University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

MEDUSA

Methane **E**ngine **D**esign for **U**nmanned **S**mall **A**ircraft
Conceptual Design Document

September 29, 2014

1.0 Information

1.1 Project Customer

RYAN STARKEY
AES, University of Colorado at Boulder
Boulder, CO 80309

(303) 492-0871
rstarkey@colorado.edu

1.2 Group Members

Huikang Ma (303) 903-0682 huikang.ma@colorado.edu	Daniel Frazier (720) 470 – 1887 daniel.frazier@colorado.edu	Crawford Leeds (401) 595-7606 crawford.leeds@colorado.edu
Corey Wilson (719) 200-4623 corey.a.wilson@colorado.edu	Carlos Torres (720) 384-7344 torrescp@colorado.edu	Alexander Truskowski (303) 945-6291 altr6476@colorado.edu
Christopher Jirucha (719) 322-7937 chji5281@colorado.edu	Abram Jorgenson (303) 204-8138 abram.jorgenson@colorado.edu	Nathan Genrich (720) 936-5958 nage9899@colorado.edu

Table of Contents

2.0 Project Description

The JetCat P90-RXi engine is a miniature turbojet gas turbine, which currently runs on kerosene fuel. Methane fuel, as opposed to kerosene, features lighter weights, easier combustion, increased cost effectiveness, and the production of more thrust per unit mass of fuel than kerosene. Thus, the mission of this team is to modify the engine to use gaseous methane as a fuel instead of kerosene, investigating the feasibility of methane as a fuel for a wider scope of mini turbojet engines.

2.1 Purpose

The Methane Engine Design for Unmanned Small Aircraft (MEDUSA) team will modify an existing JetCat P90-RXI engine that uses a kerosene-oil mixture for both fuel and lubrication to run off gaseous methane as a fuel source. In order to complete this conversion, three critical subsystems of the engine must be modified, including the Engine Control Unit(ECU), the Fuel Delivery System(FDS) and the Combustion Can(CC). The other subsystems of the engine will not be modified, as they are not necessary for running the engine on methane. The following sections describe how this will be accomplished beginning with the overall purpose and objectives of the project followed by a more detailed description in the concept of operations and functional block diagram.

Figure 1: Stock JetCat P90-RXi Turbine with Engine Control Unit

2.2 Objectives

MEDUSA will modify the three main subsystems, including the ECU, FDS, and CC, under the functional requirement of running the engine on Methane. The current ECU is a “black box”, meaning there is little to no community or professional support. The ECU has been known to shut down the engine whenever any modification is made, and cannot be understood without support from JetCat beyond what they currently provide. Thus, an entirely new ECU is required that can operate the engine with fully known functionality. The original ECU will be completely removed and replaced with a new ECU to have the desired control over the engine. The new ECU will input data from two sensors – an RPM sensor on the compressor and a thermocouple on the exhaust port. The output of the ECU is a single commanded fuel flow that will be sent to the FDS. The hardware and software used will be determined using the results of a trade study. The new ECU will be tested using a companion engine simulator, capable of creating simulated engine outputs (RPM, exhaust temperature) based on the commanded fuel flow by the ECU.

The current kerosene based FDS uses one main line to supply a kerosene oil mixture to both the bearings and the CC. This is configured for liquid fuels only. The FDS modifications must facilitate the transportation of gaseous fuel, to supply the CC with the required methane fuel, while maintaining the ability to also provide a kerosene-oil mixture for lubrication. Thus, the fuel line and lubrication line must be separated in order to allow the delivery of kerosene-oil lubricant to the bearings, and methane fuel to the CC without any mixing. The FDS will be tested outside of the engine before integration in order to measure the systems capabilities, verifying the ability of the FDS to deliver the required fuel and lubricant amounts. Part of the test will also be tested to ensure the FDS acts as desired in the case of a failure. The FDS must “fail shut,” meaning that a failure of the system will cause the system to shut off the fuel flow, rather than either remain on, or allow full fuel flow.

The current CC is designed for burning kerosene, and thus is designed around the burning temperature of kerosene. Methane burns at a higher temperature than kerosene, and thus will force the current CC and turbine to expand if the temperature is not controlled. The Combustion Can will be modified in order to control the exhaust temperature and prevent the expansion and subsequent grinding of the turbine. A model of the CC will be used to analyze the temperature changes and will drive the Combustion Can redesign.

2.3 Concept of Operations

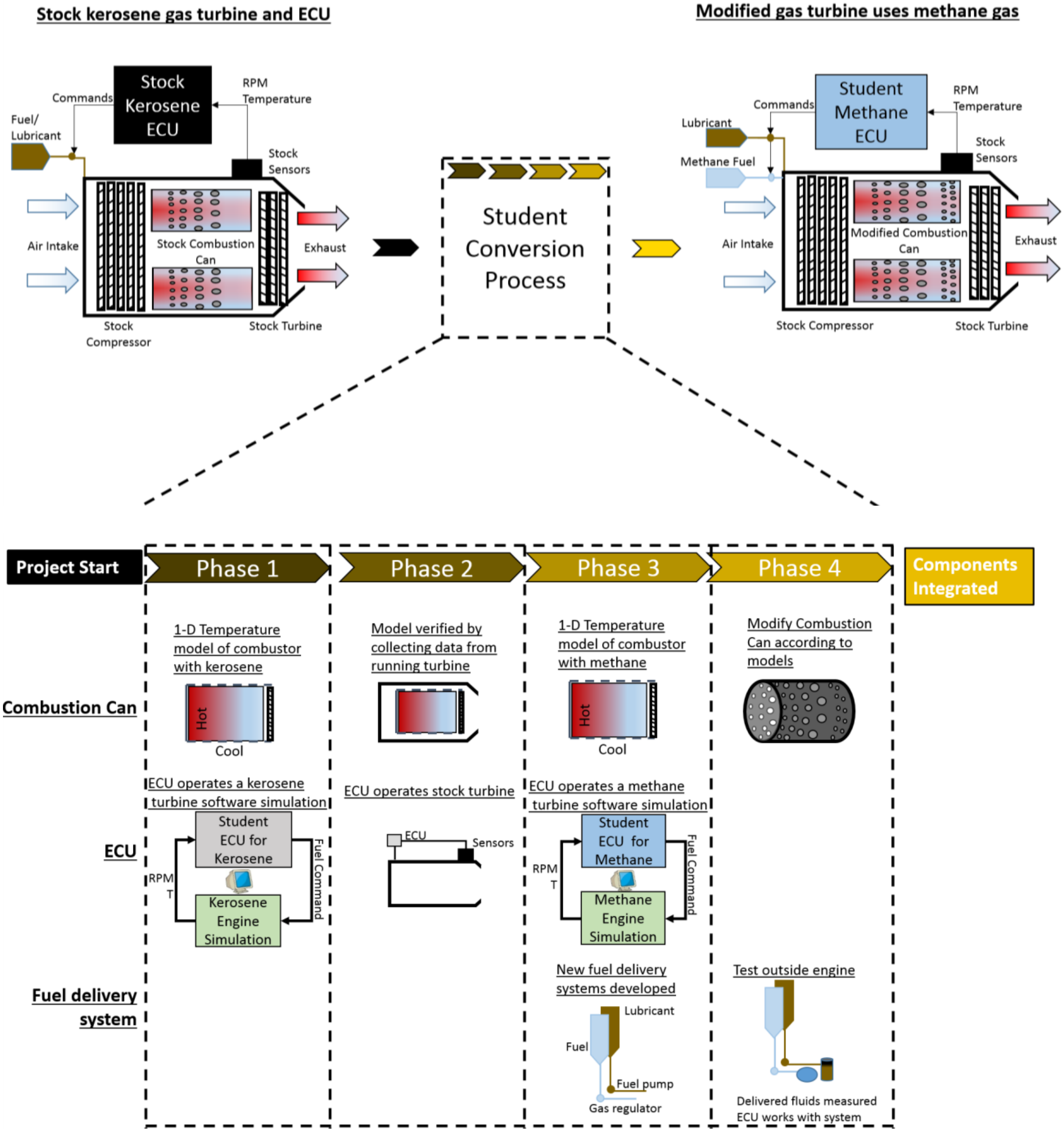


Figure 2: Mission Concept of Operations

Figure 2 illustrates the project's Concept of Operations (ConOps) which outlines the evolution of the critical components from development to integration. This ConOps does not detail how the gas turbine will run since the design components will be run simultaneously. Instead the ConOps describes how the project objective will be achieved. The team will start with a stock kerosene gas turbine (left) and convert it to the methane capable gas turbine (right). This conversion process requires modifying the Combustion Can to allow adequate cooling to prevent failure with the hotter methane burn. A 1-D model will be used to analyze the cooling amount and placement needed. The conversion process also requires development of a new ECU which will be tested in software simulation of the gas turbine before hardware. A new Fuel Delivery System is required to deliver the methane and keep the bearings lubricated. The conversion process is broken into four chronological phases. In a particular phase multiple subsystem stages will be in parallel development. The project cannot move past phase 4 until all items prior have been completed since they are interdependent on one another.

2.4 Functional Block Diagram

Figure 3 shows the functional block diagram of the engine which illustrates how the different components will interact with the engine. Since all components are operating simultaneously the FBD shows how the engine will run. The electronics component is a feedback control system which gives commands to lubricant and Fuel Delivery Systems, and receives RPM and exhaust gas temperature data from the stock sensor package. The hardware component of the FDS takes fuel and lubricant from reservoirs and injects them into the engine.

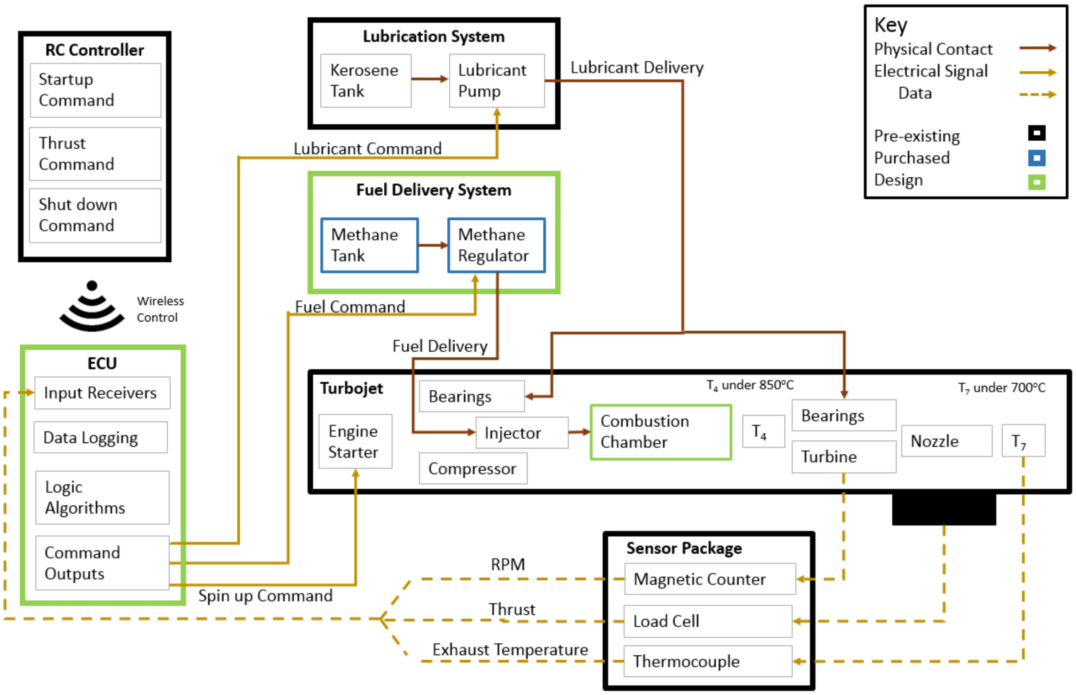


Figure 3: Mission Functional Block Diagram

2.5 Levels of Success

In order to meet the objectives of this project, the design team separates each subsystem to have three levels of success, the project must be able to satisfy these elements in order to obtain mission success. In levels of success section, Level 1 represents the minimum acceptable level of success while level 3 represents the highest level of success.

- **Level 1:**
  ECU - ECU capable of interfacing with a simulated JetCat P90RXI engine running on kerosene fuel is designed and constructed.
  Combustion Can - Combustion Can is modelled for JetCat P90RXI engine
  Fuel Delivery System - Fuel Delivery System is designed to provide the correct amount of methane fuel and kerosene lubricant
- **Level 2:**
  ECU - ECU in Level interfaces with JetCat P90RXI engine running on kerosene fuel at idle state
  Combustion Can - Level 1 Combustion Can model is modified to support methane fuel
  Fuel Delivery System - Fuel Delivery System in level 1 is built and provides lubricant and separated methane fuel
- **Level 3:**
  ECU - ECU is modified for JetCat P90 RXI engine running on methane gas fuel
  Combustion Can - Combustion Can is integrated into JetCat P90RXI engine; keeps the engine within acceptable temperature tolerances.
  Fuel Delivery System - Fuel Delivery System is integrated into JetCat P90RXI engine

It is key to note that the system does not have to be fully integrated until Level 3 success. The ConOps in Figure 2 show the operations of the project through all levels of success. It is possible to obtain a lower level of success without reaching all phases of the ConOps as shown in Figure 2.

3.0 Design Requirements

Based on the customer requirements and the actual needs of the project, the design team separated this project into three different subsystems in order to make the project easy to analysis and design. These three subsystems are: Engine Control Unit (ECU), Fuel Delivery System (FDS), and Combustion Chamber (CC). Each subsystem has its own top-level functional requirement. Table 1 describes the top-level functional requirements required to achieve the project objective.

Table 1: Functional Requirements

Functional Requirements	
0. Objective	The JetCat P90-RXi mini turbo jet engine shall be modified to run on methane fuel, rather than the stock kerosene fuel.
1. Engine Control Unit (ECU)	The ECU shall be capable of interpreting the received signals from a provided remote control (Spektrum DX7) unit and monitoring sensors from the engine, while sending commands to the FDS and storing data.
2. Fuel Delivery System (FDS)	The Fuel Delivery System (FDS) shall be capable of delivering methane fuel to the combustion chamber and lubricant to the bearings.
3. Combustion Chamber (CC)	The CC shall support the controlled burning of methane gas within the operating temperature range.

Many restrictions are imposed to ensure that the functional requirements are achieved in a reasonable manner; such requirements will drive design solutions and trade study metrics. These requirements have been broken into three sections, one for each of the subsystems. Table 2 details the ECU design requirements. The project will require the team to build its own ECU. This unit is used to control engine operation by invoking user commands and ensuring the engine does not exceed the safe operating parameters.

Table 2: Electronic Control Unit (ECU) Design Requirements

1. The ECU shall be capable of interpreting received signals from a provided remote controlling (Spektrum DX7) unit, monitoring sensors from the Engine, while sending commands to the FDS and storing data.			
Requirement	*Description*	*Verification & Validation*	*Justification*
1.1	The new ECU hardware shall be no more than ten times the mass of the existing ECU.	Demonstration: The new and existing ECUs will be weighed	The customer requires the new ECU be contained within the test cart.
1.2	The ECU shall receive power from a 12V power supply.	Inspection: Product label on power supply shall read 12V	The ECU must have enough power to operate for the duration of the test.
1.3	The ECU shall receive temperature and RPM data at a rate of 10Hz.	Testing: The ECU's data rate will be timed with the engine simulator.	The ECU needs to have the most current sensor readings so it can implement safety routines before component failure.
1.4	The ECU must have a processor speed of at least 1MHz.	Inspection: Information on the chosen product will state processor speed.	The ECU must be able to process data and send shut down commands before damage to components occurs.
1.5	The ECU shall receive start, throttle and shut off commands from a Spektrum RC controller, as long as the controller is within 15 meters.	Testing: The ECU will be tested with a separate test RC controller to verify data rate.	15 meters is twice the distance given for safe viewing from the side of the engine.

1.6	The ECU shall read data from the existing thermocouple and RPM sensor.	Testing: The ECU-sensor interface will be tested in a dry run.	Existing sensors are already integrated and calibrated for the engine.
1.7	The ECU shall implement a control law to control fuel flow rate.	Testing: The ECU will be tested with the engine simulator to verify ECU controlling performance.	PID laws are required to operate the engine safely, responding to user inputs in a timely manner and damping out disturbances.
1.8	The ECU shall send a shutdown signal to the FDS should the exhaust temperature exceed 700°C or the RPM exceed 130,000.	Testing: A simulation will provide these signals to monitor and test ECU performance.	These are the maximum values given in the JetCat manual.
1.9	The ECU shall store up to 5 min of data containing the histories of thermocouple data, RPM sensor data, and commands sent.	Demonstration: Data will be collected in the software simulation and hardware run of the engine.	The ECU must be able to store data for future analysis. 5 Minutes was chosen as an adequate time to prove design success.
1.10	ECU shall detect an ignition failure, shutoff fuel flow, and drive compressor.	Testing: A false start will be forced with the engine.	Failsafe to avoid excess buildup of flammable methane gas.

Table 3 contains the Fuel Delivery System requirements which define how methane will be delivered to the combustion chamber and how the bearings will be lubricated. This is very important for proper combustion of fuel, and lubrication of the bearings. Without proper lubrication of the bearings, they will incur unnecessary wear, and potentially seize which incurs significant damage to the engine.

Table 3: Fuel Delivery System (FDS) Design Requirements

2. The Fuel Delivery System (FDS) shall be capable of delivering fuel to the combustion chamber and lubricant to the bearings.			
Requirement	*Description*	*Verification & Validation*	*Justification*
2.1	The FDS shall deliver a controlled flow of methane fuel to the CC, ranging from 0 g/s to 4.2 g/s based on the throttle input from interfacing with the ECU.	Testing: The FDS will be tested by measuring methane quantity injected into the fuel system.	FDS must deliver enough fuel to provide the same amount of energy as in the stock engine. These numbers came from a basic ideal cycle analysis.
2.2	The FDS shall store at least 1.5 kg of methane gas at 2000psig to facilitate testing of the FDS at full throttle for 5 minutes.	Demonstration: Cylinder will be weighed prior to testing.	Minimum required fuel quantity to facilitate adequate testing of the engine. The numbers came from delivering 5g/s for 5 minutes.
2.3	The FDS shall be capable of continuously delivering lubricant to the bearings, matching the lubricant delivery at max thrust on the kerosene run.	Testing: The original signal to the flowmeter will be replicated by the new ECU.	By using the same amount of lubricant as at maximum turbine speed safe operation of the bearings is guaranteed.
2.4	The FDS shall store lubricant to facilitate testing of the FDS at full throttle for 5 minutes.	Demonstration: The FDS lubrication storage will be filled to demonstrate success.	The FDS needs to contain enough lubricant to deliver for the full 5 minutes.

2.5	The FDS will operate the fuel and lubricant lines separately and independently from one another.	Inspection: The lines will never mix, and will stay completely separate from each other.	The lines must be independent since one is gas and another is fluid.
2.6	The FDS shall fit in a typical mid-size passenger vehicle light enough to be handled by any team member.	Inspection: The mass and volume of the complete FDS system will be measured.	The FDS will be transported by hand in a mid-size car.
2.7	In the event of electronic or mechanical failure the valves shall be in closed position.	Inspection: Valves are in close position without power	The engine must stop upon system failures.

Table 4 contains the requirements imposed on the combustion chamber design. Because methane has a higher heat of combustion (55.0KJ/g) than kerosene (43.0KJ/g), it is likely that additional cooling will be required. If the air is not cooled to a low enough temperature then the turbine downstream will expand and begin to grind on other components destroying the engine.

Table 4: Combustion Can (CC) Design Requirements

3. The CC shall support the controlled burning of methane gas within the operating temperature range.			
Requirement	*Description*	*Verification & Validation*	*Justification*
3.1	Methane shall undergo a controlled burn within the combustion chamber.	Demonstration: Methane flame remains lit while the engine is run. Proven by showing RPM remains at a minimum of 35,000 RPM without aid from - starter motor.	If the CC cannot burn methane, the engine will not function as intended.
3.2	The CC shall start with methane fuel, and bring the engine to a working idle (35,000 RPM).	Demonstration: Start the burn in the CC and show consistent RPM of 35,000 after deactivating the starter motor.	Engine must be able to start on methane. Idle RPM defined as 35,000.
3.3	The CC design solution shall maintain the exhaust temperature below 700ºC.	Testing: Thermal sensors measure this value while engine is running and the ECU stores data.	JetCat manual recommends exhaust temperature below 700ºC
3.4	The 1-D flow model shall match exhaust temperature from the CC within 70ºC.	Inspection: Compare the test results to the 1-D model and verify.	Customer desires no more than 10% error in 1-D flow model

4.0 Key Design Option Considered

This project is comprised of three main design aspects: ECU, CC and FDS. In order to provide a viable design solution, many design options were considered. Figure 4 provides an overview of the design options considered for each aspect of the project.

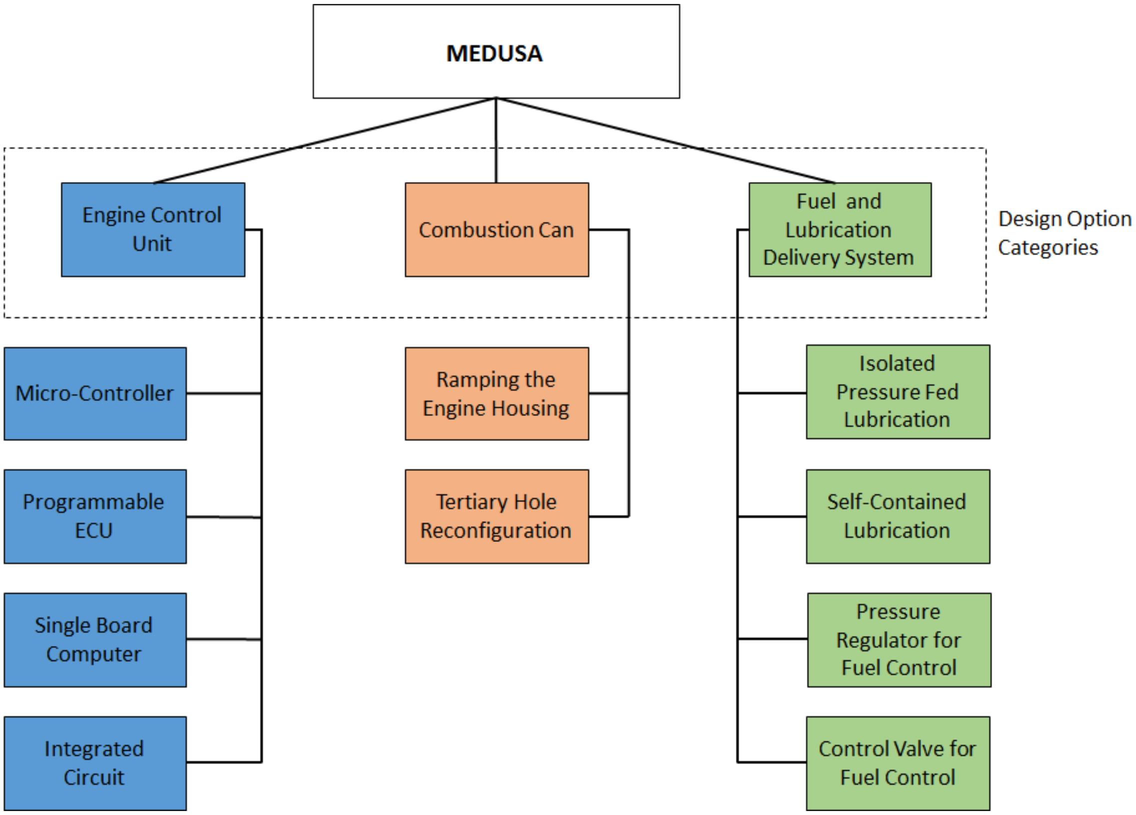


Figure 4: Mission Design Option Flow Down

4.1 Engine Control Unit Design Option

The ECU is a critical part of this project, as the current ECU is unsatisfactory to the customer due to a lack of documentation and unreliable performance. Thus, a new ECU must be built entirely from scratch that fulfills the requirements set forth and operates the engine. The new ECU must be able to receive two inputs, including exhaust temperature and turbine RPM, and process those signals along with a throttle command which will generate a signal to send to the Fuel Delivery System to regulate fuel flow.

4.1.1 Micro-Controller

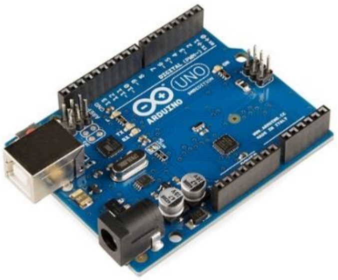


Figure 5: Example Micro-controller

A micro-controller is a feasible selection for the ECU, as it fills all of the ECU design requirements while featuring several benefits. Any stock micro-controller, such as, but not limited to an Arduino as seen if Figure 5, is capable of reading inputs from sensors and generating an output command on a pre-manufactured circuit board. Small in size and typically inexpensive, the programming would be simple, and micro-controller shopping could be done to select a specific micro-controller that supports the functionality the project requires. The previous experience among the team further highlights the feasibility of the micro-controller as a design option. This option can be limiting, however, in that these boards will only be capable of accepting inputs and outputs based on how the product was built. This limits the functionality as the team may be required to construct additional circuitry outside the board in order to convert signals.

Table 5: Pros and Cons for Micro Controller

Pros:	Cons:
Team has microcontroller experience	Manufacturer coding languages
Inexpensive	May be large and bulky with lots of wires
Extensive company support	No built in wireless capacity
Reliable and flexible	No built in mass storage capacity

4.1.2 Programmable ECU

Figure 6: An Example Programmable ECU

The current JetCat ECU is a black box, nobody knows what is inside of it or how it works, and it cannot be reprogramed. However, there are distributors who sell more user friendly ECU's such as that seen in Figure 6. For this design option the team would purchase a reprogrammable ECU, since it already has dependable hardware and software, then make changes to its code. This could eliminate almost all circuit design and thus was worth looking into. After researching ECU manufactures though this idea was quickly thrown out. The cheapest ECU's were several hundred dollars, and the companies had disclaimers which, in essence, said they would not give any support to those we were reprogramming the ECU. They also did not mention the extent to which ECU's programming could be changed. This could not be investigated without committing to the design, which is far too high a risk as it could be an impossible solution.

Table 6: Pros and Cons for Programmable ECU

Pros:	Cons:
Minimize micro-processing hardware requirements.	Very little support from companies
Reliable software already in place, could be a simple plug and play	Could be very limited in how "programmable" the ECU is, not designed for anything close to methane gas use
	Could be impossible to reprogram
	Very few products to choose from
	More expensive

4.1.3 Single Board Computer (SBC)

Figure 7: An example SBC

For this design option the team would purchase an SBC and use it to operate the engine. The Rasbery Pi as shown in Figure 7 was selected because it is inexpensive and has a large hobbyist base. Other SBC's are available but they are significantly more expensive (hundreds of dollars) and do not have. The appeal of an SBC is its similarity to a standard desktop computer. Since the team has already worked with sensors in many labs using computers this option allows for a familiar operating concept. The Raspberry Pi is a SBC which has recently gained great popularity among hobbyists and is very inexpensive. People have used it to control robots, home brewery's, and build their own supercomputer. It will likely support the team's needs. However, the team has no previous experience with SBC's and it will be limited to two USB ports. There is the potential for complications to arise from these restriction. It could easily result in having to use other, self-made, boards with the SBC to achieve the project goals.

Table 7: Pros and Cons for SBC

Pros:	Cons:
Can run Linux, which allows coding in familiar languages such as C or Labview.	No team experience with single board computers
Large hobbyist support base, many complicated projects done by enthusiasts.	Only USB I/O
Inexpensive (under $100 with all cables and accessories)	
Small and lightweight, about the size of credit card	

4.1.4 Custom Integrated Circuit: (Microcontroller on PCB, with proto board development in tandem)

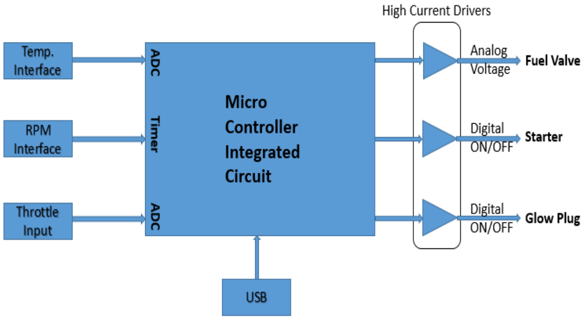


Figure 8: Integrated Circuit Flow Chart

A proto board with a microcontroller on it can be purchased and thus the circuit can be built and tested on proto board. In tandem, the circuit board layout can be completed and changes can be made from the results of tests on the proto board. The basic function of the microcontroller and circuit is shown in Figure 8. Contrary to the previous microcontroller design option, this microcontroller would not come direct from the manufacturer with circuitry included outside the chip itself. This option, although requiring design of a Printed Circuit Board (PCB), would allow the team to determine how the integrated circuit would interface with the rest of the engine. Designing a PCB would also minimize the overall size of the ECU as the PCB would be customized for the MEDUSA project.

Table 8: Pros and Cons for Integrated Circuit

Pros:	Cons:
Optimize Power (processor on selected micro can have a smaller power rating)	Must design and print PCB
Small and lightweight, about the size of credit card	Significant effort involved in board design
Risk reduction scheme uses proto board with microcontroller already installed (can build on proto board while simultaneously laying out PCB)	Risk associated with engine interfacing (need to know what interface signals are)
Built in A/D and D/A	

4.2 Fuel and Lubrication Delivery System Design Options

The current Fuel Delivery System delivers a kerosene oil mixture to the engine, serving as both the fuel and the lubrication. Since the goal of this project is to convert the engine for methane fuel use, the Fuel Delivery System must be redesigned. This involves designing a separate Fuel Delivery System and lubrication system to deliver the kerosene mixture to the bearings as well as deliver the methane to the engine. During the design, a pressure tank will be used to store the pressurized methane gas in order to minimize the size of the system. The end goal of the methane Fuel Delivery System is to deliver methane gas to the injectors at a desired fuel flow rate. The section below has four design options: two for bearing lubrication and two for fuel delivery

4.2.1 Pressure Fed Lubrication System

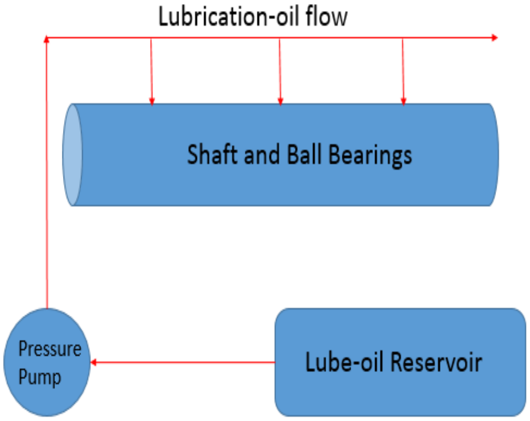


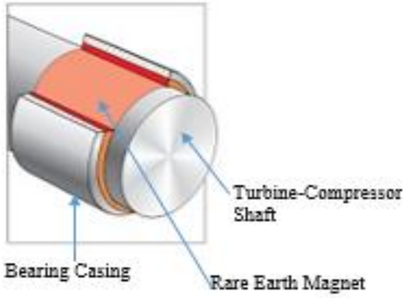
Figure 9: Isolated Pressure Lubrication System

This design option would involve a mechanical system similar to that of the stock engine which forces a kerosene-oil mixture from a reservoir into the crankcase to lubricate the shaft and ball bearing as demonstrated in Figure 9. In the stock engine, the Kerosene-oil mixture is delivered to the cowling through a single injection tube, and split into a separate lubrication and fuel delivery tubes. Since gaseous Methane cannot be used for lubrication, the methane gas fuel delivery, and lubrication delivery must be isolated.

Table 9: Pros and Cons for Pressure Feed Lubrication system

Pros:	Cons:
Current lubricant system on board. Only needs to separate fuel delivery and lubrication	Uses kerosene fuel without extracting any energy from it.
No analysis requirements as it will mimic the current lubrication delivery system.	Risk in not providing enough lubrication which would cause damage to engine.

4.2.2 Self-contained Lubrication System



A self-contained lubrication system such as that seen in Figure 10 would eliminate the need for bearings, and a steady stream of a kerosene-oil mixture. The addition of lubrication is required in the stock engine to reduce friction of the shaft, and continuously remove heat from the bearings. A self-contained lubrication system would remove friction by separating the rotating shaft from the engine by magnetic levitation from rare earth magnets.

Figure 10: Self-Contained Lubrication

Table 10: Pros and Cons for Self-Contained Lubrication System

Pros:	Cons:
Eliminate need for kerosene lubricant	Requires redesign of the current Fuel Delivery System
Eliminate need to design a system to separate methane and kerosene	Requires substantial analysis on heat transfer of new bearings.
	Would require a lot manufacturing work that carries huge risk. Any damage to the shaft may result in a total replacement of the shaft. If this was to happen it would put stress on the financial and time budgets given for the project.

4.2.3 Pressure Regulator for Fuel Control

The end goal of the methane Fuel Delivery System is to delivery methane gas to the injectors at a desired fuel flow rate. There are several ways to accomplish this task. For all options a compressed methane gas canister will be used as the fuel source. From there the flow must pass through a pressure regulator that is attached to the canister. This will ensure that the pressure entering the line is high enough to provide sufficient flow rate but not damage the line or components downstream. For this design option, the gas will enter an electronic pressure regulator as seen in Figure 11. An electric pressure regulator maintains a desired outlet pressure using two high speed servo valves, a push valve and a vent valve. Most models can accept either analog or digital communication that will need to interface with the engine ECU. Different models will need to be considered depending on the desired flow rate. A typical electronic pressure regulator layout as described above is shown in Figure 11 along with the pros and cons of the system.

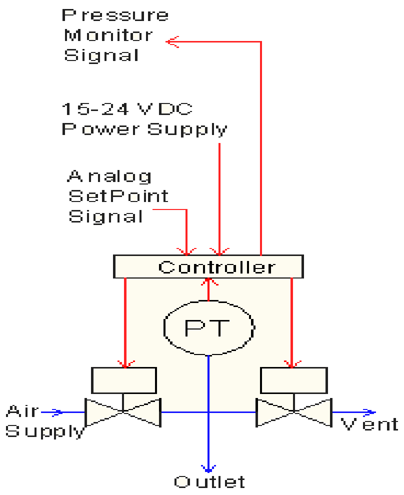


Figure 11: Pressure Regulator fuel control

Table 11: Pros and Cons for Pressure Regulator

Pros	Cons
Quick pressure change	Electronic versions are expensive
Cheaper than flow regulators	Will also need a flow meter
	Requires more equations for ECU

4.2.4 Control Valve for Fuel Control

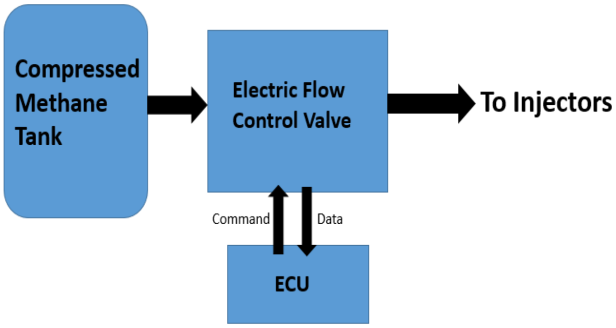


Figure 12: Control Valve for Fuel Control

The other design option would be to use an air flow control valve. This option differs slightly from the pressure regulator in that instead of delivering fuel at a constant pressure, it is delivered at a constant flow rate as shown in Figure 12. The pressure regulator will deliver fuel at a constant pressure while the flow control valve will deliver the methane at a specified flow rate. Since the desired output of the system is a flow rate, the pressure regulator would have to change its outgoing pressure based on the commanded throttle level. There are electronic flow control valves and electronic pressure regulators that can be integrated with the engine ECU to provide commanded flow rates based on throttle level.

Table 12: Pros and Cons for the control valve

Pros	Cons
Delivers commanded flow rate	Low range of flow rates
Some versions contain flow meter	Electronic versions are expensive
	May require pressure regulator upstream

4.3 Combustion Can Design Options

The focus of the Combustion Can in this project is to ensure there is sufficient cooling air to maintain the turbine within its thermal limits. This is partly ensured through the ECU, as the controller will shut off the engine when a maximum temperature limit is reached. However, the engine must be engineered to meet the minimum operating conditions. This requires there to be a sufficient burn of methane gas, but also sufficient cooling to prevent the turbine and combustion liner from overheating. It is expected that due to the higher flame temperature of methane (1950°C), more cooling will be required than in the stock kerosene engine which burns kerosene and as such a number of design options have been explored.

4.3.1 Ramping the Engine Housing

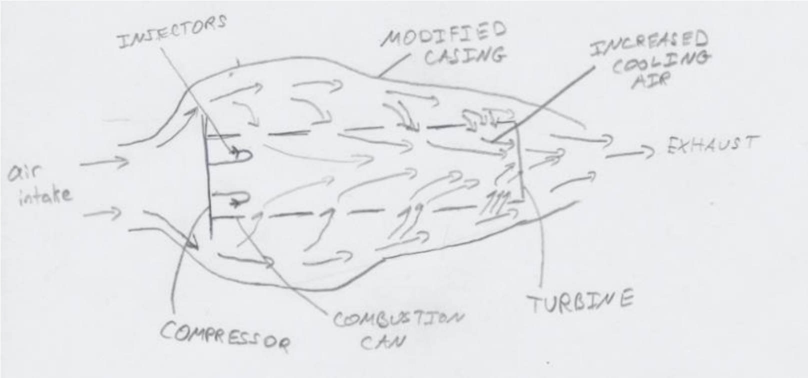


Figure 13: Modified Engine Housing – Increased Cooling Air

The main idea of this design option is to change the shape of the outer casing of the engine in order to change the pressure differentials across the Combustion Can. In the stock engine, the air is compressed to the outer regions of the engine through a centrifugal compressor. This high pressure air moves towards the exhaust through two paths. Some of the air moves along the outside of the Combustion Can, and some flows inside the Combustion Can due to the pressure differential across the can. Changing the shape of the engine casing as seen in Figure 13 would directly affect the pressure differential across the can, thus changing the amount of cooling air entering the Combustion Can. If analysis determines there is more cooling air required, the casing will be modified to squeeze more air into the trailing end of the Combustion Can. There would be two ways to practically accomplish this design solution. It could be done by making modifications to the current engine casing, or by building another one. If a new Combustion Can was made, none of the modifications for this design option should require a structural change of the Combustion Can or other components of the engine. If a new case was to required changes to the Combustion Can or other components, more costly analysis may be required to ensure functionality. However, in order to do this, the engine must be slightly reverse engineered in order to fit a new engine casing.

Table 13: Pros and Cons for Ramping Engine Housing

Pros:	Cons:
Simple Flow Analysis	Requires manufacturing additional parts
Relatively Easy to Model	Difficult to Optimize
	Small Margin of Error
	Not a lot of design documentation or previous work

4.3.2 Reconfiguration of the Combustion Can Tertiary Holes

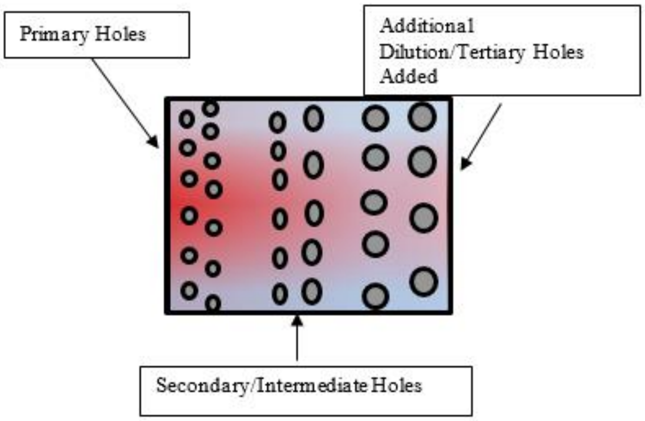


Figure 14: C.C cooling holes

In order to properly cool the hot gas exiting the Combustion Can, a number of design options were considered. One such design option is the implementation of additional tertiary, or dilution holes in the liner of the Combustion Can as shown in Figure 14. In the current configuration, the liner consists of three sets of holes located around the circumference of the liner. The first set of holes, known as the "primary holes" are located on the liner closest to the compressor. These holes are smaller in area than the other two sets and are meant to supply the air to be mixed with the fuel to begin the combustion process. The secondary holes are located in the center of the combustion liner. Their purpose is to complete the combustion process by diluting the high concentration of combustion products such as carbon-monoxide and hydrogen. The third set of holes, located closest to the turbine and Combustion Can exit are known as the tertiary or dilution holes. Ideally, these holes will not contribute to the combustion process and are simply there to cool the exiting gasses to prevent overheating of the turbine. These are carefully designed to produce an even temperature profile that will prevent large temperature spikes from damaging the turbine. Adding additional dilution holes to the combustion liner would allow for an increased volume of air to mix with the exiting gas which would decrease the temperature of the gas to an acceptable level.

Table 14: Pros and Cons for modify the C.C cooling holes

Pros:	Cons:
Easy to manufacture	Difficult to model placement of holes
Relatively simple to analyze as a whole	Difficult to ensure even temperature profile of exiting gas
Cost Effective	
Fair amount of documentation and previous work.	

5.0 Trade Study Process and Results

Trade studies will be done to determine a baseline design of the methane gas engine in order to satisfy the functional requirements stated in Section 3.0. Each subsystem will have their own trade study section and take account of the major factors need to be considered like Cost, Risk, complexity, which relate to the project's functional requirements and critical project elements. For each trade study, a value of 1-5 will be assigned to each design option based on the option's unique characteristics. The lowest rating is equivalent of a 1 and the highest rating is equivalent to a 5. In the trade study, a higher final number for a design solution is more favorable.

5.1 ECU Trade Study

The major factors that were taken into account to perform a trade study for ECU subsystem are shown in the table below.

Table 15: ECU Trade Study Metric Table

Cost (15% weight)	This metric is based on the price of the ECU. This includes the price of all electronic components that will make up the Engine Control Unit. Since the electronic hardware for most design options are relatively inexpensive, cost won't be a major factor and so was given 15% weight. Nonetheless it is still important to take into consideration. Given that the exact electrical architecture is not fully known for each design option, the costs associated with the different options were estimates. For this trade study, a lower cost corresponds to a higher ranking.
Processing Power (10% weight)	This metric is based on the processing power of each ECU design option. The number of instructions per second of each processer type was determined and used for ranking purposes. In this trade study, a higher processing power corresponds to a higher ranking. Given that the processing power is each design option is relatively compatible, this metric was only give 10% weight.
Simplicity/Risk (30% weight)	This metric is based on the simplicity of the design option and therefore the risk involved in pursuing it. Given that the work load is dictated by the complexity, this metric will be weighted at 30% as it has a major bearing on the success of the project. For this trade study, a more complex design option corresponds to a lower rating.
Size (10% weight)	This metric is based on both the size and the mass of the ECU design option in question. The design option has to be able to fit within the confines of the test stand and thus its size is important. Given that all of the design options are capable of sitting on the test stand, the weight chosen was only 10%. However, some of the design options require more space than others so it is still an important factor to consider since, eventually, the ECU may be integrated with a UAV. For this trade study, a more compact design option corresponds to a higher ranking.
Support (20% weight)	This metric is based on the resources and tools available to aid design and construction. Given the complex nature of the ECU, advising, documentation and tools are required which is why it was assigned 20% weight. A design option that offers more support in terms of resources and documentation corresponds to a higher ranking.
Team Experience (15% weight)	This metric is based on team experience with the design options involved. Having team members who have experience with a certain design option will greatly improve the chance for success and decrease the time required to implement it. Therefore, this metric has a 15% weight. More team experience corresponds to a higher ranking.

The six factors above were chosen as they were determined to be the most significant in terms of determining the best design solution. Other factors were chosen but, after consideration, were left off the list as they weren't critical factors. One factor abandoned was flexibility. Given the uncertainty of the sensors, it was unclear whether or not the signals were digital or analog. Therefore depending on the input, D/A and A/D converters could be needed. Since each of the design options was accommodating in this regard, the metric was abandoned.

Table 16: Trade Study for ECU

Metric	**Weight**	**Microcontroller**	**Programmable ECU**	**Single Board Computer**	**Integrated Circuit**
Cost	15%	4	2	5	5
Processing Power	10%	3	4	5	4
Simplicity/Risk	30%	3	1	3	4
Size	10%	2	4	3	5
Support	20%	5	1	4	3
Team Experience	15%	4	2	3	4
Total	100%	3.6	1.9	3.6	**4.05**

The trade study provided enlightening results. The programmable ECU had the lowest overall score. This was a very risky option for multiple reasons. The programmable ECU's are very expensive and offer little support. Since the manufacturers will not support those who attempt to reprogram the ECU, this option proves to be extremely risky. The trade study results reflect the high risk, little experience, and lack of support that this design option presents. The single board computer had the second lowest score, but by a much smaller margin than that of the programmable ECU. The single board computer is relatively cheap and is accommodating in terms of processing power and size, but there are many uncertainties associated with it. Since there is little to no experience with single board computers on the team, it could prove difficult when problems arise. In addition, the lack of experience would take time away from the project while the team discovers its capabilities. Ultimately, the risk and lack of experience speak to why the single board computer will not be implemented as a design option.

The PCB option scored very well in the trade study and has many advantages. The PCB is relatively inexpensive and can provide adequate processing power in that the desired microprocessor can be chosen. In addition, this option has no unused parts. Unlike the other options, all of the components will serve a purpose when it comes to the ECU function. The microcontroller and the SBC have capabilities that will not be required for this project and are thus wasted parts. The PCB is also accompanied by a risk reduction scheme in which the circuit would be made on a proto board and tested until its operation is verified. Then after confirmation, the PCB could be constructed. Given the ECU requirements, it is also possible to make the board as small as the current ECU which is desirable in terms of mounting to an aircraft. This option does present potential risk and would require a good amount of work. Although there are many challenges, this is a very good design option, as is confirmed by the trade study results.

Like the PCB option, the microcontroller proved to be a very good ECU design option. The microcontroller would be inexpensive and each team member has experience working with them. In addition, there are many people, such as Trudy Schwartz, that can assist and provide clarification when it comes to the microcontroller's capabilities. The microcontroller option is the largest of the design choices but it can still fit on the test stand, thus satisfying the design requirements. Although there are some drawbacks, the microcontroller with PCB option appears to be the most effective design of those investigated.

5.2 FDS Trade Study

The major factors that were taken into account to perform a trade study for FDS subsystem are shown in the table below.

Table 17: FDS Trade Study Metric Table

Complexity (20% weight)	This metric involves the complexity level of design and build the Fuel Delivery System. Because a relatively simple design usually means less manufactory and more reliability, in order to receive a high rating in this category, the design of the Fuel Delivery System must be relatively simple and easy to achieve. Since this metric will significantly affect the work load in the design, level of difficulty in manufacturing and probably the total cost of the system, the complexity will rank one of the highest weight (20% weight) in the trade study
Safety (20% weight)	This metric involves the safety of the Fuel Delivery System to the users and the engine. This category including the safety during transport, testing and operation. Safety is a critical term of this subsystem because it is very important in the feasibility and practicality of the project. Thus, safety also rank one of the highest weight (20% weight) in the trade study
Cost (10% weight)	This metric involves the estimate price of the Fuel Delivery System. The cost ranking are based on the estimate price of the components since the detail design have not been decided yet. This category is relatively less important (10% weight) in FDS trade studies since all components in this subsystem are relatively inexpensive.
Reliability and Durability (20% weight)	This metric involves the lifetime of the Fuel Delivery System. For a system to receive a high rating in this category, the Fuel Delivery System needs to delivery correct amount of fuel and lubrication every time the engine is turned on, the system should have a relatively long lifetime since the project will at least test the engine for couple months. Also, the system must be easy to troubleshoot and fix if it does not work. This metric is also rank one of the highest (20% weight) because a reliable and longevity Fuel Delivery System will significantly improve the performance of the engine
Analysis Required (15% weight)	This metric involves the amount of time and level of difficulty of analysis that needs to be put into research and design items before the integration of the subsystem. Since the project only has one semester for the initial design, the time put into the analysis needs to be as short as possible. The ranking of this metric is middle (15% weight) since it is not as important as complexity and reliability.
Testability (15% weight)	This metric involves how easy and accurate it is to measure the critical data when the system is operating. For the Fuel Delivery System, the critical data which needs to be measured is the fuel flow rate, fuel flow pressure and lubrication flow rate. An easy and accuracy measurement will improve the performance of the ECU and Combustion Can. The ranking of this metric is also middle (15% weight) since there are other ways such as cycle analysis to determine these data.

While there are many factors to consider when choosing the metrics for the trade study, the six chosen here were deemed the most important. Several other metrics were considered for the trade study of the Fuel Delivery System but for a multitude of reasons were left out of the study. One example a metric not chosen is size. Unlike the other subsystem no requirement was given from the customer on the required dimensions of the methane source, tubing or regulators necessary to delivery fuel and lubricant to the engine. Size is not deemed to be one of the most important metrics as all of the design options will satisfy the size requirements of the customer. Another metric not chosen is longevity. Obviously the Fuel Delivery System needs to be reliable when called upon to delivery fuel and lubricant to the engine. However it will not be tested to the point where the maximum number of cycles for the regulator or flow controller is reached. If down the road the engine is going to be implemented on a UAV the Fuel Delivery System will need to be reconsidered and longevity will be a more primary focus.

Table 18: Trade Study for FDS

Metric	**Weight (%)**	**Pressure-lubricated**	**Self-lubricated**	**Mass flow controller**	**Pressure regulator**
Complexity	20	5	2	4	3
Safety	20	4	5	4	4
Cost	10	5	2	2	3
Reliability and Durability	20	3	4	3	3
Analysis requirements	15	3	1	4	2
Testability	15	4	3	3	4
Total	100 %	**3.95**	3.00	**3.45**	3.2

Table 18 above shows the trade study of the four design options for the Fuel Delivery System. There are total of four design options; two from methane delivery items and two from lubrication items. After trade studies, two designs will be chosen, one for lubrication delivery and one for methane delivery. Both systems have complex mechanical and electrical components internally, however integration with the Fuel Delivery System should be easier. The mass flow controller is more complex electrically and has more moving parts. Both systems should be safe assuming intrinsically safe parts are used. Electronic mass flow controllers are relatively expensive (about $1000) compared to several hundred dollars for a pressure regulator. Both have similar components that should prove durable enough to run only a few tests. The pressure regulator may require some additional analysis since it produces a commanded pressure as opposed to the commanded mass flow rate that the injectors need. The pressure regulator is slightly easier to test because pressure gauges are cheaper and more readily available. However, the pressure regulator would require a control loop for acquiring engine pressure readings, which are very difficult to obtain. From the chart, it seems that using a mass flow controller (total grade of 3.45) is the more desirable option.

For the lubrication system, pressure-lubrication option reached a much higher score than self-lubrication option on complexity, Cost and Analysis requirements metrics since pressure-lubrication option is the current system onboard, and it just needs to be modified to fit the new feature of separate methane fuel and kerosene lubrication. In this case, it would be much less complex and less cost to modify the current system than design and build an entire new system. Also, since self-lubrication system placed in a high RPM Jet engine is a new technology, it would require a lot of research and analysis (like how to carry away heat by not using liquored lubrication) in order to build this system to the engine. On the other hand, self-lubrication option reached a higher score than pressure-lubrication option in safety and reliability metrics since self-lubrication system is not required to use explosive kerosene oil as lubrication oil. Also, a working self-lubrication system would be more reliable than pressure-lubrication because it do not need oil pump, valve and oil line to feed oil to the system. After the entire trade study, the overall grade for pressure-lubrication was 3.95, which is higher than the grade in self-lubrication (3.00). It seems that using a pressure-lubrication is a more desirable chose.

5.3 Combustion Can Trade Study

The major factors that were taken into account to perform a trade study for C.C subsystem are shown in the table below.

Table 19: C.C Trade Study Metric Table

Manufacturability (20% weight)	This metric represents the technical difficulty to manufacture the components required for each design option. A low score in manufacturability means the design option requires manufacturing that is high risk, difficult, requires high precision, or requires significant time to complete. A high score represents a system that is easy to manufacture to the needed tolerances. Proper combustion design according to our analysis is critical to the project success, thus the manufacturability is very key in choosing the best design. Thus Manufacturability will be given a weight of 20%.
Safety (20% weight)	This project deals with explosive fuel that when handled improperly could lead to a catastrophic failure of the engine. This metric represents the relative safety of each design option. A high score represents a stable system with minimal hazards. A low safety score is due to complexities that put the project at higher risk and lower necessary tolerances. Safety hazards are not only a risk for people, but a risk to the project as failures would either require more time, finances, or resources to fix than the project has available, thus a 20% weight will be given to this metric.
Financial (10% weight)	This metric refers to the relative cost of each design option. Each option is planned such that it will not exceed the budget, but a design that requires fewer financial resources reduces the overall risk of the project, and therefore will correlate to a high score. Since most of the components in this subsystem are relatively inexpensive, a 10% weight will be given to this metric.
Reliability (15% weight)	This project requires substantial testing to characterize the engine. Currently, the limiting component of the engine is the bearings, which require replacement every 25 hours. If any components wear out in the time it takes to test the engine, it would require more financial resources to build more components, and more time to prepare for replacing the components. A high score in reliability represents a system that has minimal points of failure and made of durable components with low tolerance requirements. Since reliability is not a critical element compared to manufacturability and safety, a 15% weight will be given to this metric.
Analysis requirements (20% weight)	Analysis will define the specific modifications (if any) that will be made to provide adequate thermodynamic properties to the turbine. This metric defines the relative difficulty of the analysis that would be required for each design option. The goal of each design option is the same – to change the amount of cooling air that goes into the combustion can. However, the means of making these calculations is different, and requires different types of computing. A high rating represents a system that has a simple means of analysis with a high degree of accuracy. Analysis requirements is a key component of this subsystem, thus a 20% weight will be given to this metric.
Testability (15% weight)	This metric involves how easy and accurate it is to measure the critical data when the system is operating. An easy and accuracy measurement will improve the performance of the engine. Since there are other ways such as cycle analysis to determine the data, a 15% weight will be given to this metric.

There are more metrics to characterize the design options for combustor modification than are shown in the table. However, the table represents all metrics necessary to analyze in support of the requirements. The metrics not included in the table are the dimension, mass, and time for each design option. Each design option will have different sizes and masses, but all within the required specifications. So long as the design option fits within the requirements, the relative size and mass is irrelevant to the levels of success. Time is also not included in the metrics because it is indirectly included in the other metrics for the project. Testability, Analysis Requirements, Safety and Manufacturability is all partially based on the time commitments for the design options in the respective section.

There are a number of other design options that were considered increasing or decreasing the cooling of the turbine, but were not analyzed in this section. This includes modifying the injector pattern, remaking the can from a porous material for transpiration cooling, and adding an active cooling system. These options were not considered due to their immediate complexity, expense, lack of knowledge, or lack of the ability to gain the knowledge required to implement the option.

Modifying the pattern of injection would require analysis that would not be sufficient with 1-D analysis, and would require more complicated analysis or a computational fluid dynamics program that requires more experience than available with this project. The current injectors are known to be acceptable for a gaseous fluid as they have been used with Propane in the past. However, any modification to how the fuel is injected, or the distribution of injects would require analysis beyond the scope of this project.

Transpiration cooling would require making a new combustion can from a material that allows for a coolant to be pumped through the walls. The group has no experience working with materials like this, and does not have enough time to gain the experience necessary to design a combustion can out of these materials with the proper analysis.

An active cooling system would involve a control system to control a cooling agent through the turbine. This could be done with transpiration cooling, or another system such as pumping liquid nitrogen through the combustion can. This option was ruled out as it was too complicated to be done in time, and would require far more thermodynamic analysis than the passive cooling options.

Table 20: C.C Trade Study Table

Metric	**Weight**	**Combustion Can Hole Modification**	**Casing Shape Modification**
Manufacturability	20%	4	1
Analysis requirements	20%	2	1
Safety	20%	3	2
Financial	10%	3	1
Reliability	15%	3	1
Testability	15%	4	4
TOTAL	100%	**3.15**	1.2

This trade study was used to aid in the decision of how to modify the amount of cooling air that flows through the combustion chamber. This is potentially due to the different burning temperature of Methane compared to Kerosene, and will be confirmed by analysis. The result of this trade study showed that the best way to solve the problem is through changing the hole pattern and size of the combustion can. This design option scored significantly better in the two highest weighted metrics – Manufacturability and Analysis Requirements.

The manufacturability of the combustion can has varying levels of difficultly depending on if the modified engine requires more or less cooling air. If the engine requires more cooling air, the current can will be modified with more cooling holes. However, if the engine requires less cooling air, the can will have to be remade to support fewer cooling holes. In primary research of methane conversions, it seems far more likely that the engine will need more cooling holes than less cooling. In the design option of modifying the engine casing, a whole new casing will be manufactured whether more cooling air or less cooling air is required. The manufacturing of the casing is also more challenging than manufacturing a combustion can. Both components would need to mount to the rest of the engine using the same structural connects. However, the turbine rotates very close to the inside of the engine casing. They are so close that overheating the engine will cause it to seize due to thermal expansion of the blades. This leaves a very small tolerance for machining, which adds risk and difficulty to the process. If the casing was not made to the same level of precision, new flow analysis would have to be performed to characterize the flow through and around the turbine blades.

6.0 Selection of Baseline Design

6.1 Trade Study Discussion

The three subsystems of the project -- ECU, Fuel Delivery System, and Combustor were analyzed with individual trade studies to come up with the optimal baseline design.

The ECU subsystem looked at the various computer options for active control. The result found that using a microcontroller with a custom designed PCB would be best suited for the project. Many systems are relatively low cost, simple in design, and offer a lot of support through online communities. Purchasing a pre-build microcontroller significantly reduces the risk of the project as they have been tested before purchase, and the ability to build and test on a proto board while designing the PCB offers more flexibility as the project progresses.

The Fuel Delivery System requires two design options: one for the lubrication and one for the fuel delivery. In the stock engine, the fuel and lubrication is a kerosene-oil mixture. Thus, the lubrication and fuel is integrated together. In the conversion process to methane, the lubrication and fuel become isolated systems. There were two options for a new lubrication system. The option chosen was a pressure injected lubrication system. This is due to the similarities it has to the current system. It will use an isolated injection system with an electrically controlled liquid pump. Many of the components required for this system are already installed on the stock engine, and can be repurposed with the new system.

Controlling the flow of Methane gas to the injectors is much more challenging than controlling liquid kerosene. Two design options were analyzed: a pressure controlled system, and a mass flow controlled system. The mass flow controlled systems are much more complicated and expensive than a simple electrically controlled pressure regulator, but is necessary to deliver methane within the required specifications. Using just a pressure regulator would require knowledge of the pressure at the fuel injectors at each RPM setting. This analysis would be extremely difficult and potentially impossible given the project team’s current knowledge level. This would also have to be incorporated into the control system with a live feedback loop. Thus, a mass flow regulator was chosen as is drastically reduces the complexity and risk associated with the fuel delivery system.

The combustor modifications for temperature control could be done using one of two options: modifying the shape of the engine casing, or modifying the holes in the combustion can. The best option is to modify the combustion can to change the amount of cooling air flow into the can.

6.2 Baseline design

The total scope of the project includes the following: removing the stock ECU, replacing it with a microcontroller/PCB design with software written specifically for this methane engine, replacing the current fuel and lubricant delivery system, and modifying the Combustion Can to safely cool the methane combustion. The current fuel and lubrication delivery systems will be thrown away. The lubrication and fuel inputs in the cowling will be split, and isolated. The lubricant will be distributed to the bearings in a similar fashion to the current system. An electrically powered liquid pump will directly push a kerosene-oil mixture to the bearings. Only the delivery of the lubrication will change, not the lubrication injectors to the bearings. The fuel storage device will be replaced with a high pressure, gaseous container of methane. This will be connected to any necessary pressure regulators to depressurize the gas, and a mass flow regulator that will receive commands from the new ECU. This will control the mass rate of methane gas injected to the engine. Burning methane instead of kerosene may require some cooling changes to avoid overheating the turbine, will still maintaining a sufficiently high temperature for normal operation. The changes required will be found through one dimensional analysis. Any changes made will be by changing the dilution hole design of the Combustion Can. Adding more or less holes will change the operating temperature of the turbine.

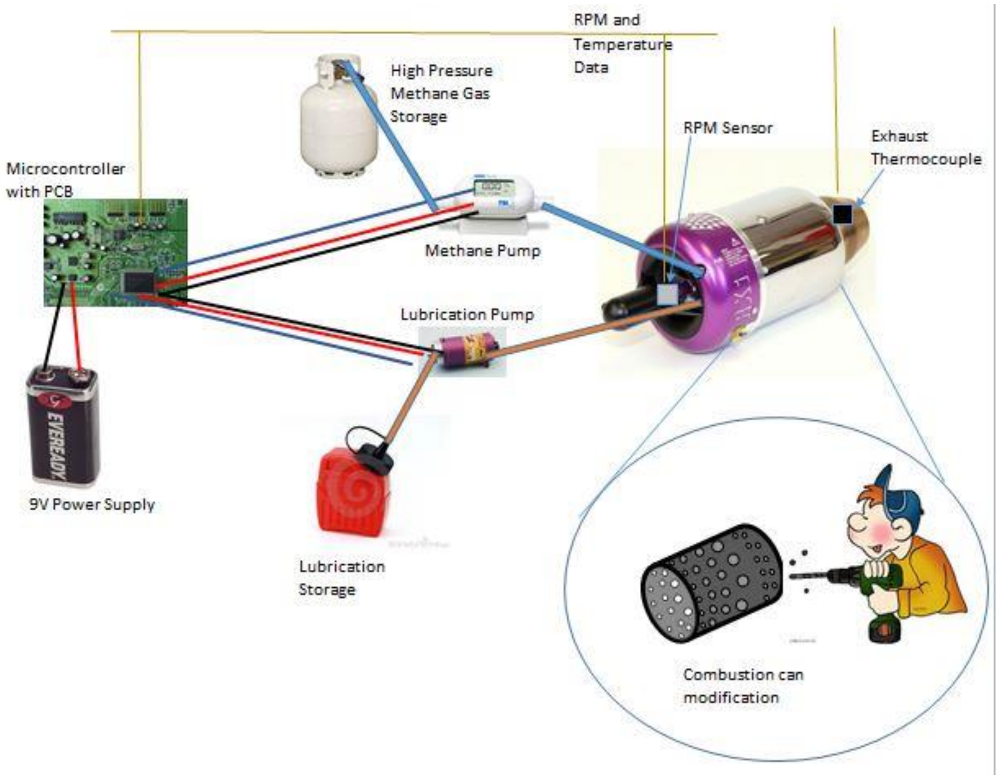


Figure 15: Baseline Design$^{\text{See Ref 12-19}}$

7.0 References

JetCat Properties

[1] “http://www.troybuiltmodels.com/items/JCATP90RXI.html” - Last Accessed 9/21/14

[2] “http://www.jetcat.de/downloads/rx--engines_manual_eng.pdf” Jetcat RX Turbines with V10 ECU Last Accessed 9/21/14

ECU info

[3]: “http://www.rchelicopterfun.com/fadec.html” Understanding the FADEC Turbine Engine Controller - Last Accessed 9/21/14

[4]: “http://www.dreamworksrc.com/catalog/Xicoy-Fadec-Autostart-Ecu-Kit-V10” - Last Accessed 9/21/14

[5]: “http://www.xicoy.com/catalog/product_info.php?products_id=196” Fadec main unit v10 GAS START - Last Accessed 9/21/14

[6]: “http://jetandturbineowners.proboards.com/thread/469/arduino-fadec” Arduino for FADEC - Last Accessed 9/21/14

[7]: “http://www.5bears.com/ecu.htm” 5bears Research - Last Accessed 9/21/14

[8]: “http://www.evaluationengineering.com/articles/201001/optimizing-maintenance-for-turbine-engines.php” Optimizing Maintenance For Turbine Engines - Last Accessed 9/21/14

[9]: “http://www.raspberrypi.org/” Site Main Page- Last Accessed 9/21/14

[10]: “http://www.element14.com/community/community/code_exchange/blog/2013/01/02/c-tutorial--hello-raspberry-pi - C++ on the Raspberry Pi” C++ Tutorial - Hello Raspberry Pi - Last Accessed 9/21/14

[11]: “http://www.sunstone.com/docs/pcb-123-manuals/pcb123_v5_manual.pdf?sfvrsn=16” PCB123 Version 5 - Last Accessed 9/21/14

References for Baseline Design Image

[12]: “http://www.9voltbattery.net/9-volt-battery-and-the-risks-associated-with-it/” 9 volt battery and the risks associated with it - Last Accessed 9/27/14

[13]: “http://tools.phillipmartin.info/tools_drill.htm” - Last Accessed 9/27/14

[14]: “http://www.inmotion.pt/store/arduino-uno-rev-3” Arduino Uno Rev. 3 - Last Accessed 9/27/14

[15]: “http://www.bvmjets.com/Pages/turbine_e.htm” - Last Accessed 9/27/14

[16]: “http://www.fallstoolrental.com/propane.html” All Power Ranges Available - Last Accessed 9/27/14

[17]: “http://www.keison.co.uk/tsi_massflowmeters.shtml” TSI Series Mass Flowmeters for Gases - Last Accessed 9/27/14

[18]: “http://www.dreamstime.com/stock-photo-small-gas-tank-image15749490” Stock Photo: Small gas tank - Last Accessed 9/27/14

[19]: “http://www.intairco.net/products.php?product=JetCat-Fuel-Pump-%252d-Bus-System-type” JetCat fuel pump – Bus System Type - Last Accessed 9/27/14