University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018
Project Definition Document (PDD)
3D Printed Solid Rocket Motors

Approvals

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1.0 Problem or Need

Current Solid Rocket Motors (SRM) manufacturing has limitations based on the available cross sections (bores) in which propellant can be cast. The different cross sections allow customization of each rocket's thrust profile to meet specific mission requirements[1], however only certain cross sections can be created because the casting process is limited by the thickness and ease of cracking of the casting material[2]. Missions that might benefit from more complex three-dimensional cross sections currently have to settle for traditional SRM manufacturing technologies. Creating a 3D printer capable of printing solid rocket fuel will allow for the design and production of more complex cross sections such as the ones shown in Figure 1.

This project will focus on modifying an existing automated additive manufacturing machine in order to manufacture sugar-based SRM's in cross sections similar to those in Figure 1. The printed motors must contain both a fuel and an oxidizer and therefore be classified as SRM's and **not** hybrid rocket motors. Validation will focus on the accuracy of the printer in its ability to produce SRM shapes while verifying propellant integrity. Successful completion of this project will allow future testing of new and complex cross-sections that would otherwise be impossible to form using traditional casting techniques.

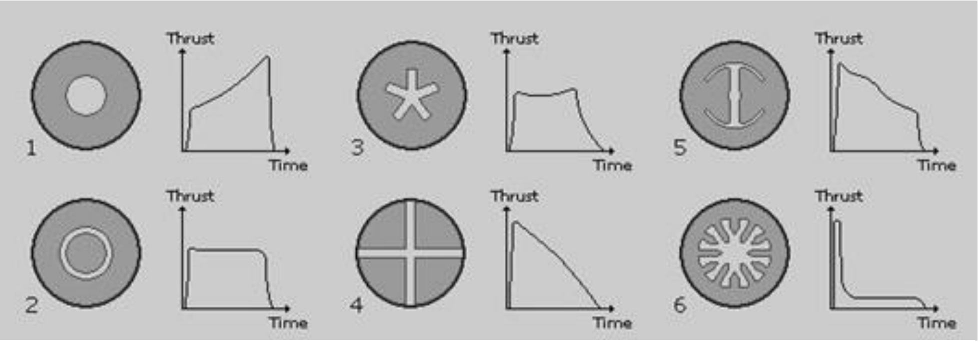

Figure 1- Examples of SRM cross section designs [3]

2.0 Previous Work[1]

Most commercial 3D printers print one of two plastics: acrylonitrile butadiene styrene (ABS) or Polyactic acid (PLA).[4] These are melted and cooled to produce intricate designs and shapes pre-modeled in 3D software.[5] Other materials introduced over the years include metal, carbon fiber, plastic composites, and Kevlar.[6] One company, Stratasys, has formed a hybrid rocket motor through 3D printing using an ABS base with a fuel additive[7]; however, their design only prints the fuel. Only with the addition of an oxidizer such as liquid N2O can these motors be ignited. A basic diagram of additively manufactured ABS hybrid fuel material is shown in Figure 2.

The novelty of this project lies in the design of a printer that produces valid SRMs. The printed material will be ready for immediate ignition. Future applications may include a larger print volume. Printing a 15 cm diameter “propellant cake” could provide an O-class or greater solid rocket motor, giving 970 lbs of thrust. [8]

Figure 2 - ABS Hybrid Fuel

3.0 Specific Objectives

This project aims to additively manufacture sugar-KNO_3 solid rocket propellant into specific bore patterns. Through the addition of heat, solid granules of sugar and potassium nitrate are bonded together into a specific geometric shape.

The sugar-KNO_3 propellant needs characterization as soon as possible -- specifically the phase changes. The process sugar propellant undergoes as it experiences heat transfer and phase changes must be understood to then consider printer design options.

Safety is the primary concern for the team and for the University of Colorado. However, fire is extremely likely despite full safety compliance. It is the duty of the team to comply with all safety standards throughout all levels of the project, and to defer to faculty concerning safety. To reduce the risk in the manufacturing and testing processes, no single point of failure shall exist in any system dealing with reactive material.

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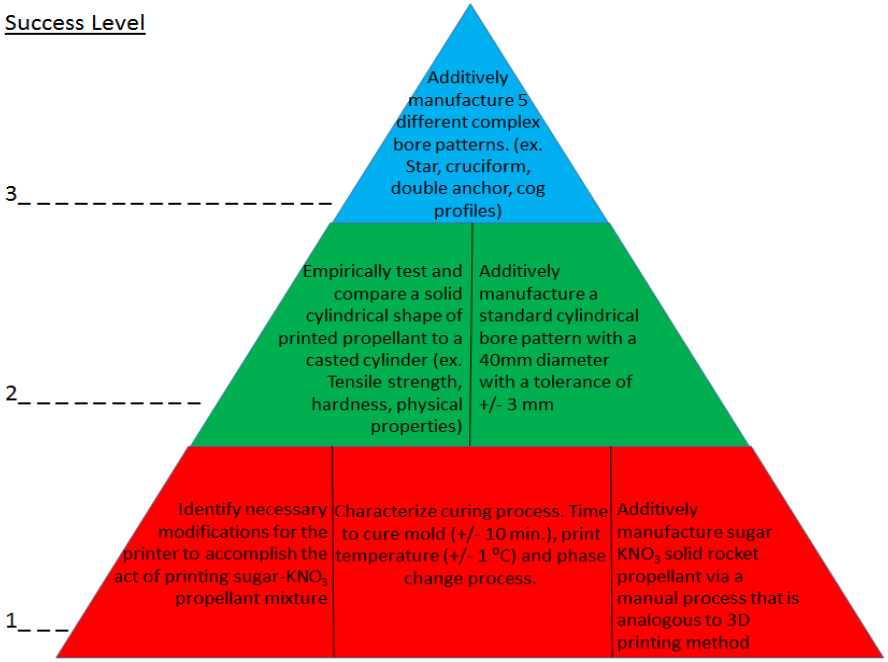

Additively manufacture 5 different complex bore patterns. (ex. Star, cruciform, double anchor, cog profiles)

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

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

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

Characterize curing process. Time to cure mold (+/- 10 min.), print temperature (+/- 1 ºC) and phase change process.

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

The propellant will undergo various phase changes due to heat transfer during manufacture. First, the team must characterize the behavior of propellant due to thermal effects in powder, liquid, and solid phases. Next, the team must compare printed characteristics (physical and chemical) with those of a traditionally cast SRM of the same fuel mixture. Physical characteristics that the team will consider include the dimensions of the printed motor, the tensile strength, the final material hardness, and other parameters. A thermodynamic analysis will also likely be used to determine the enthalpy released from the rocket motor. However, no consideration will be given to the actual thrust profile of the motor since a propulsion analysis is outside the scope of this project. Finally, the team must produce various printed SRMs with complex bore patterns, as on page 2.

4.0 Functional Requirements

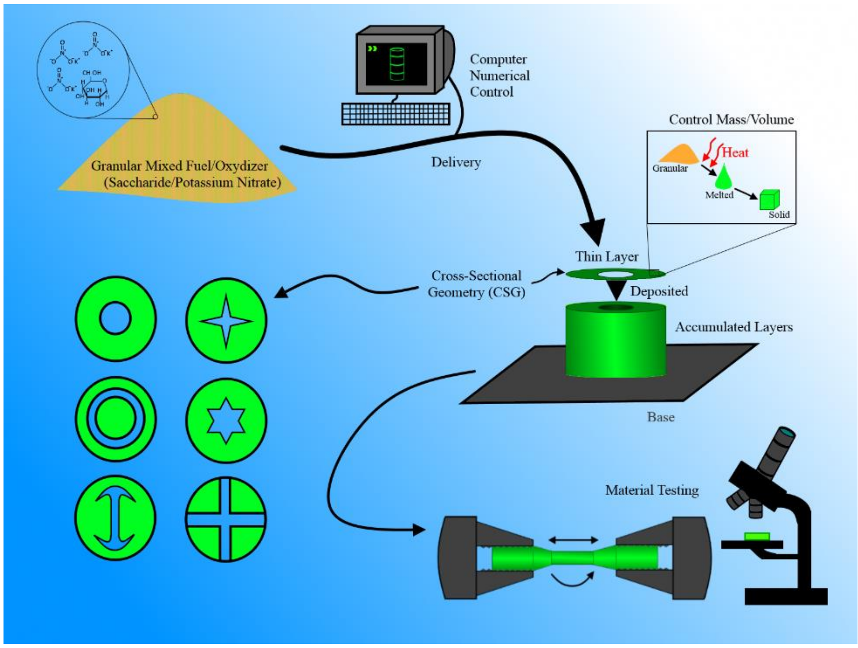

Figure 3 - Project CONOPs

The CONOPs (Figure 3) illustrates the project and its component interfaces at a high level. Ultimately, the project shall begin with raw ingredients for solid rocket fuel, use additive manufacturing to create a functional motor of size at least equivalent to a model size D, and gather test data to compare the motor’s structural performance against equivalent model rocket engines made by casting. The project elements naturally separate into matching functional steps and hardware pairings as follows: mixing the propellant to the desired composition, delivering the propellant to the printing device, manufacturing the solid motor via additive methods, and comparing the physical characteristics of the printed motor to a cast motor. Further development of requirements and a trade study shall refine the specifics of both component designs and interfaces as yet to be determined. Safety concerns encompass the entire CONOPs and predominantly drive the specific procedures of the functional steps that in turn define the parameters and mechanisms of the associated hardware.

Shown in Figure 4 is a Functional Block Diagram (FBD) for the solid rocket propellant additive manufacturing system. The legend underneath the FBD shows the meanings of the different colored arrows and boxes in the FBD. If two boxes are physically touching in the FBD, then those two elements in the Additive Manufacturing system are physically connected. Several elements in the FBD were left vague intentionally so that the system design space is not unnecessarily constrained.

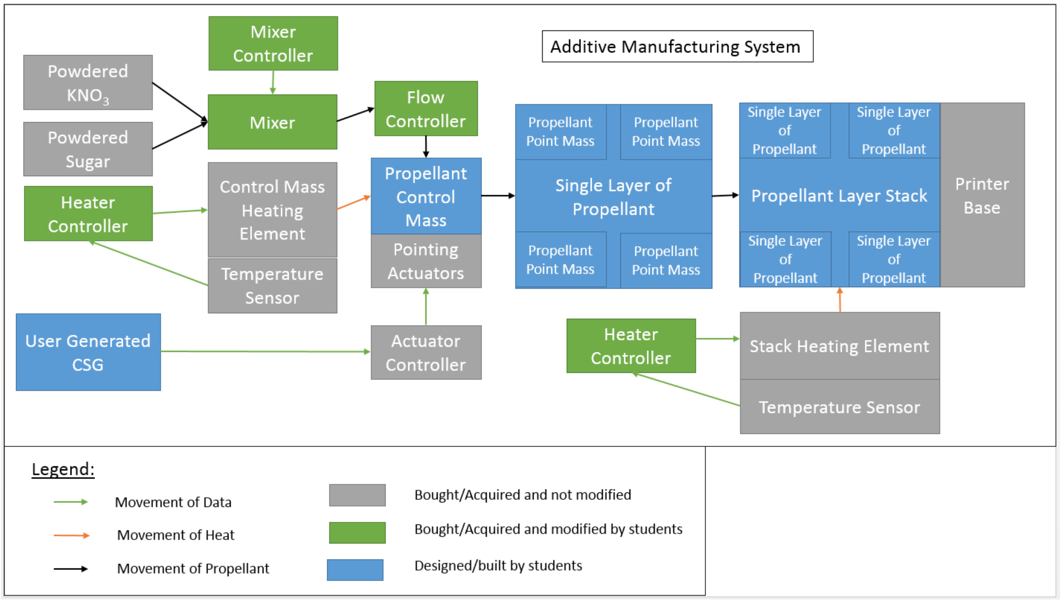

Figure 4 - Project FBD

The system works by mixing powdered potassium nitrate and powdered sugar with an automated mixer. The mixed propellant powder then moves through a flow controller. The flow controller limits the mass of propellant mixer that will be used in the propellant control mass. The propellant control mass is heated to its melting point by the control mass heating element. The temperature of the element is measured by a temperature sensor. The temperature sensor reports the measured temperature of the heating element to the heater controller. The heater controller adjusts the commanded temperature of the heating element to maintain the desired temperature. A pointing actuator or pointing actuators move the propellant control mass. The actuator controllers command the actuators to move the control mass to a desired location based on a user input Cross-Sectional Geometry (CSG). A single layer of propellant is made by placing large numbers of control masses into the desired location on top of the propellant layer stack. The propellant layer stack is made by stacking single propellant layers on top of one another. The propellant layer stack is placed on top of the printer base plate. The temperature of the propellant layer stack is controlled by the Stack Heating element, which operates in a similar manner as the control mass heating element. The stack heating element seeks to maintain a uniform temperature for propellant curing.

5.0 Critical Project Elements

5.1 Printer

Determining a specific 3D printer to modify is critical to the project. Material jetting, fuse deposition modelling (FDM) and powder bed fusion printers are current additive manufacturing techniques that could be modified to print the propellant. Cost, reliability, and technology readiness level are some important factors that will heavily influence printer selection.

5.2 Safety

Based on the flammability of the monopropellant, safety will be critical to the project. The manufacturing process will occur in a designated facility equipped to handle open flames, and safety procedures and documentation will reduce the risk and consequence of propellant ignition. To ensure safety and printer integrity, no single point failure can exist.

5.3 State of Health (SOH) System

Gathering real time data about the system as a whole is vital to ensuring that the system safety and reliability. The SOH system might record chamber pressure, chamber temperature, nozzle temperature, bed temperature, mass flow rate, or other to-be-determined parameters. Data about the condition of critical components provides improved safety, control, production quality, and hardware longevity.

5.4 Propellant Handling/Mechanical Transport System

The mechanical aspect of the propellant mixing and transport might include a mixing chamber, tubes, pumps, pipes, valves or other hardware. The printer selection as well as the characteristics of the working material largely drive this design choice.

5.5 Design Integration

The full system integration of the mixing apparatus, the SOH system, and the printer stands out as another critical component. Software modifications on the printer might need to be made to account for the different printing material and system temperature requirements, and overall system power budgeting need consideration.

6.0 Team Skills and Interests

Team Member	Skills/Interests
Cameron Brown	UAV Avionics (Beaglebone/Arduino microcontrollers, Matlab, Python, Linux OS, Solidworks CAD
Erick Chewakin	Matlab, C, Python, Jython, Scala, Bash, Gherkin, Mathematical modelling/simulation, LaTeX
Max Feldman	Systems integration and testing, CREO 2.0 modeling, manufacturing (welding), 3D Printing Experience
Anthony Lima	Matlab, Python, Bash, C++, Solidworks, 3D Printing Experience, Circuit Design/Manufacturing, Rocket Propellant Chemistry
Nicholas Lindholm	Python, Java, Fortran, Groovy, Solidworks, SolidCAM, CNC Manufacturing
Caleb Lipscomb	C/C++, Python, Mathematical Modeling, PCB Designing/Manufacturing, Arduino Microcontroller, Rocket Propellant Chemistry
Ryan Niedzinski	Java, C, C++, Python, Scala, C sharp, SQL, Visual Basic

Jonathan Sobol	UAV Avionics (Arduino), EFK and Control Algorithms in C, C++, UAV modeling and testing, Chemistry/Thermodynamics of Rocket Propulsion

Critical Project Elements	**Applicable Skills**	**Team Member With Associated Skills**
Printer	-Chemical -Electrical -Mechanical -Modeling -Software	Cameron, Erick, Max, Anthony, Nicholas, Ryan, Caleb, Jonathan
Safety	-Documentation -Testing	Erick, Max, Jonathan
State of Health (SOH) System	-Electrical -Mechanical	Max, Anthony, Caleb, Jonathan
Material Delivery to Printer Area	-Chemical -Mechanical -Modeling -Software	Cameron, Erick, Anthony, Nicholas, Caleb, Ryan
Design Integration	-Electrical -Mechanical -Software -Testing	Cameron, Erick, Max, Anthony, Caleb, Ryan, Jonathan

7.0 Resources

Critical Project Elements	**Resource/Source: Equipment, Software, Facilities, Personnel**
3D Printer	-Purchase commercially available 3D printer, open source, or requisition from S.A.S. -Hardware modifications may include electrical components -Open source software modifications
Safety	-Known and documented equipment/fuel limitations -Procedure documentation on safe printer use -Handling hazardous material must have proper fire extinguisher and procedures in place to prevent and deal with emergency situations. -Safe testing area for the printer and fume hood for mixed propellant
State of Health System (SOH)	-Temperature, pressure, voltage sensors as needed for design-specific printer modifications -Trudy Schwartz and Matt Rhode expertise on critical locations and how to monitor them in the printer
Material Delivery to Printer Area	-Reservoir material for dry propellant mixture (Aluminum or plastic) -Mixing apparatus to evenly distribute fuel and oxidizer
Design Integration	-Combined software, hardware, electrical modifications to propellant delivery, sugar caramelization, and software adjustments into a single cohesive device -Facility needed for printer storage and fire safe are for printer testing -Matt Rhode machine shop use for modification integration into the printer

8.0 References

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