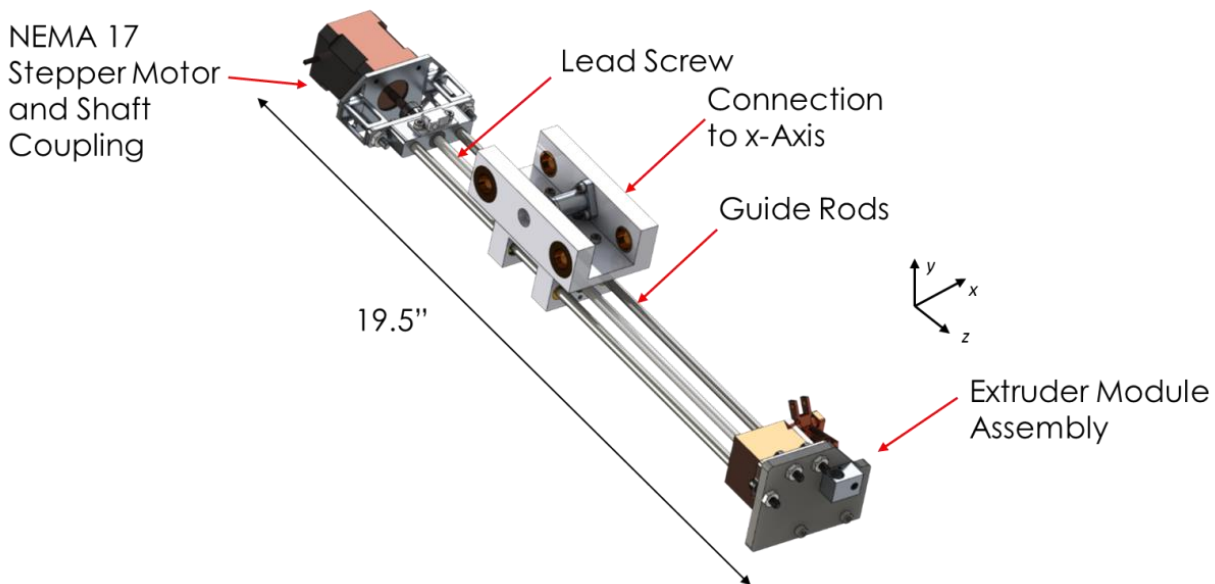


Figure 18: Z-Axis Assembly

Motor Mount Assembly

The driving stepper motor for the assembly mounts to a rigid frame, providing clearance for the shaft coupling, as well as enhanced torsional stability. The motor mount assembly also contains a mounting location for the z-axis contact sensor, which will provide limit-stop feedback to the control software during operation. The overall layout of the motor mount assembly is shown in Figure 19. Any individual component of the motor mount assembly can be removed without the need for a complete teardown.

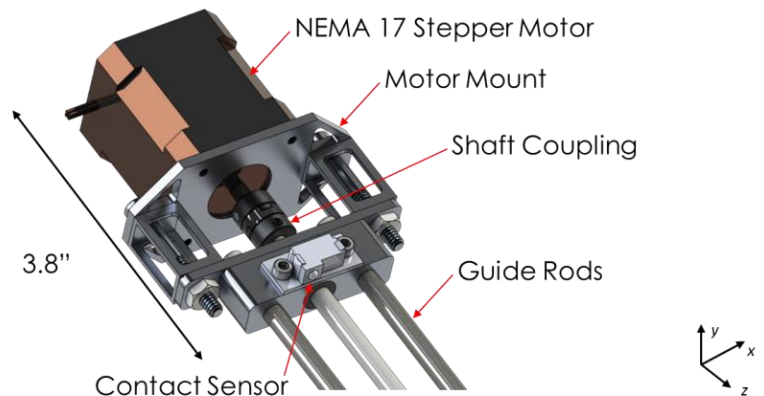


Figure 19: Motor Mount Assembly

X-Axis Interface Bracket

Lateral motion of the z-axis assembly is accomplished through a direction coupling with the driven x-axis lead screw, as shown in Figure 20. Precision dowel pins ensure the perpendicularity of the two axes, and constrain pendulum motion of the z-axis and extruder module assembly. The z-axis contact sensor, not shown, will trip upon coming into contact with this bracket, thereby communicating the limits of z-axis motion to the control software and stop motion.

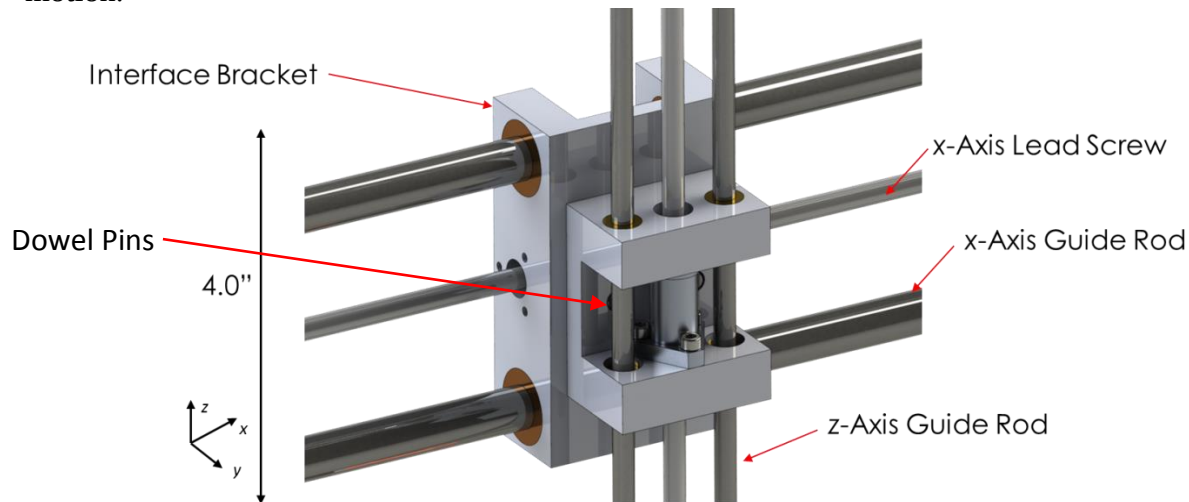


Figure 20: X-Axis Interface Bracket

Guide Rod Alignment

Proper guide rod alignment is of paramount importance to print quality and overall system functionality. This is particularly true of the z-axis, which houses the extruder module assembly (hot end) and is the final mechanical linkage in the Badger COMET's actuation system. Alignment of the z-axis guide rods was accomplished through the use of an alignment plate, mounted as shown in Figure 21 below. This plate interfaces with the machined ends of the guide rods and holds them in the guide rod mounting fixture, thus ensuring both rods are indexed and parallel to one another.

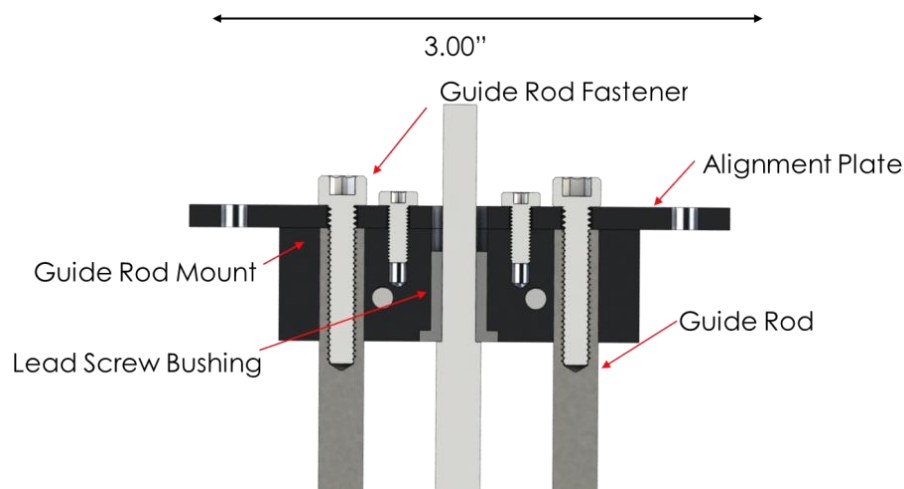


Figure 21: Guide Rod Alignment

Extruder Module

The design of the extruder module follows many design conventions employed in traditional FDM 3D printing systems, including the application of a resistive heating element embedded in a heating block, a closed-loop feedback system for temperature control, and an independent mechanical feed system for print material. This reduces the complexity of the system while maintaining the required level of performance.

The extruder module divides into the following components:

Heating Element Assembly: The assembly includes the extruder nozzle, the heating element, temperature sensors, insulating material, and filament feed tube.

Filament Feed System: This component encompasses the mechanical movement of the filament, from the spool to the nozzle.

Material Selection

A need for low weight, thermally tolerant components drove the material selection for the extruder module. As the extruder nozzle processes material at roughly 250°C, all plastics used in construction of the extruder module hold their properties at temperatures exceeding this value.

Plastics: All plastic components on the extruder module are Nylon 6/6, per ASTM D4066.

Metals: The heating block and motor mounts are produced using standard ASTM B209, 6061-T6 aluminum. The heating block mounting plate is produced from standard ASTM A859-89, 303 stainless steel which provides a lower thermal conductivity than 6061-T6 aluminum, and further thermally isolates the heating block from the rest of the assembly.

The extruder nozzle is produced from 360 brass per ASTM B16, selected for its ease of machinability and low cost.

Insulation: A ceramic insulation and a layer of Kapton® insulating tape thermally isolate the heating block from other extruder module components. Interfacing components experiencing heat transfer through conduction are manufactured from PEEK, providing additional thermal insulation.

Fasteners: All fasteners on the extruder module are M3 socket head cap screws, to allow for simple replacement and disassembly.

Heating Element Assembly

The heating element assembly consists of an aluminum heating block and brass extrusion nozzle mounted to the bottom of the z-axis on the Extruder Plate. Figure 22 below shows a rendering of the heating block assembly.

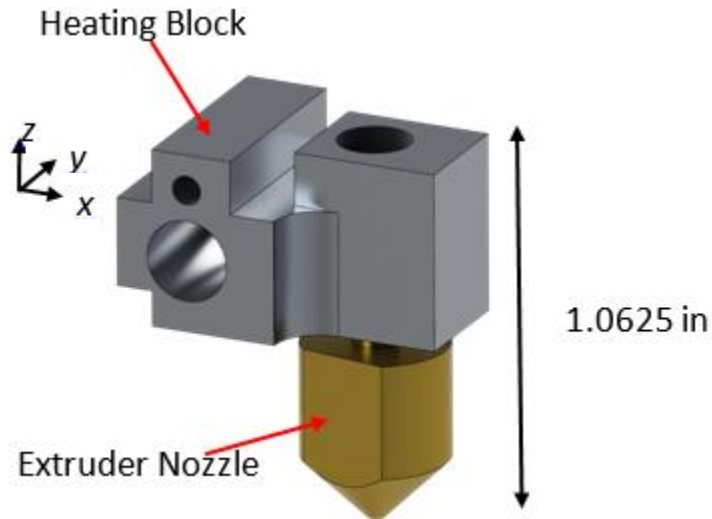


Figure 22: Heating Block Assembly (Heating Element and Temperature Sensors not Shown)

Heating Block

The heating block houses the resistive heating element, temperature sensor, and extrusion nozzle. A single resistive heating element brings the temperature of the block and extrusion nozzle to the processing temperature of 250°C. The geometry of the heating block is shown in Figure 23.

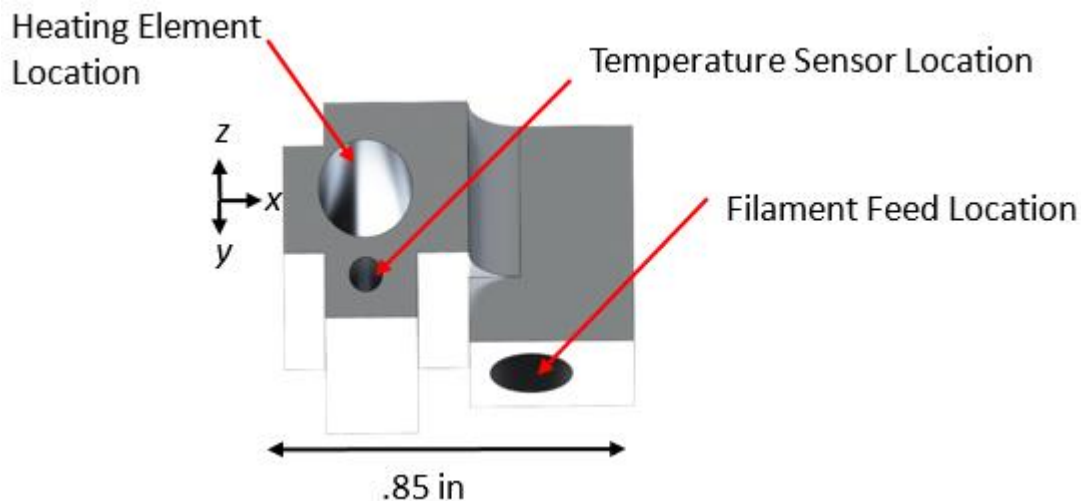


Figure 23: Heating Block Geometry

Heating Element

A Vishay RWM 4 x 10 high power dissipation resistor is the resistive heating element. This resistor possesses the required power output and was selected for its size and cost.

Temperature Sensor

A Honeywell 135-104 LAG-J01 Discrete Thermistor temperature sensor is embedded in the heating block. This low cost thermistor functions within the temperature range of the extruder nozzle and is widely available.

Extrusion Nozzle

The extrusion nozzle possesses an external M6 thread for assembly to the heating block, and a 0.4 mm bore at the tip. The nozzle is turned from 306 Brass hex stock. Figure 24 shows the nozzle geometry

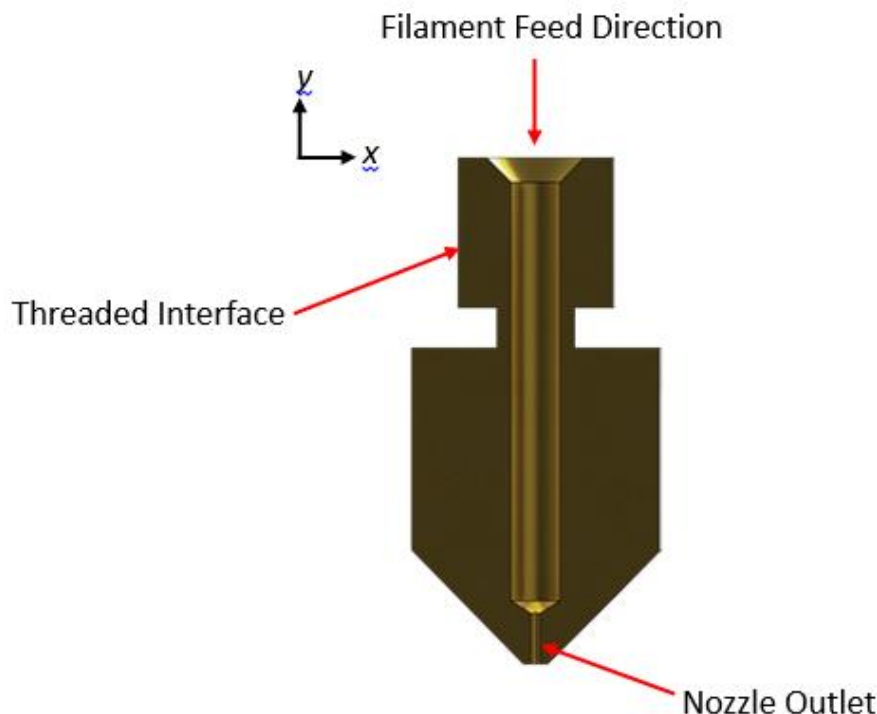


Figure 24: Extruder Nozzle Geometry

Filament Feed System

A NEMA-14 motor turns a friction wheel to draw the filament from the spool and push it into the heated extrusion nozzle. The rubber wheel forces against the filament with a spring, drawing filament from the feed spool during operation. The spring allows for irregularities in the filament feed diameter while keeping a constant friction force on the material. This ensures the extruder continuously feeds the heating element at a controlled rate during operation.

Storage Box

The electronics and the feed material are held beneath the base. Two internally facing C-channels create the main structure of the storage box with six half inch aluminum square tube cross members attached for support and structure stiffness. Sixteenth inch thick aluminum sheeting covers the outside of the base for aesthetics and internal component safety. The LCD screen mounts internally on the front face near the power supply I/O, allowing the user to complete all necessary operating tasks in one section of the base. Access to the internally mounted Printed Circuit Board (PCB) Power Supply Unit (PSU) is made possible through a hinged door on the bottom with a recessed latch, preventing movement during user access. Internal fans and ductwork allow for removal of heat from the system.

The filament is held in a swinging drawer that hinges from the back-side of the base. The drawer holds a variety of feed spools and closes and opens using the same type of recessed latch as on the bottom. A feed material tube is located in the drawer, which runs the feed material from the feed spool to the extruder module.

Electronic Hardware

All necessary control and safety circuitry can be found on either of two custom printed circuit boards. The main board mounts on the GPIO pins of the BeagleBone Black processor board and routes all control signals to the off-board components. The extruder board contains the thermistor temperature sensor and an analog-to-digital converter circuit, which converts the thermistor's analog temperature signal into a digital signal, read by the BeagleBone Black.

Subsystem Design

Motor Drivers: Badger COMET uses a Pololu A4988 stepper motor driver, an integrated circuit capable of converting step signals into power signals, directly driving the stepper motors used for axis control and filament feeding. For simplicity, a pre-built A4988 motor driver carrier board contain all necessary auxiliary circuitry. An onboard potentiometer can also be used to adjust the current for the requirements of the motor. Two bypass capacitors between ground and the 12V power input serve as the only required supplementary circuitry.

Fan Control Circuitry: The fan control circuit is based on the RepRap PWM Driver 1.1. It utilizes a freewheeling diode as back EMF protection to prevent voltage spikes from inductive loads when power is turned off. The fan tachometer inputs use a simple voltage divider to convert from a 12V input to a 3V, 1mA max signal, which can be input to a GPIO pin on the BeagleBone Black.

Heating Element Control: The heating element uses the same circuit design as the fan controls, but with a pulse width modulated (PWM) transistor control signal to provide the necessary amount of power to the heating element. Feedback for the heating element is provided by the thermistor.

Temperature Sensor: The design uses DS18B20 1-Wire temperature sensors for temperature data feedback from the PCB and each motor. These sensors communicate digital signals over the Dallas 1-Wire communication protocol.

Thermistor/A2D Converter: For high-temperature sensing on the extruder module, only analog components provide high enough range. The design utilizes a standard thermistor with a MAX882 Thermistor-to-Digital converter. The converter measures the voltage drop of the thermistor and compares it to the voltage drop of a known series resistance. It then converts the value into a 10 bit signed integer which is transmitted via the SPI protocol to the BeagleBone Black.

Power Supply: The board uses a standard ATX power supply unit to provide power to the BeagleBone Black as well as all peripheral components. It provides GND, 3.3V, 5V, and 12V rails, as well as a power switch connection to turn on power from the supply. Other voltage levels are available but are unused on the board. Test points are available for each of the voltage rails. Bypass capacitors are used to smooth the voltage levels from the power supply.

Endstops/Contact Sensors: Mechanical switches are used as both contact sensors and endstops. The contact sensors output a 12V signal when the printer is fully deployed, indicating to the BeagleBone Black that it is safe to begin printing. Endstops are used on each axis to zero the location of the print head prior to starting the print. They are also used as extra safety mechanisms during print to ensure that the extruder is not moved past the end of the axis track. Both the endstops and the contact sensors look like 0V at the board input when disconnected, and 12V when connected. As with the fan tachometer inputs, resistive voltage dividers are used to convert the 12V signals down to 3V to be read by the BeagleBone Black.

Lighting: The print surface is lit by a standard LED light strip. The LED strip is powered by 12V and controlled by a switch on the outside of the printer, completely independent of the firmware.

Human-Machine Interface: The human-machine interface is provided by an LCD panel with buttons. The LCD displays the status of the print as well as various options. The buttons can be used to select options, navigate menus, start, cancel, or pause the print.

Electrical Component Selection

This project uses all commercially available standard components, for ease of replacement if needed. Each component category is followed by its schematic designator.

Capacitors (C): All onboard capacitors function as bypass capacitors. All ceramic capacitors are 0.1 μ F, and all other capacitors are electrolytic, so polarity must be considered when assembling the board.

Diodes (D): The 1N4004 is a general purpose rectifier with a very high reverse voltage of 400V. This will prevent any undesired reverse current flow through the diode. It also has a relatively small forward voltage of 1.1V.

Headers (J): All off-board connections are connected with standard 100 mil headers, in the size specified in the schematic document, with the exception of the ATX connector. The ATX power uses a 24 pin Molex Mini-Fit Jr. power connector.

Transistors (Q): The board uses TIP120 NPN power transistors for switch control. They are capable of handling the necessary currents to power the fans and heating element. They can power a 12V component with a signal of 3.3V as provided directly from the BeagleBone Black.

Resistors (R): The board uses standard 0.25W through-hole carbon film resistors, in the values given in the schematic.

Integrated Circuits (U): The design includes A4988 Stepper Motor Drivers (attached as breakout boards) and DS18B20 temperature sensors.

Final Prototypes

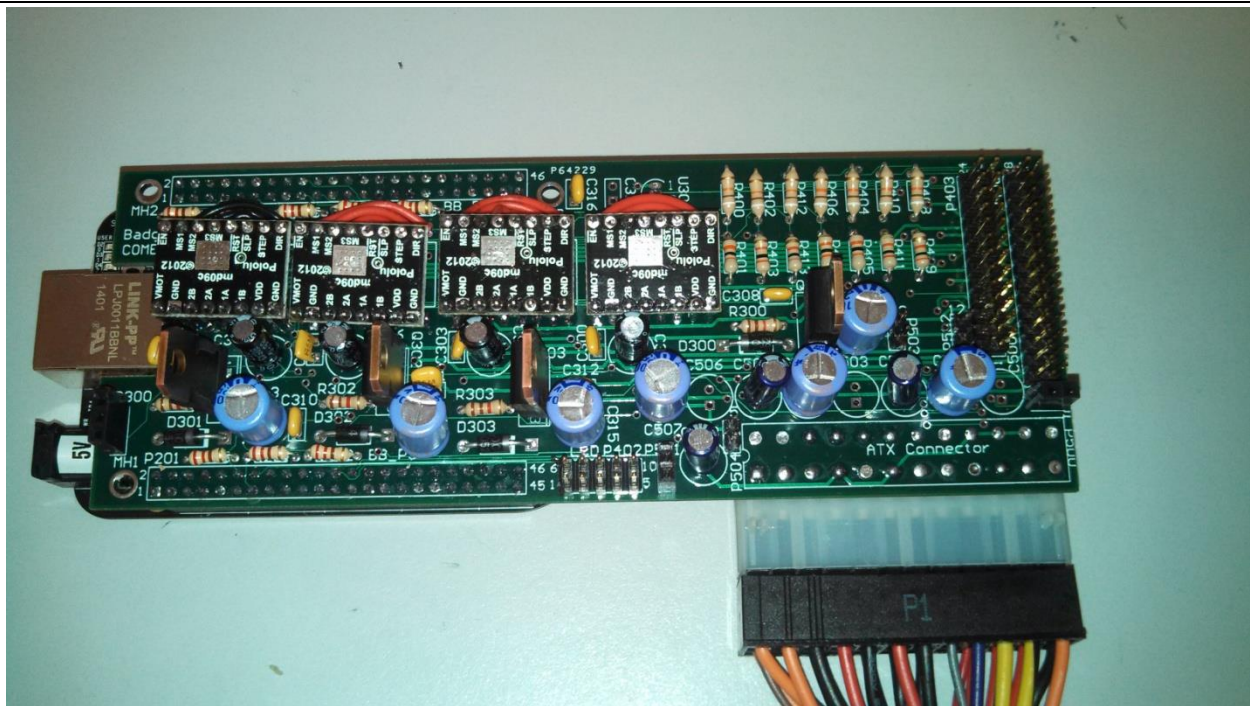


Figure 25: Final assembly of main PCB

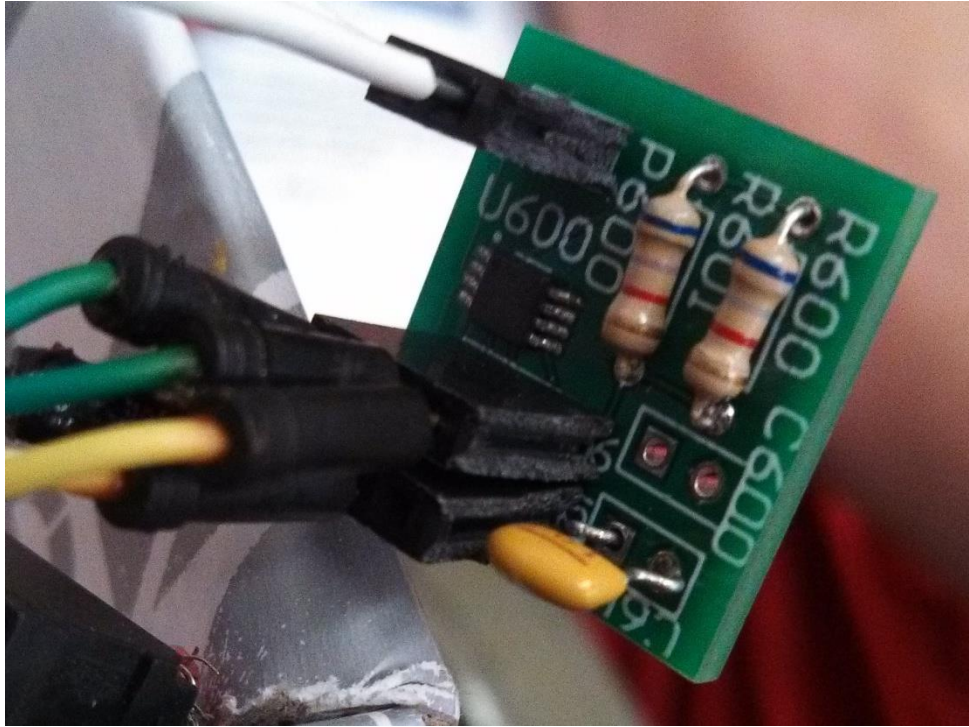


Figure 26: Final assembly of extruder PCB

Firmware

The firmware runs five different threads, each representing a different state as outlined in Figure 27. Each thread is responsible for executing the necessary actions of that state. These threads are mutually exclusive to each other; only one thread is active at a time. Additionally, the motors are controlled by a Programmable Real-time Unit (PRU). The operator communicates with the firmware through an LCD and set of buttons. The firmware interfaces with motors to move the mechanical devices, contact sensors to ensure structural integrity, temperature sensors to protect against overheating, a temperature sensor to maintain extrusion temperature, heating resistor to heat the extruder module and a Universal Serial Bus (USB) flash device to read G-code files.

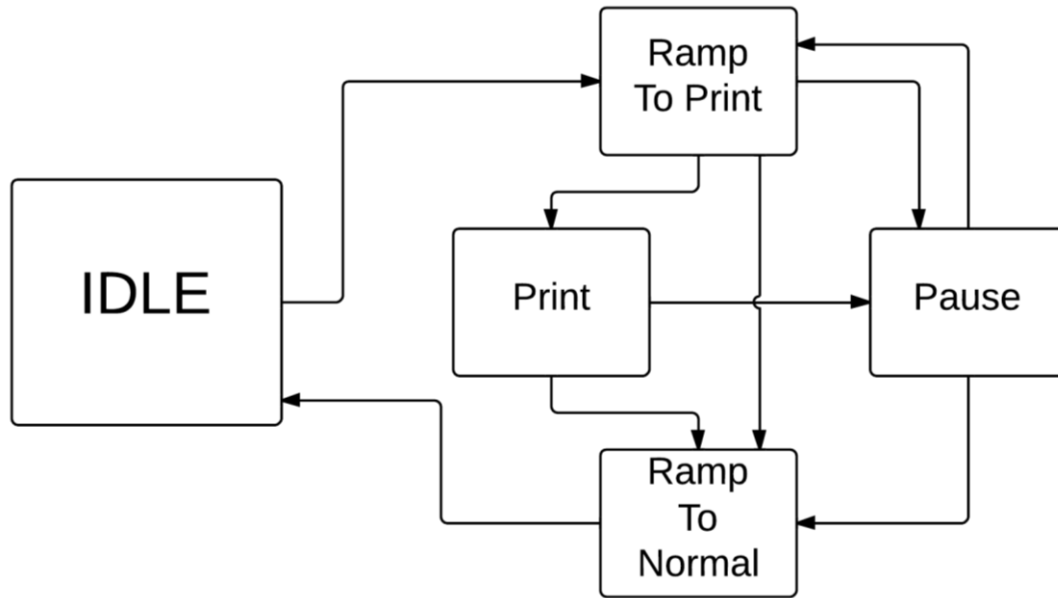


Figure 27: Firmware Thread Outline

Each thread represents a different state in the firmware. Each state represents distinct different interactions with the system and the user. The Idle stage is responsible for basic human interaction and starting the system. Once a file is chosen, the Ramp to Print state is entered. This state is responsible for preparing the system to print. Once the system is ready, then the Print state is ready, where the main print cycle occurs. Once the print is finished, it enters the Ramp to Normal state. This state allows the printer to reach a state ready for human interaction. At any point during the main print cycle or preparing the system, the system can be paused. Then the print will enter the pause stage and wait for the user to resume or cancel the print. Additionally, at any point the print can be cancelled and will enter the Ramp to Normal state.

The Idle state interacts with the user through a Liquid Crystal Display (LCD) and through four directional buttons, a check and cancel button. The Idle state is the first state entered on power on to the system. It will print a welcome message to the user, display how to navigate the system, then the menu options. The menu options allow the user to check the contact sensors, calibrate the system, and choose a file. If no USB device is plugged in, the system will notify the user. Since the Angstrom distribution, an embedded BeagleBone function, does not allow for hot plugging USB devices, the system will have to be restarted after a new USB device is plugged in. If the user has properly placed the files to print in the file “G-Code-Files”, the firmware will display the filenames to the user. The user can use the buttons to choose between the different options. Once the user has selected a file to print, the program will transition to the Ramp to Print cycle.

The Ramp to Print state’s primary purpose is heating the extruder module to proper temperature. This state interacts with the heating unit to create the heat needed on the heating block. It controls the heat being dissipated through a pulse width controlled signal. Additionally, the heating unit has a thermistor and an analog to digital converter. This stage constantly checks the

contact sensors to make sure the system is still properly functioning, moves the motors to the ready position, and checks for either cancellation or pausing. Once the system has reached the optimal printing temperature, the main print cycle is entered.

The Print state is where the actual printing occurs. The main print cycle monitors the state of the machine and processes the commands that control the print. However, the PRU controls the signals to the stepper motors. First, in the main print cycle, the firmware checks if the user pressed either pause or cancel. Next, it checks to see the contact sensors are still engaged. If they are not, the print is aborted. Then, the motor slice is run. This will read the next command from the file, process it and plan its motion. Then it will pass the instruction to the PRU. If the file is done, then the main print cycle exits. Next, the temperature is checked and adjusted.

The PRU is used for real-time control over the motors. Since the Angstrom operating system has built in latency for control, the real-time unit allows for parallel real-time control of the motors. The PRU checks the motors end stops and does the proper timing to move the motors.

The Pause state only waits for user input. This will move the extruder head away for the print surface. This state will wait for user input to either resume the print or cancel it.

The Ramp to Normal state cools the system down. It will stop the heating unit, but run the fan. Once the system has cooled to safe levels, then the user can remove the item. The user will be notified to confirm part removal. The firmware will move the motors to their stowaway position. Once this is done, then the system returns to the idle state.

The source code was created in C++. This allows for control and tracking of the system variables that other languages do not provide. Additionally, C is a common language used in embedded systems. All of the hardware components have their own class that allows control for that specific hardware unit. Additionally, each section, such as the motors, heating module and the human interface have their own classes that encapsulate the hardware classes they use.

Threads were chosen to implement the states because of their ease. Each thread allows for a unique code base to be used in that thread. Additionally, this concept allows for easy transition between the threads. Additionally, threads allow for sharing of the processor memory. This allows for the one class to be used across multiple threads.

Safety

Multiple safety features are integrated into each subsystem to ensure proper and safe Badger COMET functionality. The following safety systems focus on preventing user injury and damage to the device.

Sensors

Five Honeywell ZD Contact Sensors have been installed on the device. Three of these sensors are used for limiting axial motion. These sensors ensure that the extruder head remains within the boundaries of the print surface. The other two contact sensors are installed within the base structure. During deployment, these sensors indicate when the z-axis makes contact with the base. These five sensors increase the safety of the entire system by limiting the motion of any motorized component, thereby reducing the potential risk of accidental damage or destruction.

In addition to the five contact sensors, the Badger COMET has temperature sensors located on all motors, the extruder module, and the board. By providing accurate data to the user, the temperature sensors decrease accidental burn risks and system overheating.

Manual Deployment

The Badger COMET incorporates manual deployment to increase the simplicity of the system. By requiring the user to manually deploy the printer, there is little risk of unintended printer deployment. Furthermore, requiring user interaction directly increases user control over the system. For specific operation requirements, including deployment, see the Badger COMET User Manual.

User Safeguards

To decrease risk of user injury, all pinch points have clear signage on the 80/20[®] base structure and supports cautioning the user. All moving components include shielding to prevent any accidental damage to the system and to prevent user injury.

Standards and Chemical

All NASA and IEEE standards within the Product Design Specification (PDS) are followed in terms of safety components. Ergonomic standards are followed with regards to component temperatures, exposed wiring, mechanical components, and user interaction facets.

Construction and Assembly

Badger COMET contains several custom components requiring specific machining. Following the Badger COMET standard drawing template, all 3D models were made into technical drawings for machining. After following a procedure of several rounds of drawing checks, revisions, and design change documentation, each part received clearance for manufacture in the UW-Madison College of Engineering Student Shop. The shop contains a variety of machines, including mills and lathes for most metal and plastic stock and brake presses for sheet metal bending and punching. Knowledgeable industry professionals staff the Student Shop, providing training and ensuring the safety of all students.

Despite best efforts, some complications arose during manufacturing and assembly. The main problems were as follows:

- **Solid models do not always represent part accuracy.**
After parts had been machined, more often than not, the final product was not exactly produced as expected from the solid model assembly.
- **Tolerances can prove too advanced for inexperienced machinists.**
As a student team of engineers, some of the machining tolerances were too tight and should have been loosened for greater ease of manufacturing and assembly.
- **Technical drawings must be clear and easy to follow.**
If a part drawing has several levels of complexity and does not follow the proper standards set forth, there is little to no chance of accurate machining.
- **With correctly manufactured and in stock parts, assembly is simple.**
When each part is over or under tolerance even by the slightest margin and the proper fasteners cannot be located, complications, problems, and delays arise quickly.

Some complex, high-tolerance, critical components required manufacturing expertise beyond student team level and were outsourced to ensure proper fabrication. UW-Madison Space Science and Engineering Center (SSEC) machinists manufactured several critical z-axis components to a high degree of accuracy. Other y- and x-axis components have been created by rapid prototyping CNC labs, capable of holding a tolerance within a few thousandths of an inch.

Electronics and Firmware Testing

The electronic hardware subsystem has been thoroughly tested for functionality and robustness. Testing included manual voltage and conductivity testing, as well as scripted tests. All of the voltage rails on the PCB were checked with both an oscilloscope and multimeter to verify proper levels. All onboard components were tested for solder and routing connectivity. Once manual testing was complete, the team began software-based tests using the BeagleBone. Through these tests, the team was able to verify functionality of the fans, motors, temperature sensors, and contact sensors.

The only testing failure was the onboard temperature sensor, which overheated when power was applied. It was removed from the board and replaced with another unit. Also, in the initial test of the heating element, the wire gauge was too small for the current requirements and melted the plastic casing. This issue was mitigated by soldering larger gauge wires directly to the transistor controlling the heating element.

Final Mechanical Prototype

The final Badger COMET prototype is shown fully deployed in Figure 28. The motor control firmware, despite significant development focus over the course of the project is non-functioning. This halted a significant amount of anticipated hardware testing.

As with the initial Badger COMET design, manufacturing proved a more significant challenge than initially anticipated. Many of the components on the current mechanical prototype were outsourced to local machine shops, thereby reducing the errors previously encountered in components manufactured by students. The result of refinements to the manufacturing process was a complete mechanical prototype that assembled with little need for modification.

The initial Badger COMET design was deemed wholly non-functional from a fundamental standpoint. Its development, however, provided a baseline for the current mechanical platform, thus allowing for the production of a more robust solution. The current prototype possesses a substantially lower system weight and fewer components. Assembly methodology was improved between iterations as well. Where the original COMET design required specialized tooling and assembly fixtures, the current prototype was assembled with standard tooling on a lab bench in less than three hours.

Articulation testing of each independent axis was performed. The lead screw based actuation methodology employed by the Badger COMET functioned as designed, with high accuracy and repeatability. The system collapsed as intended with no difficulty (Figure 29) and maintained full articulation when re-deployed.

The following sections contain a discussion of each mechanical subsystem prototype, as well as a

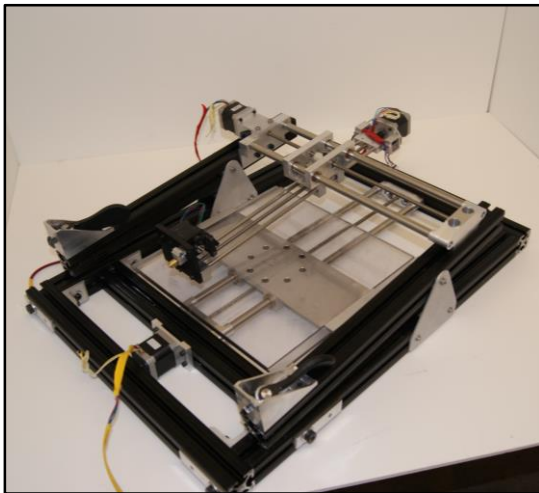


Figure 29: Collapsed Badger COMET Prototype

critique of the assembly process.

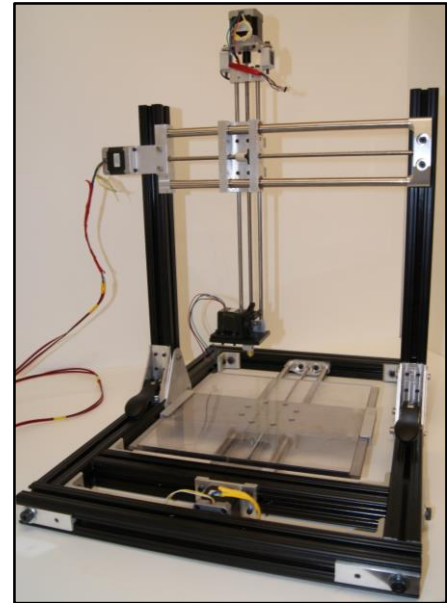


Figure 28: Deployed Badger COMET Prototype

Base Structure

The use of standard 80/20 extrusion in the base structure provided versatility and ease of replacement. The extrusion material, however, was difficult to machine to the tolerances specified, and maintaining alignment accuracy in the base was an issue during assembly. The standardized extrusion material is attractive for this application, but it adds unnecessary weight to the overall system. Future refinements to the Badger COMET design should focus on a custom frame material, more suited to the application.

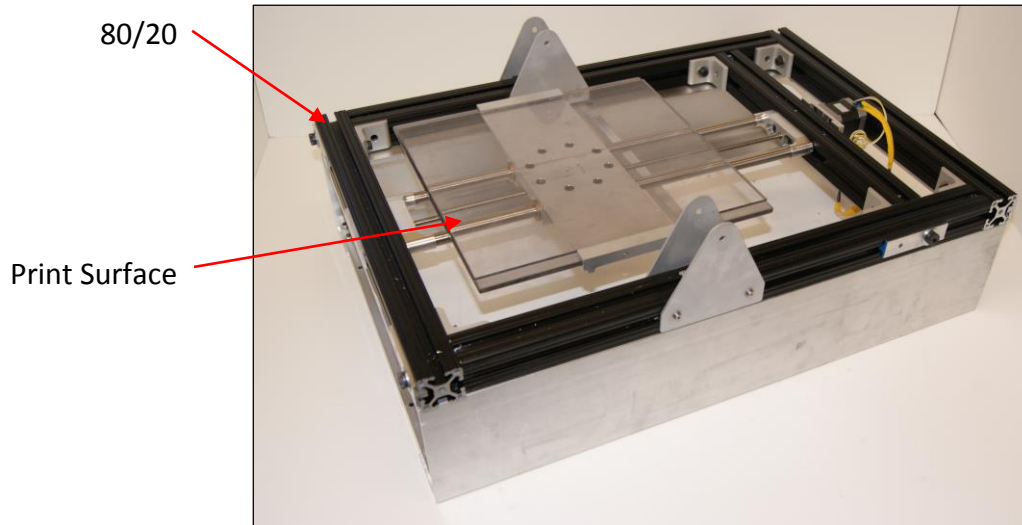


Figure 30: Assembled Base Structure

All functional mechanisms on the print surface platform and overall base structure functioned as intended. One benefit to the standard extrusion material is the guaranteed flatness of its sides. This ensures that the base frame can be assembled and its perpendicularity assured without the need for additional fixtures.

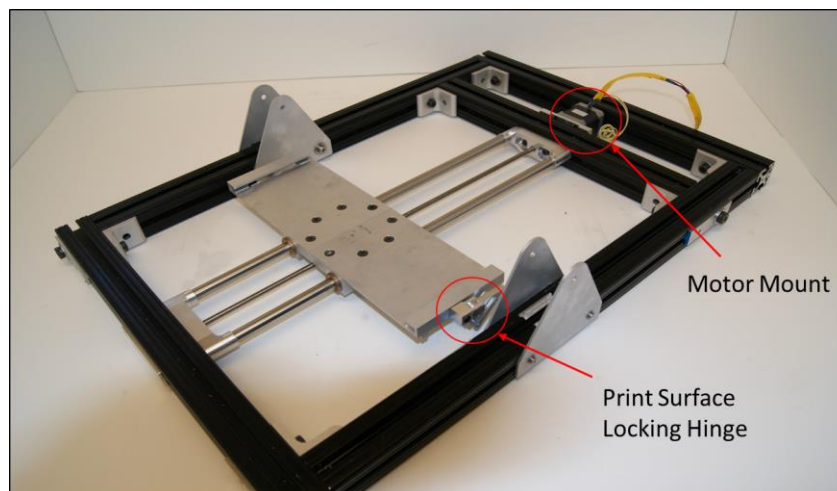


Figure 31: Base Structure with Print Surface Removed

The print surface carriage and the completed lead screw bracket were assembled without modification. The carriage had full travel along the guide rods without jamming.

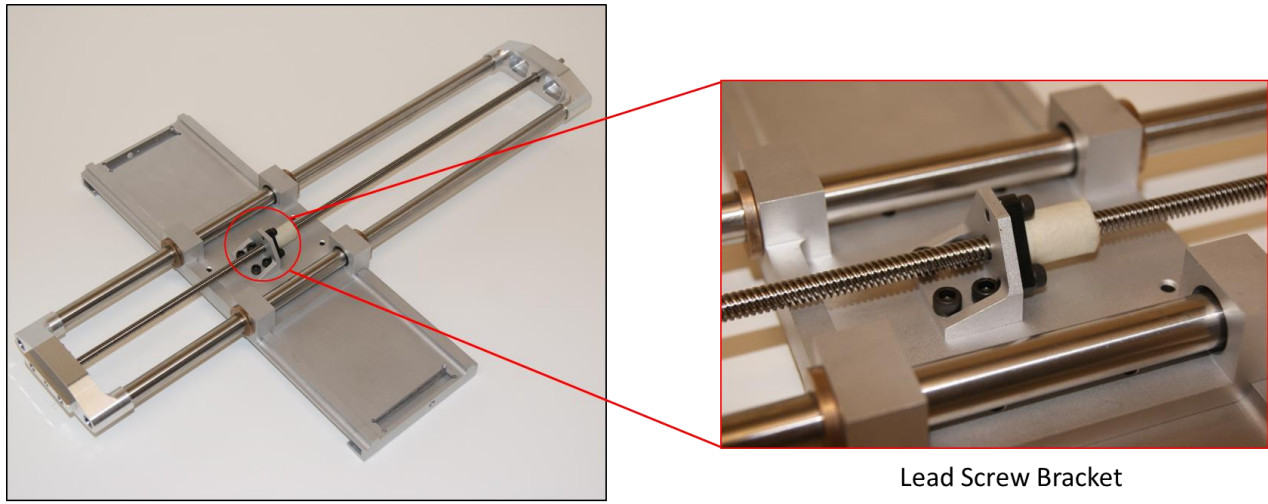


Figure 32: Print Carriage Underside and Lead Screw Bracket

Vertical and Lateral Actuation

The vertical and lateral actuation systems, referred to as the x - and z -axes, were assembled and able to travel freely along the expanse of the printing envelope.

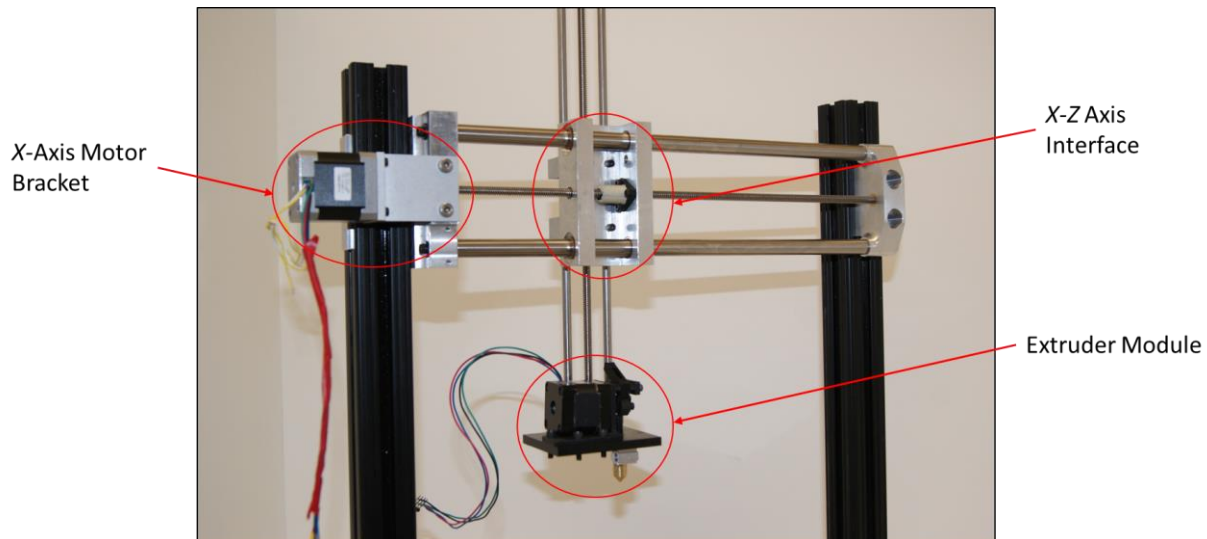


Figure 33: Vertical and Lateral Actuation Assembly

Tolerance stackup proved to be an issue with the z -axis motor mount assembly, shown in Figure 34. The motor mount spacer components were produced from square stock, and where not

produced to the specified tolerance; this was the only area of the Badger COMET that required modification during assembly.

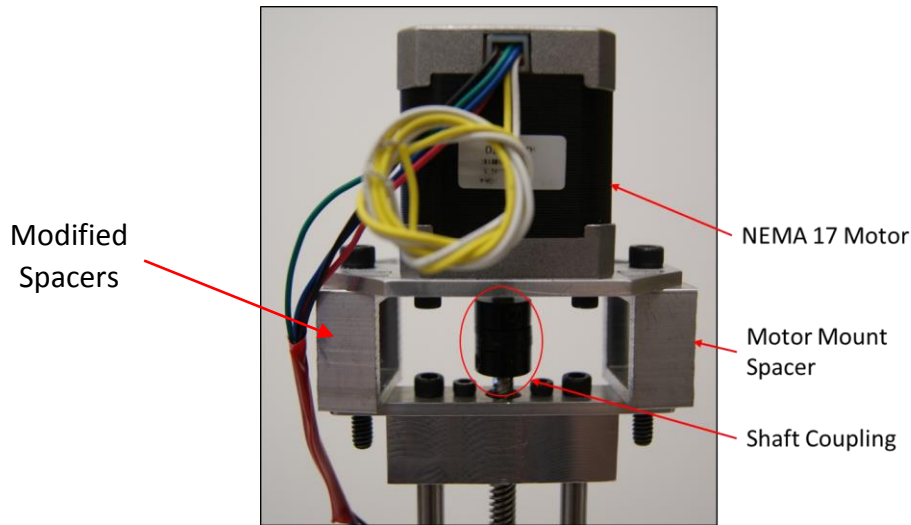


Figure 34: Z-Axis Motor Mount Assembly

Extruder Module Assembly

The extruder module assembly has remained essentially unchanged from the initial Badger COMET design. Minor modifications have been made to the platform to accommodate the new vertical axis design. The spring-loaded filament feed mechanism gripped the filament and pulled it to the heating element, as designed. Figure 35 below shows the completed extruder module assembly, detached from the main device.

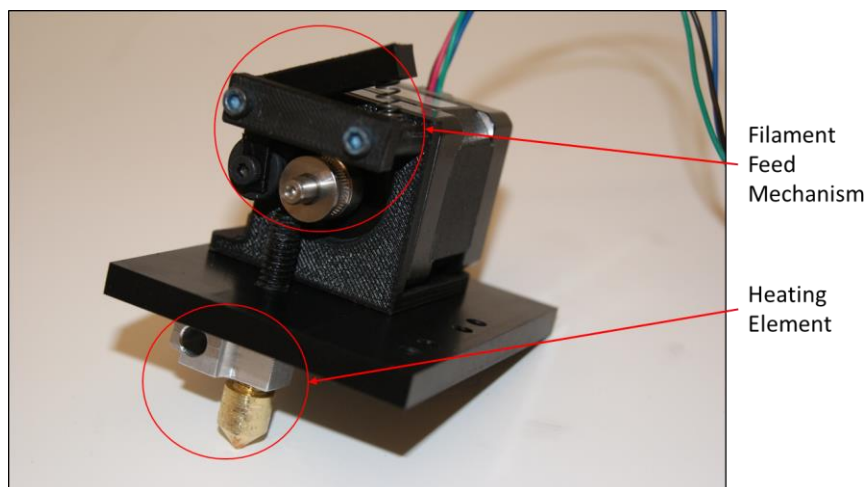


Figure 35: Extruder Module Assembly

The completed extruder module interfaced with the vertical actuation assembly with no problems. An initial concern was the alignment of the precision guide rods at the connection point with the extruder module, but this proved to be a non-issue in the final assembly. The extruder module, as assembled to the vertical actuation system, is shown in Figure 36.

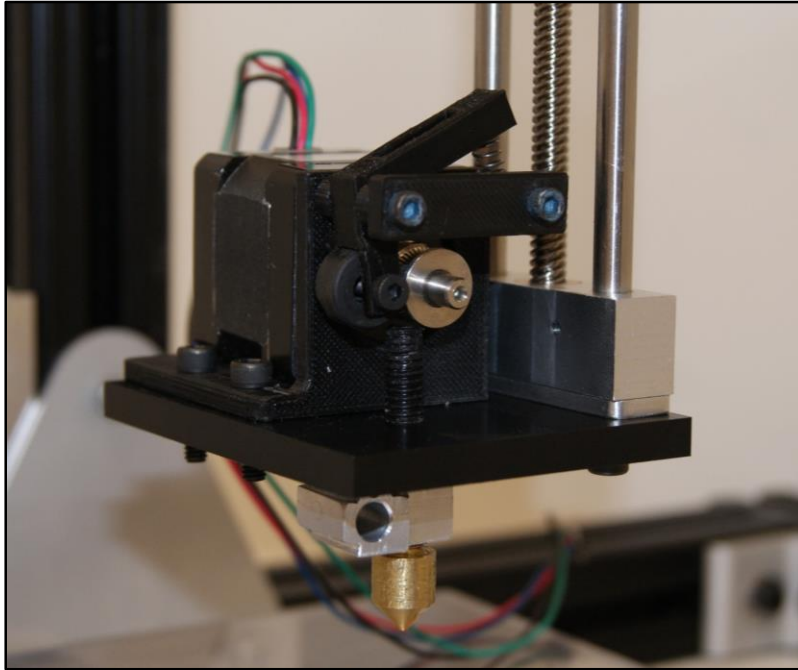


Figure 36: Extruder Module Assembly Attached to Z-Axis

Final Budget

The budget shows the source of funding, and the flow of funds throughout the completion of the project. The budget specifically identifies costs for electrical development and mechanical development. Table 2 shows Badger COMET funds and the associated sources.

Table 2: Funding Generated

Benefactor	Funding Type	Monetary Value
National Space Grant Foundation	Research Grant	\$
College of Engineering	Indirect Costs	\$
Mechanical Engineering	Department Grant	\$
Engineering Physics	Department Grant	\$
Mechatronics Laboratory	Consultation	\$
Space Science and Engineering Center	Materials and Travel	\$
Bjorksten bit 7	Consultation	\$
	TOTAL	\$

Public and private sources fund the Badger COMET through monetary donations, material donations, and consultation. Overall, the Badger COMET budget contains \$ worth of funding.

Future Work

For further development, Badger COMET plans to continue improvement of the system over the summer term, with the end goal of producing a fully functional additive manufacturing workstation for the benefit of future design projects. Design refinement will be focused in several key areas.

1. Control Code

An open-source motor control code will be re-purposed for use on the Badger COMET. The largest area of focus in open sourcing lies in the coding of small additive manufacturing workstations, and many comprehensive control solutions exist for a system of this size.

2. Mechanical Performance Refinement

Additional work will be performed to improve the system's quality of motion. Several components on the COMET can be remade or modified to this end. Additionally, once a control code has been fully implemented and the system is again functional, print testing will generate additional design refinements for improved print quality and functionality.

3. Investigation into Additional Modularity and Functionality

The team plans to investigate the addition of alternative functionality in the system. This includes alternative print materials, printing methodology, and assembly or dis-assembly process refinements. The team hopes to further interface with ongoing research at NASA and elsewhere to develop technological solutions that provide utility on future missions.

Outreach

As students at the University of Wisconsin-Madison, Badger COMET embodies the tradition of the Wisconsin Idea: education is never solely for personal gain and the privilege of a world-class education carries the responsibility to influence the world beyond the classroom. To keep with this philosophy, research and progress was shared throughout the local and regional area. Through the website, Twitter feed, Facebook, Google+, visiting local schools, and articles published about the team, progress and innovation are demonstrated to the general public and the scientific community alike.

The project website (<http://xhab.engr.wisc.edu>) is a source to read about Badger COMET. Member biographies, information about the academic challenge and contest, a repository of news articles, a project schedule, current images and photographs, and outreach events can all be found by navigating from the main page. The link to the website is distributed during each outreach conversation to generate more page views and search engine hits. Updates are continually made to maintain the newest information.

During the course of research, design, and project construction, local middle school and high school students learned about the project through team visits. PowerPoint presentations with pictures and models conveyed information in a media rich format. Preparatory students, not much younger than university students, were connected to science and technology.

Collaborative work with various journals, newspapers, and social media inform a larger demographic, expanding outreach throughout the state and beyond its borders. Upon completing various components of the design, student and statewide publications on campus have discussed the design and testing, and encouraged students and faculty to become involved in space exploration research.

Completed Outreach Events

Deep Space – Epic’s 2013 Users’ Group Meeting [9/19/2013]

In collaboration with the Wisconsin Institutes for Discovery (WID) and the UW-Madison 2011 X-Hab project, Badger COMET team members presented current information about the project, demonstrated the capabilities of FDM, and informed guests about the current state of deep space habitat research. The 3D printer and printed parts were displayed to show the printing technique.

Da Vinci Fest [1/14/2014]

Da Vinci Fest was an educational fair highlighting art, science, and technology projects in the Stillwater School District in Stillwater, Minnesota. In 2013, more than 3,000 attendees came to see the projects done both by students and professionals. Through the festival, Badger COMET team members showed current components of the project and the capabilities of 3D printing through demonstration.

Published Articles

NASA Press Release:

<http://www.nasa.gov/press/2013/july/nasa-selects-seven-projects-for-2014-x-hab-innovation-challenge/#.UiDFsT8mhNQ>

Badger Herald (also published in print):

<http://badgerherald.com/news/2013/09/15/uw-comet-project-looks-to-take-off-to-space/>

Wisconsin Engineer Magazine (also published in print):

<http://wisconsinengineer.com/magazine/609/623/>

Social Media

The project website (<http://xhab.engr.wisc.edu>) is continually updated with the newest information related to the project. The team blog (badgercomet.tumblr.com), Twitter (@BadgerCOMET), and Facebook group (Badger COMET) keep project followers up to date on the latest news with updated project photos and FAQ.

Importance of Being X-Hab

The following section contains some observations by the students on the Badger COMET team regarding their experiences, the value of the project, and their academic and technical development over the course of the year.

“Throughout this year in Badger COMET, I not only improved my skills as a future engineer, but also had a great opportunity to network with peers, UW faculty, and even NASA professionals. Prior to this year, I had no experience in design, and I did not realize the difficulties that accompany the design process. As the COMET team learned this year, some designs are not realistic, but this gave me great insight that I will not soon forget. I am looking forward to using the skills I have gained throughout this last year as I move forward with my engineering career, both next year when I begin the senior design curriculum and eventually when I graduate, becoming a practicing engineer.”

- Skylar Dhaese

“Throughout my courses at UW-Madison, I never had the opportunity to learn how to correctly make a proper Printed Circuit Board design. X-Hab gave me the great opportunity to do so and integrate it directly into the system, which is why I became an Electrical Engineering student in the first place.”

- Sara Beyer

“X-Hab was valuable to me because it gave me lots of experience with the design process. I got a chance to create 3D models and technical drawings, and machine parts. This experience will be invaluable when I am looking for a job.”

- Jake Ptaszynski

“X-Hab has been vital to my development as an engineer. Putting together a multi-dimensional team to execute on a project of this scale forced us to work hard and develop a basic background on how to work with other disciplines of engineering. This project taught me a ton about mechanical dynamics of electrical driven systems, how to set a detailed project schedule for huge designs, and how to compensate for manufacturing tolerances, by building flexibility into the design. Most importantly, I learned the quirks of a large team and how to motivate team members to succeed in the development of an innovative design. Overall, X-Hab was a great learning experience and would recommend it to future generations at University of Wisconsin-Madison.”

- Ben Lange

“Working with a large, interdisciplinary group taught me how to effectively work on a team and how to communicate my work to the group as a whole.”

- Sean Kelly

“X-Hab is, at its core, the hardest type of engineering design, from complicated concepts to a short timeline; struggling through the process provides real-life experiencing in how design projects work, from the great ideas to the unfortunate failures that require rapid redesigning. To be able to accomplish this in an academic setting is crucial for any engineer like myself that has an interest in design engineering. X-Hab provided this experience alongside useful information that can apply to a wide array of employment opportunities.”

- Alex Schwartz

“This project has demonstrated, in painful, sharp detail, the most valuable trait the modern engineer can possess is an ability to distinguish abstract, idealized, and unrealizable designs from those which can be brought into physical existence.”

- Casey Sennott

“X-Hab maintains a working similarity to magma from the earth’s core: a mixture of semi-molten rock, volatiles, and solids. Just like the design team, each part of the composition serves a valuable purpose in forming volcanic rock – the large substrates form a solid base, and the smaller particles fill in the gaps and remain unnoticed.”

- Steve Wishau

“This opportunity gave me an insight into how the design process works. Since I was one of the younger members on the team, the experience was truly invaluable and I really enjoyed working with such a diverse team. All in all, the xhab project will remain a highlight in my college career and provide experience I will be able to use when I graduate.”

- Andrew Witzmann

“I joined because I wanted to design something that would be used in a real world application. Working on a project such as this was very appealing to me because of the connection with NASA and the application of the classroom information. I know in the job market working in groups is a skill that is required and I wanted to work to strengthen that during the course of the project. Working in groups poses several challenges but overall I found skills and teammates I could trust to get tasks completed. I would recommend other groups to try to pursue this and other competitions because they teach things that can't be learned in a classroom.”

- Erik VanderSanden

“The project has been an exercise in feature creep assessment and mitigation. Early designs were crippled by unnecessary features which hindered the overall performance and manufacturability of the product. The most important lesson learned by the Badger COMET team is this: the simplest design which satisfies the design criteria is, by far, the best solution.”

- Ryan Knippel

Appendix I: System Requirements Document

Since the Preliminary Design Review, the design specifications have not been changed to any significant degree. Some specifications have been updated, mostly in tightening tolerances, dimensions, and materials utilized. Much of the work done between the PDR and the CDR focused around finalizing the overall design, dimensions, interfacing, and electronics and performing proof of concept testing for all crucial components. A more comprehensive list is seen below:

1. Mechanical and Electronic System Testing
 - a. Axis Test Stands
 - b. Motor Test Stand
 - c. Firmware Proof of Concept testing
 - d. Electronic Hardware Proof of Concept Testing
 - e. Print Surface Proof of Concept
2. Analysis of potential safety issues
 - a. Chemical containment and mitigation
 - b. Pinch points in folding components
3. Finalizing of sensors and electronic hardware
4. Interfacing between subsystems
5. Fabrication, Fastening, and Prototyping

Mechanical Product Design Specifications						
Performance Requirement	Functional Description	Worst Acceptable Performance	Desired Baseline	Associated Subsystems	Measurement Method	Current Design
Printing Tolerance	Average variance in printed component dimensions.	250 Micron = .010"	25 Micron = .001"	Print control system, Extruder head, Software	Average dimensional variation in printed test part.	Desired Baseline Met
Positioning Precision	Position of Printing Head	xy: 25 Micron, z: 12.5 Micron	xy: 5 Micron, z: 1 Micron	Printer control, printer Head, Software	Movement of the printer head in x, y, and z directions	xyz: Stepper Motor provides 35 Micron Actuation, requiring Gear Ratio of 35:1 in z and 7:1 for xy
Printing Volume	Maximum area available for printing.	6 in x 6 in x 6 in	12 in x 12 in x 12 in	Entire System	Tape Measure	Desired Baseline Met
Number of printer heads	Number of printer heads	1	2	Extruder Head	N/A	Single Printer Head
Number of printed materials	Number of printed materials	1	2	Extruder Head	N/A	Single Printed Material
Printed Material	Material to be printed	PLA	Polycarbonate ABS	Extruder Head		ABS-30M
Percent Reduction	Actual Volume ratio	25% reduction in volume	50% reduction in volume	Folding Mechanism	Dimension Ratios	About 65% Volume Reduction
Printing Speed	Volume of material printed per hour.	0.75 cubic inch/hour	1.25 cubic inch/hour	Mechanical Actuation	Stopwatch	Desired Baseline Met
Deployment	Required operations for deployment of printer	Manual fold out and set up of printing table	Completely automated printing system.	Printing table, Controls	Number and difficulty of manually performed tasks during printing; Hours of Astronaut training required	Manual Deployment

Mechanical Product Design Specifications						
Performance Requirement	Functional Description	Worst Acceptable Performance	Desired Baseline	Associated Subsystems	Measurement Method	Current Design
User Safety	Safety of assembly and normal operation.	OSHA 1910.22 General Workplace Requirements OSHA 1910.30 Machine Area OSHA 1910.132 Personal Protective Equipment OSHA 1910.176 Handling Materials-General OSHA 1910.303 General Electrical Requirements OSHA 1910.334 Use of Electrical Equipment OSHA 1910.1051 1,3-Butadiene	a. NASA-Standard-3001 Volume 1, Space Flight Human System Standard: Crew Health. b. NASA-Standard-3001 Volume 2, Space Flight Human-System Standard: Human Factors, c. FAA HFDS – Human Factors Design Standard. d. MIL-STD-1472, Department of Defense Design Criteria Standard – Human Engineering	Printing Table, Controls, Folding	N/A	All Standards Taken into account for safety mechanisms provided by NASA and OHSA. Additional safety mechanisms are designed to further create a safe product
Environment Effects	Any effects the printer has on the DSH	NASA's safety standards JSC2058-4	NASA's safety standards JSC2058-4	Electrical	Heat radiation, off gassing, static electricity	Desired Baseline Met
Thermal Leak	Heat leak to ambient air	5°C above ambient at 150 mm from device	1°C above ambient at 150 mm from device	Electronics, Extruder Head	Laser Thermometer	Desired Baseline Met
Lifetime	Hours of Run Time	1000	10000	Electrical + Mechanical	Not measured, when designing ensure all parts are rated to X number of cycles (ex: hinge can rotate table up and down 400 times)	Materials for structure and electrical components chosen to meet desired baseline of 10,000 hours

Mechanical Product Design Specifications						
Performance Requirement	Functional Description	Worst Acceptable Performance	Desired Baseline	Associated Subsystems	Measurement Method	Current Design
Mean Time Between Repair	Mean Time Between Repair	250 Hours	2000 Hours	All	Time Measurement	Desired Baseline Met
Mean Time Between Failure	Mean Time Between Failure	10,000 Hours	25,000 Hours	All	Time Measurement	Desired Baseline Met
Component Max Temperature	Maximum Temperature of any Exposed Component	44° C for exposed parts (PER NASA 3001-2 Section 9.3.1.10)	Exposed parts are ambient temperature	Electrical, Extruder Head	Laser Thermometer	Designing to meet NASA Standard
Noise restrictions	Noise level of printer while in use	<49 dB NASA 3001-2 Sections 6.6.1	30 dB	Extruder head, control mechanism	Acoustic testing	Desired Baseline Met
Fasteners	List of acceptable fasteners	Flight Certified Fasteners	Fasteners meet NASA-STD-5020 Applied in Accordance with MSFC-STD-486-B	All	N/A	Desired Baseline Met
Vibrational Loading	Design to endure vibrational loading during takeoff/landing		Should meet NASA-STD7002A - Payload Test Requirements; NASA-HDBK-7004C FORCE LIMITED VIBRATION TESTING	All	Design Phase - FEA, Prototype - Vibrational Testing	Desired Baseline Met
Structure Materials	List of acceptable Materials	Flight certified materials	Materials should meet NASA-STD-6016	All	N/A	Materials meet NASA Standards

Mechanical Product Design Specifications						
Performance Requirement	Functional Description	Worst Acceptable Performance	Desired Baseline	Associated Subsystems	Measurement Method	Current Design
Weight/Carry Distance	Total weight of system in respect to how far it has to move (mobile system only)	27.22 kg for 30.48m carry	22.68 kg for 60.96m		Scale	Current weight profile is approximately 25 kg

Electrical Product Design Specifications							
Performance Requirement	Functional Description	Worst Acceptable Performance	Desired Baseline	Associated Subsystems	Stakeholder Expectation	Measurement Method	Current Design
Energy Consumption	Max consumption at one time in the system	15 A Max Draw, 24V System, 1000 W maximum	15 A Max Draw, 12-18V System, 750 W Maximum	Controls, Power Management, Actuation		Measure power draw of device during printing.	Largest current drawn on heater (12 A), 24V system, with max power of 350 W
Power System	Overall Wattage Supplied	125% of Required Power	150% of Required Power	Controls, Power	100% of Power	Wattage of PSU compared to System Required	Designing with 750 W system, 700/350 = 200% of required power

Electrical Product Design Specifications							
Performance Requirement	Functional Description	Worst Acceptable Performance	Desired Baseline	Associated Subsystems	Stakeholder Expectation	Measurement Method	Current Design
Motor Torques	Power output and requirements for motors	Capable of Producing necessary torque within optimum range of operation (65-85%)	Capable of producing necessary torque within mid-range of operation (50-75%)				Torques are designed to operate at optimum range of control (50-75%)
Motor Step Angle	Precision Angle of Stepper Motor	Require 64 Steps for Full Actuation (5.6 Degrees)	Require 128 Steps for Full Actuation (2.75 Degrees)	Motors	N/A	Motor Specification	Step actuation is 1.8 Degrees
Processing Power	The overall processing capabilities of the system	Meets All necessary requirements to run the system at standard operation	2X Excess (Processing power exceeds requirements by 2 fold)	All	Meets System Requirements	Processing Power of Chosen microprocessor	Processing power in excess of 10X necessary
Code Generation	System of Code and style utilized	Meets IEEE Standards IEEE-1012-2004 Chapter 7 for a validation and verification test plan and IEEE-829-2008 Chapters 5 and 6 for code formatting	Fully Documented, Highly Modular code meeting all necessary standards	Firmware	N/A		All standards met
Wire Control	Handling of Wires throughout mechanical system	Exposed Wires do not interfere with system	No Exposed Wires	Electronics Hardware	Minimum Exposed Wires for Safety		Desired Baseline Met

Electrical Product Design Specifications							
Performance Requirement	Functional Description	Worst Acceptable Performance	Desired Baseline	Associated Subsystems	Stakeholder Expectation	Measurement Method	Current Design
Interference	Level of interference between signals	5% Noise In Signal	1% Noise in Signal				Desired Baseline Met
Thermal Insulation/Cooling	Allowable heat among circuit boards, motors, etc.	25% increase in ambient temperature due to circuit operation	10% increase in ambient temperature due to circuit processing				Cooling designed for <5% ambient temperature increase
User Interface	Ease of use with human interaction	Meets NASA Standards					Desired Baseline Met
Updates/Maintenance	Ability for system to be patched or repaired	Meets NASA Software Standards	System contains integrated features for patching, repair, and overwriting as necessary				Desired Baseline Met
Radiation Protection	Reduction of interference due to radiation	Prevents functional interference	Prevents all radiation interference				Desired Baseline Met
Physical Protection	Reduction of interface due to physical interaction	System secured and encased	System encased and secured in inaccessible location during system operation				Desired Baseline Met
Safety	Ability of system to prevent system failure, malfunction, and user injury	Prevents injury to user during standard use and preventing of malfunctioning systems	Prevents injury to user during all scenarios including malfunction, improper use, and unexpected circumstances	All	Injury prevented at all times		Desired Baseline Met

Appendix II: Electrical Definitions

I/O: Input/Output

GPIO: A generic pin on an integrated circuit whose behavior can be controlled by the user at run time.

G-code: A numerical control programming language which is capable of telling automated machine tools what to make and how to make it. G-Code will perform according to ISO 10303 STEP.

SPI: Serial Peripheral Interface is a synchronous method of communication between two devices.

EEPROM: Electronically Erasable Programmable Read Only Memory is a type of on-board flash data storage.

UART: Universal Asynchronous Receiver/Transmitter an asynchronous method of communication between two devices.

IDE: Integrated Design Environment is an inclusive programming environment complete with debuggers, compilers, and coding platform.

USB: Universal Serial Bus is a standard bus used to communicate between a computer and an electronic device.

STL: Stereo Lithography is a proprietary file type used to describe the surface geometry of a three-dimensional object that is widely used for 3D printing purposes.

Microstepping: A method for moving a stepper motor more smoothly than in full or half-step drive modes.

I2C: A serial single-ended computer bus invented by Philips. Used for attaching low-speed peripherals to a motherboard, embedded system, cellphone, or other electronic device.

Drivers:

The firmware uses a number of drivers to communicate with the hardware. Below are a list of all the drivers used and their corresponding hardware components:

Universal Asynchronous Receive Transmit (UART)

This is used to communicate with the LCD and the buttons. The UART is used to send messages to print on the display. Additionally, it is used to receive confirm messages and to detect when the buttons were pressed.

Universal Serial Bus (USB) Driver

This is used to communicate to a USB Flash device. This supports mounting and navigating through the file system. This can read all the files in a given directory and open a file descriptor to a file.

Serial Peripheral Interface (SPI)

This is used to communicate to an analog to digital converter. This uses the SPI interface to read in an eleven bit digital value. This allows reading in the temperature value on the heating module.

Pulse Width Modulation (PWM)

This is used to control a duty cycle signal. This is used to control the current flowing through the heating unit.

General Purpose Input Output (GPIO)

This allows for control of digital signals. This is used in a large number of interactions with hardware. This is used to control the signals to the stepper drivers and fans. Additionally, it is used to read in signals from the fans and from the contact sensors.

Dallas 1-wire

This uses the Dallas 1-wire communication protocol. This reads in the entire message stream sent back from one of the devices connected. This is used to read the temperature from the Integrated Circuit (IC) temperature sensors.

Classes:

Below is a list and description of each of the classes used in the final source code:

Main

This is the class that contains the program and the threads for each of the states.

HumanInterface

This is the class that contains all the code for interacting with a user.

Contact

This is the class for the contact sensors.

Fan

This is the class for the fans.

FanControl

This is the class that has all the control over the fans.

FileSystem

This is the class used to interact with the file system present on a flash device

HeatSensorModule

This is the class for the analog to digital converter.

HeatingModule

This is the class that contains all the hardware components and algorithms for the heating unit

LCD

This is the class with all the controls and communication necessary to interact with the LCD unit

Motor

This is the class that contains the motor functionality

PWM

This is the class that controls the PWM units.

SPI

This is the class that controls the SPI units

TemperatureSesnors

This is the class that controls and implements the Dallas 1-wire temperature sensors

UART

This is the class that controls the UART units

USBDevice

This class controls the interaction over the USB device

Test Files:

This outlines all the test functions performed:

testContact

Tests the contact sensors functionality

testFans

Tests the fan functionality

testHeatingModuleTemp

tests the pulse width modulation and analog to digital converter

testTemperatureSensors

tests the Dallas 1-wire IC temperature sensors

testUart

tests the uart functionality

testHumanInterface

tests the LCD, buttons, and USB flash device

Appendix III: Measuring 3D Printer Accuracy

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BADGER COMET

TEST PROCEDURE

HANDBOOK FOR 101-XX

Determination of Printed Part Accuracy and Precision



This handbook is for guidance only. Do not cite
this document as a requirement.

1. Scope

This Handbook shall control the testing of Badger COMET test parts per Badger COMET specification 101-XX. ASTM standards shall be used as the testing standards unless otherwise specified in this handbook.

2. Referenced Documents

ASTM Standards:

D618 Standard Practice for Conditioning Plastics for Testing

D883 Standard Terminology Relating to Plastics

D5947 Standard Test Methods for Physical Dimensions of Solid Plastics Specimens

3. Terminology

Terminology specified in ASTM D883 and the following terminology stated shall be used on all test summary sheets and test reports.

Peg – Cylindrical extrusion of the test specimen

Waviness – Term used for visual inspection of the side of the test specimen when the part has the visual appearance of waves similar to that seen on a body of water.

Float – Base layer printed before the test specimen is printed.

4. Testing Preparation

Test specimens shall be prepared in accordance with ASTM D618.

All specimens shall be created with the use of a float during printing.

5. Testing

Badger COMET TEST SUMMARY SHEET shall be used for documenting test data.

Visual inspection shall be completed of each test specimen and anomalies noted. In the summary sheet any anomalies that cannot be described must be accompanied by a photo of the anomaly attached to the test summary sheet.

All tests will be done in accordance with ASTM D5947 using *Apparatus A* (micrometer) per said standard. In the event that micrometer is not available a standard machinist's caliper shall be used as the measuring device.

If the micrometer being used does not have a calibrated ratchet or friction thimble in accordance with *Apparatus A* per ASTM D5947, tests will be performed by applying pressure until the test part can be lifted off the test table from the pressure applied to the part.

Certain measurements (Section 7) must be done with the use of a caliper as the measuring tool. All other measurements shall be done using a micrometer.

Measurements shall be taken in inches to a tolerance of .0001” when applicable, with a minimum tolerance of .001”.

A total of three (3) specimens shall be created and tested for each test to be considered a complete test.

6. Measurements

Measurements shall be taken at locations indicated on Badger COMET Specification 101-XX-0. Values shall be placed in Badger COMET TEST SUMMARY SHEET under the “Actual” column based on the respective measurement location.

“Nominal” values shall be taken from Badger COMET Specification 101-XX-1 based on the respective measurement location.

“Delta” values are defined using the following equation:

$$\text{Delta} = \text{Actual} - \text{Nominal}$$

“Error” values are indicate the percent error of the tested measurement and defined using the following equation:

$$\text{Error} = (\text{Delta} / \text{Nominal}) * 100$$

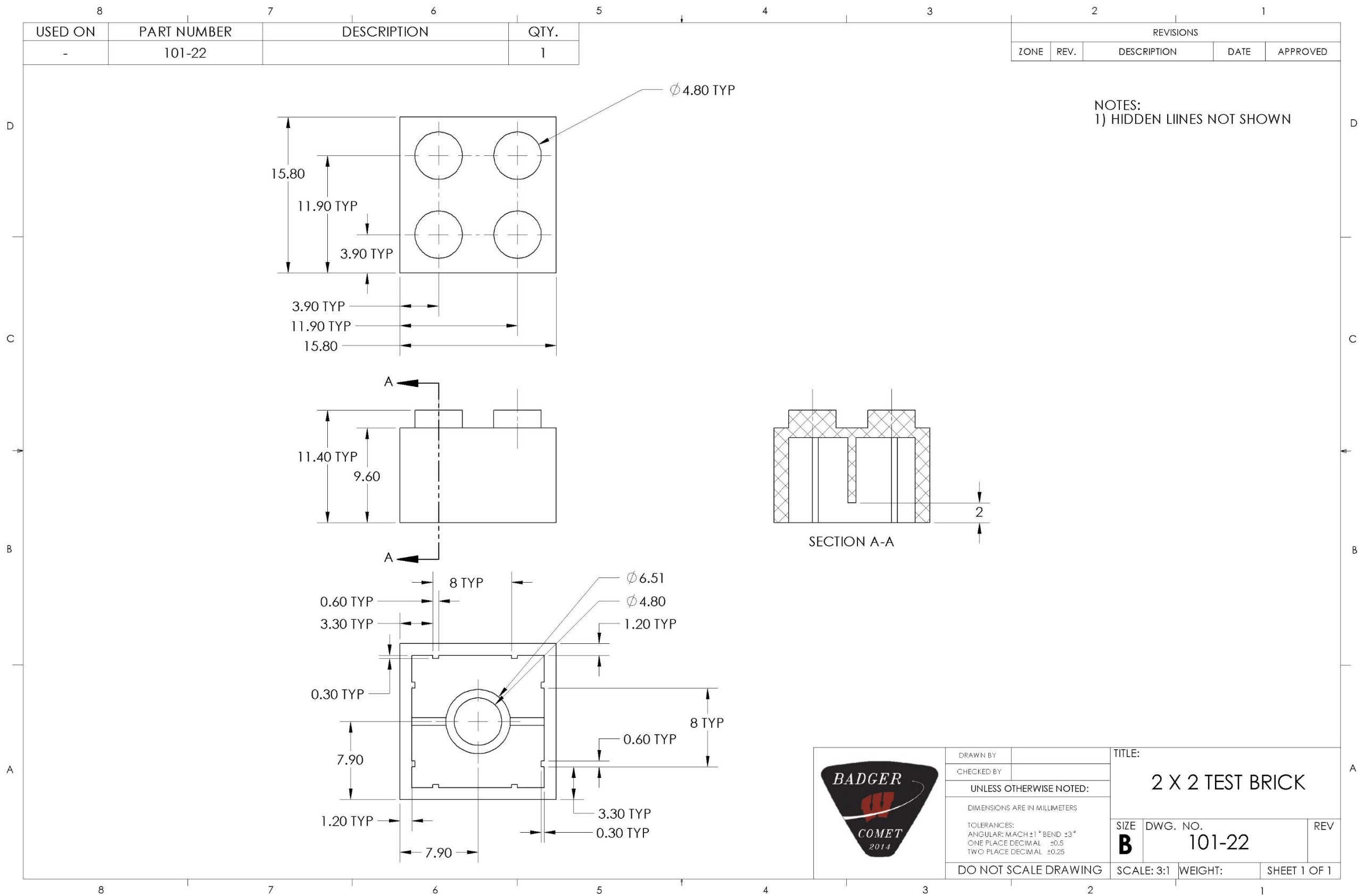
7. Variable Measurement Methods

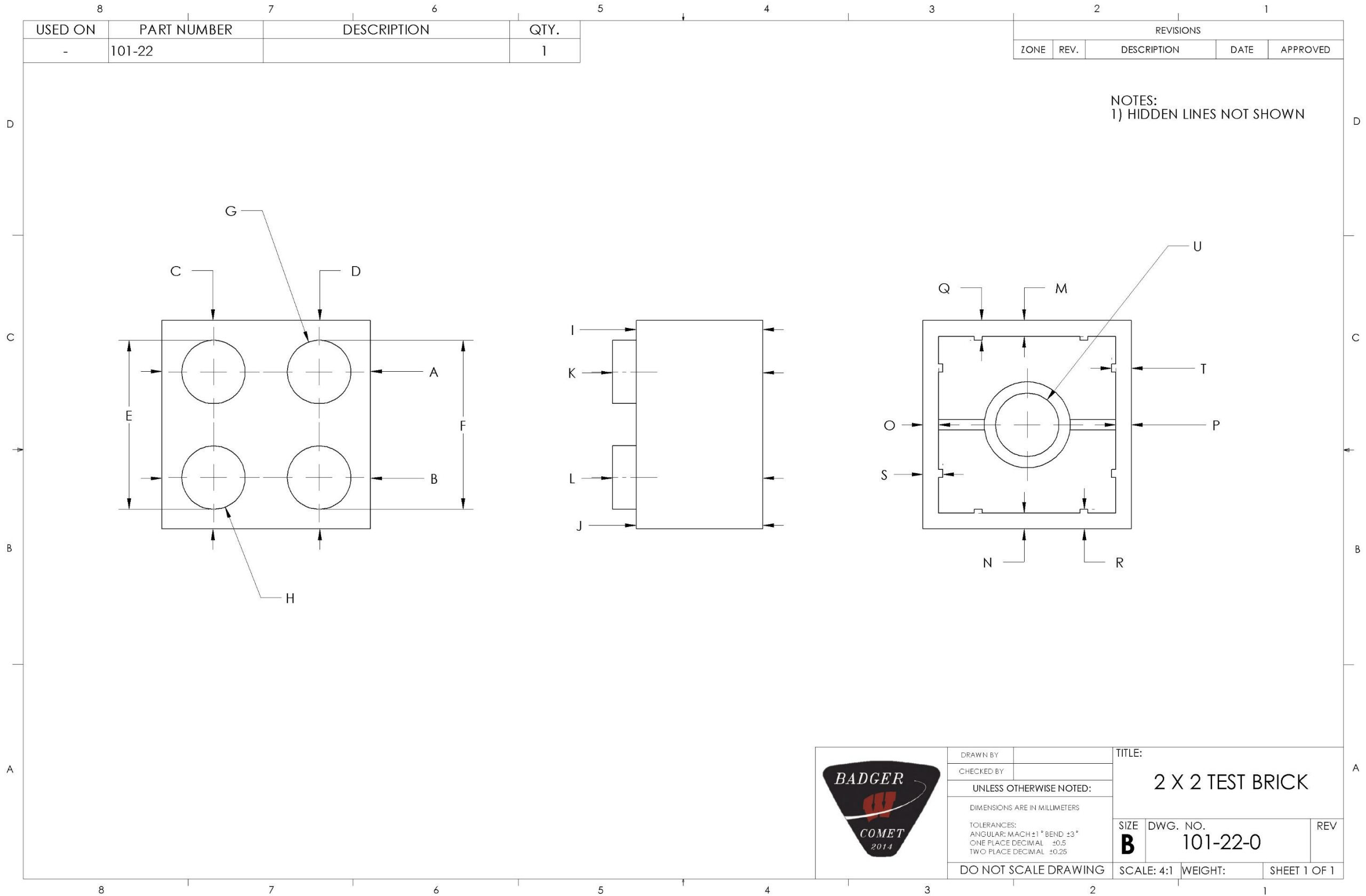
In the event that a micrometer is unable to accurately measure the specified value a machinist’s caliper shall be used as the standard measuring instrument.

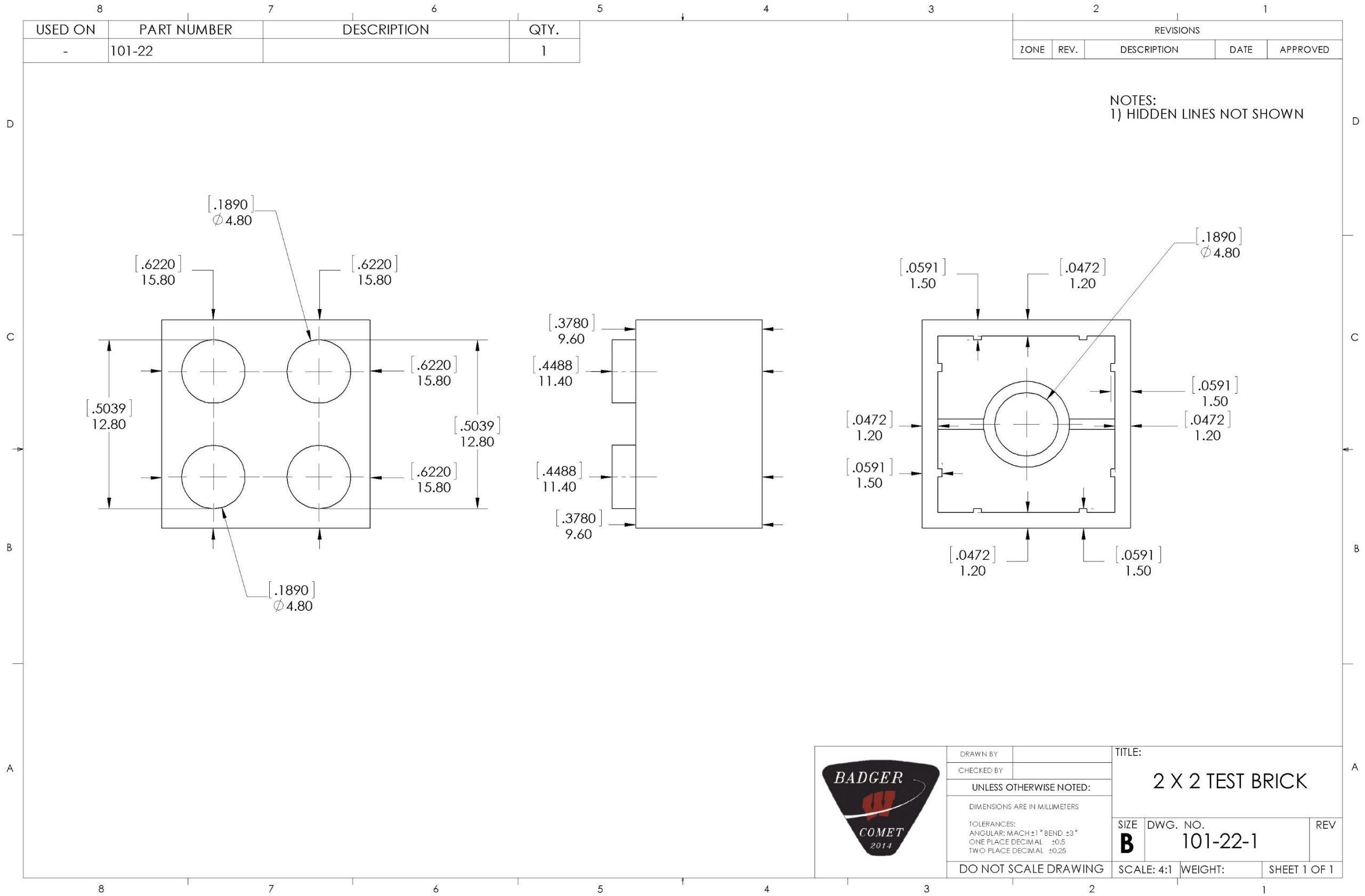
8. Report

A test summary report shall be generated for each group of tests. Badger COMET Test Report shall be used as the accepted report procedure. All Badger COMET TEST SUMMARY SHEETs created during the testing process shall be included in the report and are not considered completed without the signature of the tester.

Badger COMET TEST SUMMARY SHEET									
ITEM:		CONTRACTOR:			CONTRACTOR'S TYPE		DATE TEST START:		TEST NO:
SPEC:		PRINTER:			MANUFACTURER'S TYPE		COMPLETED:		SAMPLE NO:
TEST DIMENSION	NOMINAL	ACTUAL	DELTA	ERROR	TEST COMPLETED BY:		FILAMENT COLOR:		FILAMENT MATERIAL:
A					SIGNATURE:		PRINT SURFACE:		DATE PRINTED:
B									
C					NOTES:				
D									
E									
F									
G									
H									
I									
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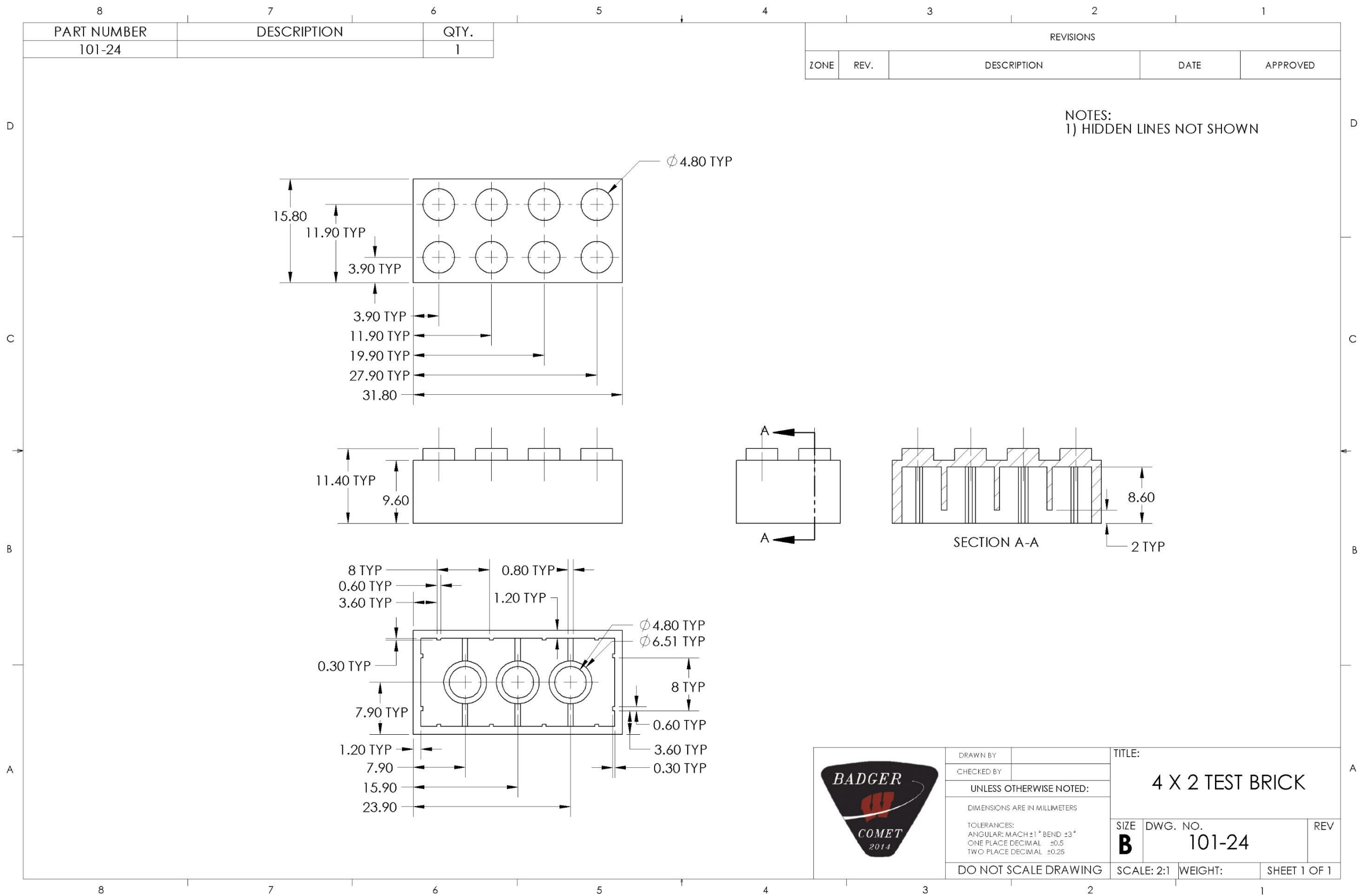


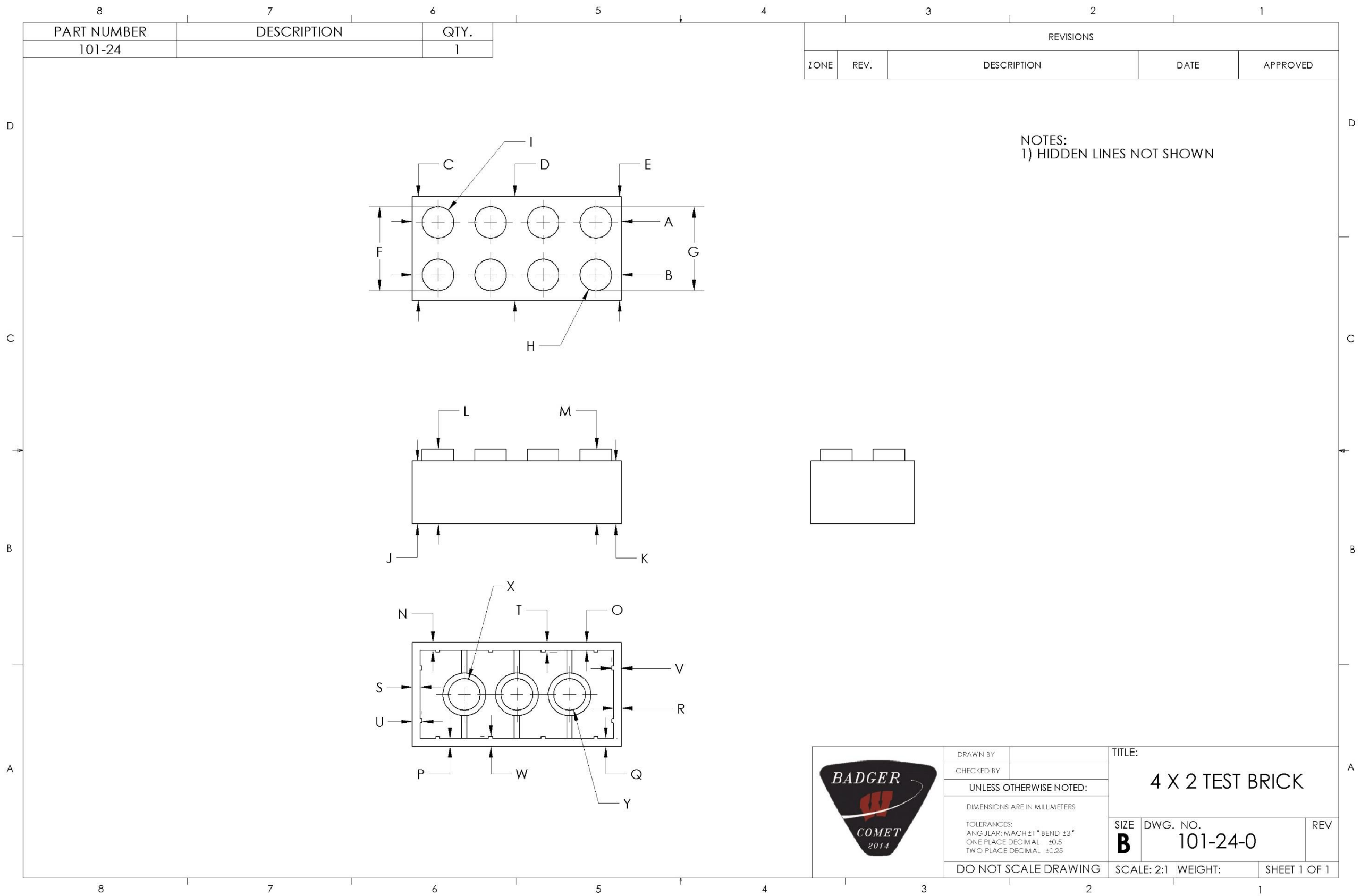


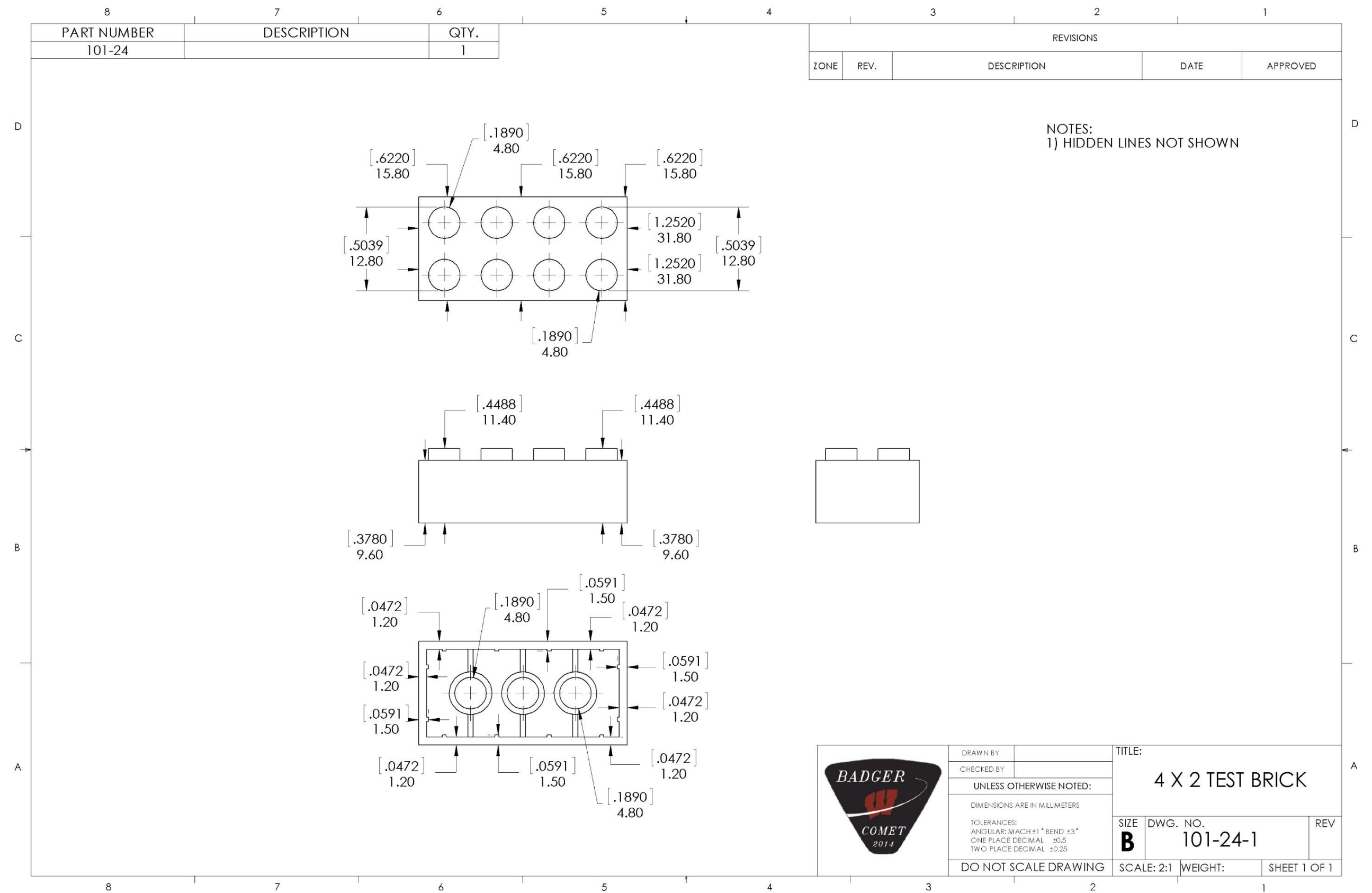


DRAWN BY		TITLE: 2 X 2 TEST BRICK		
CHECKED BY				
UNLESS OTHERWISE NOTED: DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: MACH $\pm 1^\circ$ BEND $\pm 3^\circ$ ONE PLACE DECIMAL ± 0.5 TWO PLACE DECIMAL ± 0.25				
DO NOT SCALE DRAWING		SIZE B	DWG. NO. 101-22-1	REV

SCALE: 4:1	WEIGHT:	SHEET 1 OF 1
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Appendix IV: FDM Manufacturing Materials Summary

ABS plastic can be used for fused deposition modeling. The material characteristics of ABS variants are shown in Figure 37.

Property	ABS	ABSi	ABSplus	ABS/PC
Tensile strength	22 MPa	37 MPa	36 MPa	34.8 MPa
Tensile modulus	1,627 MPa	1,915 MPa	2,265 MPa	1,827 MPa
Elongation	6%	3.1%	4%	4.3%
Flexural strength	41 MPa	61 MPa	52 MPa	50 MPa
Flexural modulus	1,834 MPa	1,820 MPa	2,198 MPa	1,863 MPa
IZOD impact	106.78 J/m ²	101.4 J/m ²	96 J/m ²	123 J/m ²
Heat deflection @ 66 psi	90°C	87°C	96°C	110°C
Heat deflection @ 264 psi	76°C	73°C	82°C	96°C
Thermal expansion	5.60E-05 in/in/F	6.7E-6 in/in/F	4.90E-05 in/in/F	4.10E-5 in/in F
Specific gravity	1.05	1.08	1.04	1.2

Figure 37: ABS Material Characteristics. Source Additive Manufacturing Technologies by Ian Gibson

Additionally, PC-based materials can be used in FDM. Typical material properties for PC-based materials are shown in Figure 3-C.

Mechanical Properties ¹	Test Method	English	Metric
Tensile Strength (Type 1, 0.125", 0.2"/min)	ASTM D638	9,800 psi	68 MPa
Tensile Modulus (Type 1, 0.125", 0.2"/min)	ASTM D638	330,000 psi	2,300 MPa
Tensile Elongation (Type 1, 0.125", 0.2"/min)	ASTM D638	5%	5%
Flexural Strength (Method 1, 0.05"/min)	ASTM D790	15,100 psi	104 MPa
Flexural Modulus (Method 1, 0.05"/min)	ASTM D790	324,000 psi	2,200 MPa
IZOD Impact, notched (Method A, 23°C)	ASTM D256	1 ft-lb/in	53 J/m
IZOD Impact, un-notched (Method A, 23°C)	ASTM D256	6 ft-lb/in	320 J/m

Thermal Properties ²	Test Method	English	Metric
Heat Deflection (HDT) @ 66 psi	ASTM D648	280°F	138°C
Heat Deflection (HDT) @ 264 psi	ASTM D648	261°F	127°C
Vicat Softening	ASTM D1525	282°F	139°C
Glass Transition (Tg)	DMA (SSYS)	322°F	161°C
Melt Point	-----	Not Applicable ³	Not Applicable ³

Electrical Properties ⁴	Test Method	Value Range
Volume Resistivity	ASTM D257	2.0x10e14 - 6.0x10e13 ohms
Dielectric Constant	ASTM D150-98	3.0 - 2.8
Dissipation Factor	ASTM D150-98	.0006 - .0005
Dielectric Strength	ASTM D149-09, Method A	360-80 V/mil

Other ²	Test Method	Value
Specific Gravity	ASTM D792	1.2
Flame Classification	UL94	HB
Coefficient of Thermal Expansion	ASTM E831	3.8E-05 in/in/°F
Rockwell Hardness	ASTM D785	R115
UL File Number	-----	E345258

Figure 1-C: PC-based Material Characteristics. Source: Fortus 3D Production Systems

Next, Polyphenylsulfone (PPSF) can be used in Fused Deposition Modeling. PPSF material characteristics are shown in Figure 4-C.

Mechanical Properties ¹	Test Method	English	Metric
Tensile Strength (Type 1, 0.125", 0.2"/min)	ASTM D638	8,000 psi	55 MPa
Tensile Modulus (Type 1, 0.125", 0.2"/min)	ASTM D638	300,000 psi	2,068 MPa
Tensile Elongation (Type 1, 0.125", 0.2"/min)	ASTM D638	3%	3%
Flexural Strength (Method 1, 0.05"/min)	ASTM D790	15,900 psi	110 MPa
Flexural Modulus (Method 1, 0.05"/min)	ASTM D790	320,000 psi	2,206 MPa
IZOD Impact, notched (Method A, 23°C)	ASTM D256	1.1 ft-lb/in	58.73 J/m
IZOD Impact, un-notched (Method A, 23°C)	ASTM D256	3.1 ft-lb/in	165.5 J/m

Thermal Properties ³	Test Method	English	Metric
Heat Deflection (HDT) @ 264 psi	ASTM D648	372°F	189°C
Glass Transition Temperature (T _g)	DMA (SSYS)	446°F	230°C
Coefficient of Thermal Expansion	ASTM D696	3.1 E -05 in/in/°F	5.5 E -05 mm/mm/°C
Melt Point	-----	Not Applicable ²	Not Applicable ²

Other ³	Test Method	Value
Specific Gravity	ASTM D792	1.28
Flame Classification	UL 94	V0 (0.126", 3.2 mm)
Rockwell Hardness	ASTM D785	M86
Dielectric Strength	IEC 60112	14.6 kV/mm
Dielectric Constant @ 60 Hz	IEC 60250	3.45

Environmental Resistance ⁴	24 hours @ 23°C (73°F)	24 hours @ 100°C (212°F)
Antifreeze (Prestone), 50%	Passed	Passed
Gasoline-Unleaded	Passed	Not tested
Motor Oil 10W-40	Passed	Passed
Power Steering Fluid	Passed	Passed
Transmission Fluid	Passed	Passed
Windshield Washer Fluid, 50%	Passed	Not tested

System Availability	Layer Thickness Capability	Support Structure	Available Colors
Fortus 400mc Fortus 900mc	0.013 inch (0.330 mm) ¹ 0.010 inch (0.254 mm)	BASS	■ Tan

¹0.013 inch (0.330 mm) layer thickness not available on Fortus 900mc.

Figure 2-C: Material Characteristics of Polyphenylsulfone (PPSF). Source: Fortus 3D Production Systems

Also, polylactic acid (PLA) is commonly used for fused deposition modeling. The material properties of PLA are shown in Figure 5-C.

Physical	Nominal Value	Unit	Test Method
Specific Gravity			
--	1.24		ASTM D792
73°F	1.24 to 1.27	g/cm ³	ISO 1183
Melt Mass-Flow Rate (MFR)			
210°C/2.16 kg	6.0 to 78	g/10 min	ASTM D1238
190°C/2.16 kg	2.3 to 35	g/10 min	ISO 1133
Molding Shrinkage			
Flow: 73°F	0.0040 to 0.0042	in/in	ASTM D955
73°F	0.30 to 1.1	%	ISO 294-4
Mechanical	Nominal Value	Unit	Test Method
Tensile Modulus			
73°F	293000 to 514000	psi	ASTM D638
73°F	96500 to 516000	psi	ISO 527-2
Tensile Strength			
Yield, 73°F	6870 to 7020	psi	ASTM D638
Yield, 73°F	2860 to 10400	psi	ISO 527-2
Break, 73°F	7080 to 8150	psi	ASTM D638
Break, 73°F	2320 to 10200	psi	ISO 527-2
73°F	6350 to 10000	psi	ASTM D638
Tensile Elongation			
Yield, 73°F	3.9 to 10	%	ASTM D638
Yield, 73°F	1.0 to 8.5	%	ISO 527-2
Break, 73°F	1.5 to 10	%	ASTM D638
Break, 73°F	1.0 to 7.2	%	ISO 527-2
Flexural Modulus			
73°F	347000 to 684000	psi	ASTM D790
73°F	319000 to 1.38E+6	psi	ISO 178
Flexural Strength			
73°F	6990 to 14200	psi	ASTM D790
73°F	5000 to 16100	psi	ISO 178

Impact	Nominal Value Unit	Test Method
Charpy Notched Impact Strength (73°F)	0.71 to 2.7 ft-lb/in ²	ISO 179
Notched Izod Impact		
73°F	0.24 to 1.1 ft-lb/in	ASTM D256
73°F	1.6 to 3.0 ft-lb/in ²	ISO 180
Thermal	Nominal Value Unit	Test Method
Deflection Temperature Under Load		
66 psi, Unannealed	124 to 126 °F	ASTM D648
66 psi, Unannealed	122 to 284 °F	ISO 75-2/B
264 psi, Unannealed	118 to 122 °F	ISO 75-2/A
Glass Transition Temperature (DSC)	133 to 145 °F	DSC
Melting Temperature	315 to 338 °F	
Peak Crystallization Temperature (DSC)	266 to 332 °F	ASTM D3418
Injection	Nominal Value Unit	
Drying Temperature	120 to 172 °F	
Drying Time	3.8 to 4.0 hr	
Suggested Max Moisture	0.010 to 0.30 %	
Rear Temperature	302 to 356 °F	
Middle Temperature	338 to 410 °F	
Front Temperature	374 to 393 °F	
Nozzle Temperature	375 to 402 °F	
Processing (Melt) Temp	353 to 464 °F	
Mold Temperature	60.1 to 221 °F	
Injection Pressure	11400 to 11500 psi	
Back Pressure	72.5 to 160 psi	
Screw Speed	75 to 150 rpm	
Injection Notes		
This data represents typical values that have been calculated from all products classified as: Generic PLA		
This information is provided for comparative purposes only.		
Extrusion	Nominal Value Unit	
Drying Temperature	113 to 195 °F	
Drying Time	2.8 to 10 hr	
Suggested Max Moisture	0.0050 to 0.30 %	
Cylinder Zone 1 Temp.	320 to 374 °F	
Cylinder Zone 2 Temp.	331 to 377 °F	
Cylinder Zone 3 Temp.	335 to 402 °F	
Adapter Temperature	338 to 392 °F	
Melt Temperature	373 to 446 °F	
Die Temperature	329 to 390 °F	
Extrusion Notes		
This data represents typical values that have been calculated from all products classified as: Generic PLA		
This information is provided for comparative purposes only.		
Notes		
¹ Typical properties: these are not to be construed as specifications.		

Figure 3-C: Material Properties of Polylactic Acid. Source: ides.com

Finally, Ultem provides excellent strength and rigidity, and its material properties are shown in Figure 6-C.

PHYSICAL	Specific Gravity	D792	-	1.27	1.34	1.42	1.51
	Water Absorption, @24 hours, 73°F (23°C)	D570	%	0.25	0.21	0.19	0.16
	@Equilibrium, 73°F (23°C)			1.25	1.20	1.10	0.90
MECHANICAL	Tensile Strength, Break, 73°F	D638	psi	15,200	16,600	20,100	17,500
	Tensile Modulus, 73°F	D638	psi	430,000	650,000	1,000,000	900,000
	Elongation, Break, 73°F	D638	%	40	6	3	3
	Elongation, Yield, 73°F	D638	%	7-8	5	N/A	N/A
	Flexural Strength, 73°F	D790	psi	22,000	28,000	30,000	25,000
	Flexural Modulus, 73°F	D790	psi	480,000	650,000	900,000	750,000
	Izod Impact Strength, Notched, 73°F	D256	ft-lbs/in	1.0	1.1	1.6	1.1
	Rockwell Hardness	D785	"M" Scale	109	114	114	110
	Compressive Strength	D695	psi	21,900	22,000	28,700	30,700
	Compressive Modulus	D695	psi	480,000	541,000	809,000	938,000
	Shear Strength, Ultimate	-	psi	15,000	13,000	13,500	14,000
THERMAL	Deflection Temperature	D648	°F	-	-	-	-
	@ 66 psi, 1/4"	-	°F	410	410	410	414
	@264 psi, 1/4"	-	°F	394	405	408	410
	Coefficient of Thermal Expansion, Flow	D696	in/in-°F	3.1 x 10 ⁻⁵	1.8 x 10 ⁻⁵	1.4 x 10 ⁻⁵	1.1 x 10 ⁻⁵
	Vicat Softening Point	D1525	°F	426	-	-	-
	Thermal Conductivity	D2214	BTU-in/hr-ft ² -°F	1.5	1.22	1.43	1.56
ELECTRICAL	Flammability	UL94	-	V-0	V-0	V-0	V-0
	Dielectric Strength, In Oil	D149	V/mil	710	700	670	630
	In Air	-	-	830	-	-	770
	Dielectric Constant, 1kHz, 50% RH	D150	-	-	-	-	-
	Dissipation Factor 1kHz, 50% RH, 73°F (23°C)	D150	-	3.15	3.5	3.5	3.7
	Volume Resistivity, 1/16"	D257	ohm-cm	1.0 x 10 ¹⁷	1.0 x 10 ¹⁷	70 x 10 ¹⁶	3.0 x 10 ¹⁶

This information is only to assist and advise you on current technical knowledge and is given without obligation or liability. All trade and patent rights should be observed. All rights reserved. Data obtained from extruded shapes material. ULTEM® Sabic Innovative. *Extruded. **Injection Molded.

MATERIAL AVAILABILITY

Rods: Diameters: 3/16" to 6"
Length 3/16" to 4-3/4" – 10'
5" to 6" – 5' (only natural material)

Plates: 1/4" to 4" thickness inclusive are 2' x 4'

Primary Specification (Resin) (Typical)

Ultem® Unreinforced ASTM-D-5205 PEI0113
Ultem® 20% Glass Reinforced ASTM-D-5205 PEI0110G20 A99269 159MPa, 7586MPa, 208C
Ultem® 30% Glass Reinforced ASTM-D-5205 PEI0110G30 A96299 159MPa, 224MPa, 208C

Figure 4-C: Material Properties of Polyetherimide (Ulthem). Source: San Diego Plastics