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

Specialized Propulsion Electronic Control System (SPECS)
Conceptual Design Document

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1. Information

1.1. Project Customers

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Contents

Nomenclature

A = Area [m^2]
a = Speed of sound [m/s]
D = Diameter [m]
F = Uninstalled Thrust [N]
M = Mach number
$\dot{m}_0$ = Air mass flow rate [kg/s]
$\dot{m}_f$ = Fuel mass flow rate [kg/s]
P = Pressure [N/m^2]
R = Gas constant [$J/kg/K$]
T = Temperature [K]
t = Thickness [m]
V = Velocity [m/s]
γ = Specific heat ratio
σ_H = Hoop stress [N/m^2]

2. Project Description

2.1. Project Purpose

The United States Air Force (USAF) has tasked the CU SPECS design team to increase the Thrust to Weight (T/W) ratio of a JetCat P90-RXi engine, without inhibiting the engines ability to run for an extended period of time. To complete this task, the team will install a T/W increasing modification to the engine and build a custom Specialized Propulsion Electronic Control System (SPECS). The performance increasing modification will highly leverage the research of previous years of CU JetCat projects. The stock JetCat Engine Control Unit (ECU) and Engine Control Module (ECM) were identified as critical elements in limiting the success of previous year's engine modifications. Stock JetCat engine control electronics have embedded software which limit the engine from operating outside the company's expected parameters. For example, if the exhaust gas temperature and compressor Revolutions Per Minute (RPM) mismatch from the undisclosed JetCat defined values, the engine will shutdown. This is not ideal since the engine may still be operating within it's performance limits, but outside normal stock running conditions. To successfully implement a T/W improving modification, a new engine control system must be additionally developed.

2.2. Specific Objectives

1. The first level of success describes energizing the engine components and sensors individually on a dedicated engine test bed. This is a crucial basic functionality before integrating computing and controls into the SPECS function.

2. Level two implements basic control functions where components and sensors are energized in a designed sequence. The engine software and simulation model begin to interface at this point.

3. Level three is a full system test for SPECS including hardware and software before integration on the engine. A more comprehensive model will supply simulated inputs to the software to evaluate proper control and safety.

4. At level four, SPECS will integrate onto the stock engine. The unmodified engine will run through the designed mission profile and test safety limits. The collected sensor data will be used to improve the theoretical engine model. The selected T/W improving modification will be developed and evaluated prior to integration on the engine.

5. Finally, the highest level of success will allow the T/W improving modified engine to perform the designed mission profile.

	Electronics	Software	Modeling/Simulation/Test
Level 1	Energize starter, igniter, and fuel pump Detect RPM input at 0 to 130,000 RPM Measure Exhaust Gas Temperature (EGT) Operate fuel solenoid valves	User interface for fuel pump and starter motor control Determine individual sensor poll rates to reduce processor overhead	Model critical engine parameters Provide simulated static test data inputs for system Manufacture test stand for safety validation of maximum RPM conditions
Level 2	Send a signal to energize the starter, igniter, and fuel pump in start-up sequence Synchronize data polling rates with sensor input (< TBD μs max for RPM, < TBD ms max for all other sensors)	Initiate start-up sequence through user interface Complete mock start-up sequence	Model fuel pump voltage-pressure relationship from 0-12 V with varying outlet flow throttling from dead-head to open channel Provide static simulated data inputs from model (T_9, RPM) to test system response
Level 3	Control SPECS from a user interface during real-time processing operations Run the test bed engine for 2 minutes at 130,000 RPM	Implement feedback control functions, safety interlock set-point, and data collection into user interface Test and verify SPECS user interface and safety protocol in a simulated environment	Provide dynamic simulated data inputs from model (T_9, RPM, T_4, P_4) to test SPECS system Perform Monte-Carlo simulation to determine system sensitivity given TBD % variation Determine fuel cutoff safety parameters
Level 4	Integrate SPECS and Hall effect sensor onto the JetCat engine	Implement SPECS user interface on JetCat engine under nominal operating conditions Complete start-up sequence and verify safety protocol	Manufacture test assembly using real components Collect test data and compare to simulations Verify T/W improving device
Level 5		Run engine over designed mission profile with full throttle control T/W improving modification will operate	Conform model to actual operating parameters with < TBD % error

2.3. Functional Block Diagram

Figure 1 is the functional block diagram that characterizes the relationship between SPECS and the JetCat engine. SPECS takes inputs from sensors on the engine and user commands. SPECS then commands the start sequence, engine operation, and shutdown of the engine if safety limits are exceeded. Data and commands must go through a

Digital to Analog Converter (DAC) and Analog to Digital Converter (ADC) to interpret and command elements on the engine. The JetCat components include a starter, fuel, and sensor system. A T/W increasing modification is also installed on-board the engine. The thrust from the engine is measured by a load cell. The thrust data from the load cell is sent to a DAQ. All of the data in SPECS is fed to a user interface.

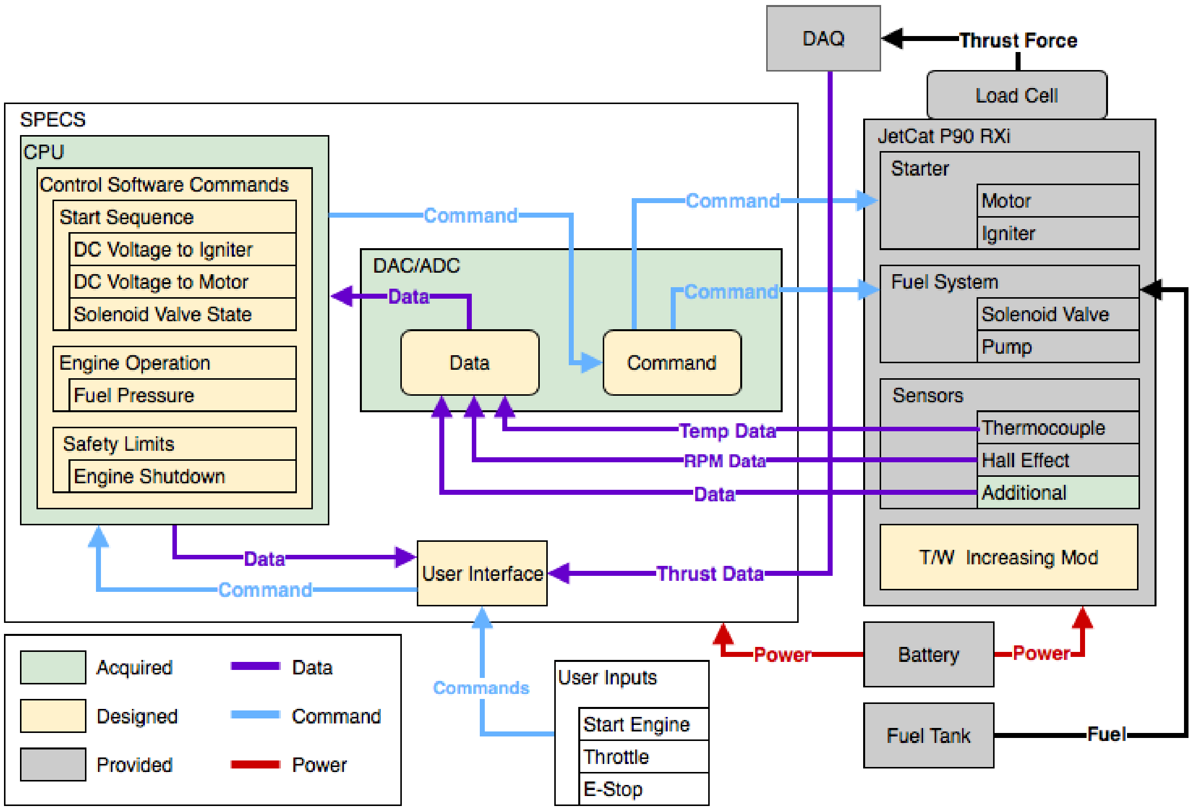

Figure 1. Functional Block Diagram

2.4. Concept of Operations

Below is the concept of operation for the SPECS mission. SPECS provides a solution that fits into the USAF's desire to test and use faster UAVs for combat operations. The SPECS design team will validate the predicted increase in T/W by performing the simulated flight profile as shown below in Figure 2. This mission profile is based on a 30 ounce tank of Jet-A fuel, which is a standard large fuel tank for remote control jet hobbyist aircraft. The Average Fuel Consumption (AFC) found from a JetCat turbine data sheet[7] allowed us to determine a reasonable mission duration of 2 minutes.

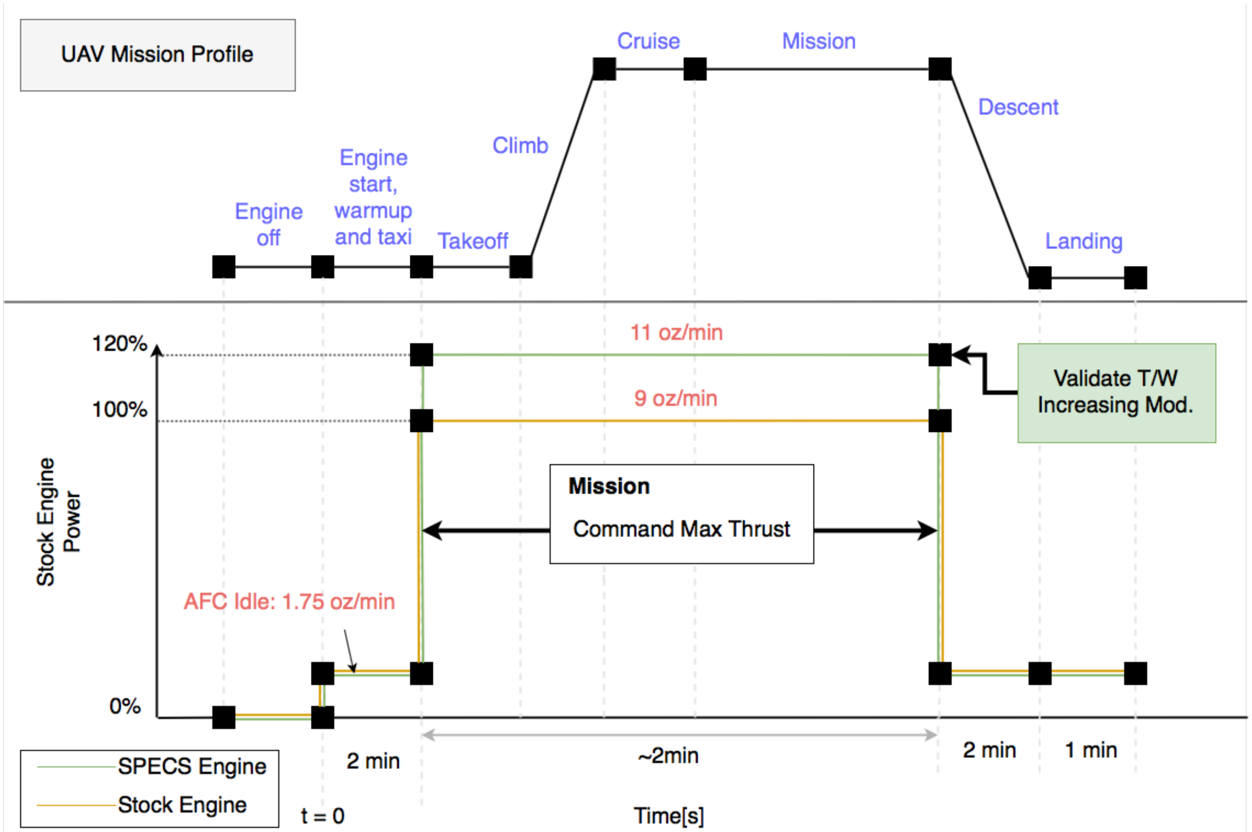

Figure 2. Concept of Operations

2.5. Functional Requirements

The functional requirements for the project are listed below. The first functional requirement addresses the most important part of the project which is increasing the T/W ratio of the engine. This was a requirement that was imposed by the USAF. The team decided that an increase in T/W of 20% is reasonable after researching past projects, as well as due to error margins that would not allow for lower increase while being able to detect a change in thrust. The second requirement involves being able to control the engine at full thrust until steady state conditions are obtained. This is vital since the client has required that the engine be able to run for an extended period of time in a controlled manner. Running the engine safely is also very important for the project, as it could incur injury to the team members or could affect the budget negatively. The SPECS project will be integrated into the JetCat engine and will have an interface for the user to control the engine. These requirements are important because they define the success of the project and they will allow for the client to more readily implement into their own fleet of Unmanned Aerial Vehicles (UAV).

FR 1: The JetCat P90-RXi engine shall have an increased T/W ratio by 20% from stock parameters.

FR 2: SPECS shall control the engine over the entire operational envelope.

FR 3: SPECS shall run the engine in a safe manner.

FR 4: SPECS shall have a user interface for engine control.

3. Design Requirements

FR 1: The JetCat P90-RXi engine shall have an increased T/W ratio by 20% from stock parameters.
Motivation: The task as given by the USAF is to increase the T/W ratio of the JetCat P90-RXi turbojet engine. The 20% figure is achievable based on previous years theoretical results and the results from a project at the

University of Cincinnati.[4]

Validation: An engine run will be performed in order to determine maximum thrust before and after the modification, where the thrust is measured with a load cell. The engine will also be weighed and compared to the original stock engine.

DR 1.1: Implement a T/W improving modification that does not affect the overall operation of the engine and it's ability to run for an extended period of time (2 minutes).

Motivation: The task for the project as outlined by the AFRL was to design and implement a modification to increase the T/W ratio of a JetCat P90-RXi that could then be installed on their systems for operational use. The installed modification will also not fundamentally change the operation of the engine from the point of view of the operator, allowing for a more expansive range of applications of the modification. Assuming that a 30 ounce fuel tank is reasonable for installation on a small UAV, the modified engine shall provide an improved maximum thrust for a comparable amount of time to the stock engine. A theoretical mission profile comparing the stock and modified engine is shown in Figure 2.

Validation: Upon installation of the modification to the engine, the mission profile outlined in Figure 2 will be simulated on a test stand to verify capability.

FR 2: SPECS shall control the engine over the entire operational envelope.

Motivation: In order to measure the effectiveness of any modification made to the engine, SPECS must be able to monitor and control the operation of the engine up to its maximum thrust conditions.

Validation: Using SPECS, the engine will be run, commanded to different thrust settings up to the maximum thrust setting, and monitored with real time and recorded data for stability at commanded throttle setting.

DR 2.1: SPECS will be capable of implementing the engine start up sequence but will modify start up parameters if needed to adapt to engine modifications.

Motivation: The factory start up sequence will be replicated as a starting point and will only be modified if required after engine T/W modification. SPECS must be capable of starting the engine for operations. However, the start up sequence has no consequence on the T/W ratio and will adhere as much to the stock sequence as possible. See Appendix A for JetCat manufacturer start up sequence.

Validation: The start up sequence will be tested on simulated and then functional engines to ensure the manufacture sequence has been replicated. The SPECS start up sequence will directly replicate the starting RPM rate, fuel flow rate, and igniter duration and frequency.

DR 2.2: SPECS shall maintain idle at or near 33,000 ± 100 RPM.

Motivation: For the engine to run independent of the starter motor, the manufacturer idle state speed for the engine is at 33,000 RPM (at or near accounts for variations which may occur due to altitude or atmospheric conditions). This ensures the engine control feedback loop is capable of maintaining idle speed. The ± 100 RPM is the current stock resolution for RPMs.

Validation: The SPECS team will start the engine and monitor the RPM with real time and recorded data for stability at the designated idle speed.

DR 2.2.1: SPECS shall measure input from the thermocouple concurrently with RPM and fuel pump Pulse Width Modulation (PWM).

Motivation: Temperature will be an indication used to validate RPM vs fuel addition and provides insight to the turbine blade temperature which is the thermal component of highest concern.

Validation: Use of a high temperature infrared thermometer during steady state and transient operation will verify analog input calibration.

DR 2.2.2: SPECS shall measure input from the Hall effect sensor up to 5 kHz rate.

Motivation: To properly control the engine and ensure safe operation, the RPM must be monitored to prevent the engine from moving beyond the operation envelope. At 130,000 RPM, the Hall effect sensor will be sensing at a rate near 2.2 kHz. The resulting Nyquist frequency requires sampling at double the rate near 5 kHz in order to prevent aliasing.

Validation: Before installation, SPECS shall be tested with simulated waveforms from a waveform generator to verify that SPECS is capable of measuring the RPM required for proper operation of the engine.

DR 2.2.3: SPECS shall send PWM fuel pump command rate as a percentage of full power.

Motivation: RPM will be mapped to an approximate fuel mass flow rate to verify position within operational window.

Validation: PWM sending signal will be calibrated to fuel pump full power limits on SPECS.

FR 3: SPECS shall run the engine in a safe manner.
Motivation: The jet fuel, high engine temperatures, and high pressures associated with running a jet engine necessitate safety conscious operations. Safe operation of the engine will protect personnel from injury and reduce risk of damage to the engine hardware.
Validation: The SPECS team will follow faculty approved testing procedures and adhere to all safety requirements as approved by faculty. A team member will be assigned as the safety officer and will run the safety checklist, ensuring completion of the checklist prior to engine start.

DR 3.1: SPECS will maintain operation below 130,000 RPM unless a new upper safety limit is determined from the engine characterization.
Motivation: The operational safety limit RPM as defined by the manufacturer is 130,000 RPM. Some thrust increasing options may require a higher RPM. An in-depth material and structural analysis will need to be performed in order to determine any higher RPM limits. Any safety limit alteration will adhere to the UAV System Airworthiness Requirements (USAR) factor of safety of 1.3.[17][18]
Validation: The on-board Hall effect sensor will be able to provide RPM data to the operator, which may then be compared to the safety limit.

DR 3.2: SPECS will maintain EGT below 700° Celsius unless a new upper safety limit is determined.
Motivation: The operational safety limit temperature as defined by the manufacturer is 700° Celsius. Some thrust increasing options may require a higher temperature for operation. An in-depth material and structural analysis will need to be performed in order to determine any higher temperature limits. These limits will not exceed the USAR factor of safety of 1.3.
Validation: The engine has a stock thermocouple for reading EGT. SPECS will be capable of reading and analyzing the thermocouple data to determine temperature in real time.

DR 3.3: Should upper limits of operation be reached for RPM or EGT, SPECS shall command a software automatic engine shutdown.
Motivation: In order to avoid catastrophic failure under extreme operational conditions, the engine must be stopped when temperatures or RPM may exceed the structural limitations of the material.
Validation: SPECS will have adjustable set points for all operational limits. During initial operation, set points below manufacturer limits will be used to test the function of the safety shutdown. When proper operation is observed, set points will be adjusted to factory levels and the test performed again by methodically increasing toward the limit.

FR 4: SPECS shall have a user interface for engine control.
Motivation: User must be able to start, stop, and throttle engine from a distance in order to have functional control of engine.
Validation: Engine may be observed to react to engine inputs according to that input's purpose.

DR 4.1: The SPECS user interface shall display to the user the EGT (10°C increments), RPM (100 RPM increments), battery voltage (0.1V increments), and calculated fuel flow rate (oz/min).
Motivation: The factory engine system displays data in this format and resolution. User needs to be able to monitor system parameters in real time to monitor and verify the system response through time.
Validation: By observation through user interface.

DR 4.2: The SPECS user interface shall take user throttle inputs.
Motivation: The user needs the capability to command a desired engine RPM such that the desired thrust is obtained.
Validation: With RPM resolution at 1 pulse per revolution, RPM readout at 130,000 RPM will be a 2.166kHz square wave. Measured controller pulses will be matched to the input value and maintain within 100 RPM as validated with handheld laser tachometer.

DR 4.3: The SPECS user interface shall have the ability to initiate the engine start up and shutdown sequences.
Motivation: The user must be able to safely start and stop the the engine through the stock sequences.
Validation: The start and stop sequences will be validated through comparison to the stock sequences as detailed in Appendix A.

DR 4.4: The SPECS user interface shall display warnings for operation within 10% of safety limits to the operator.
Motivation: Warning indication will alert users of approaching safety limits in advance of exceeding safe operational boundaries. This advanced warning will allow the operator to adjust engine conditions before

an automatic shutdown is initiated.
Validation: Initial safety limits will be selected as low values within the safe operating range. This will verify that the system works prior to modification or applying real safety limits.

DR 4.5: The SPECS user interface shall have an Emergency Stop (E-Stop) function.
Motivation: In the event of uncontrolled or improper response, a large manual E-Stop button and software based E-Stop command will immediately cut all power and fuel supplied to the engine.
Validation: Pressing the E-Stop button immediately removes all power from SPECS and by extension stops the fuel pump and shuts the fuel cutoff valve.

4. Key Design Options Considered

4.1. SPECS Configuration

A physical hardware layout must be determined prior to conducting a controller development platform trade study. There are three options for configuration: on-board, off-board, and split. The ECU controller has been identified as the most critical design choice for the SPECS controller as it is required for any physical engine modification to succeed. The options for controller hardware depend upon the physical configuration. Thus we decided to first study the base configuration and then return to the hardware.

4.1.1. On-board

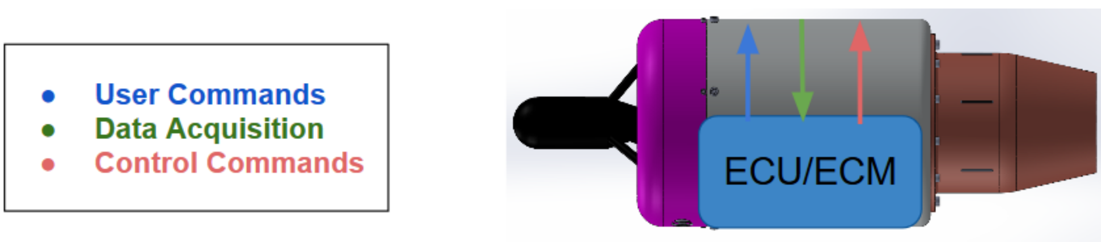

Figure 3. Theoretical onboard SPECS System

One option for SPECS system architecture is including both ECU/ECM functionalities as a combined unit on-board the JetCat. This would minimize the distance between the engine, sensors, and processing equipment. Minimizing distance would allow for minimum response time of the equipment. However, the entire system weight of SPECS would be flown alongside the engine and thus counteract the goal of increasing the T/W ratio. Additionally, peripheral control modifications or measurements would need to be programmed and measured on-board the engine, further increasing weight and components in close proximity to the engine air intake.

Table 1. Combined on-board ECU/ECM.

Pros	Cons
Reduces Response Time	Maintain or increase flown weight
	Reduced ability to control in flight

4.1.2. Off-board

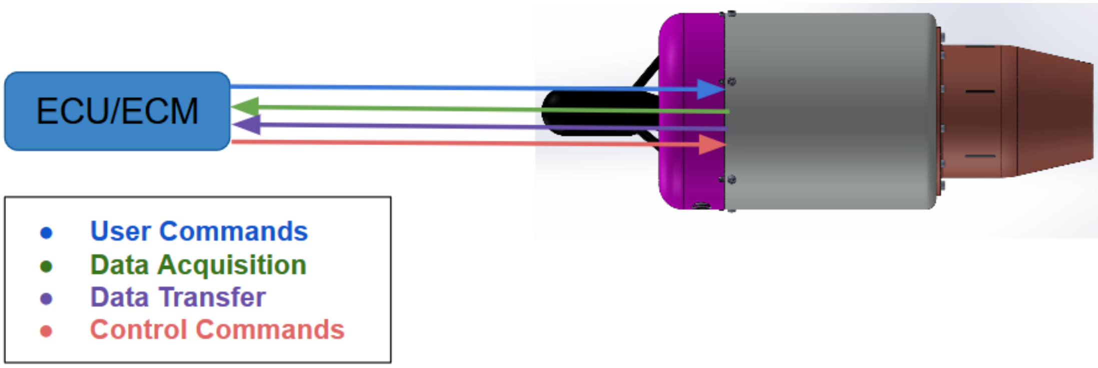

Figure 4. Theoretical offboard SPECS System

The other combined functionality option for SPECS is combining ECU/ECM completely off-board the JetCat engine. This would allow SPECS to reduce the weight of the engine by removing the current ECM and introducing that functionality external to the engine. The user would also have control over the engine state from a distance. However, the response time from the sensors on the engine would increase due to distance of communication. This may also introduce signal integrity complications for known high frequency transmissions (RPM sensing) due to the the high voltage spikes of the ignition system during operation.

Table 2. Combined off-board ECU/ECM.

Pros	Cons
Reduce flown weight	Decreased response time
High ability to control in flight	Signal Integrity Concerns

4.1.3. Split

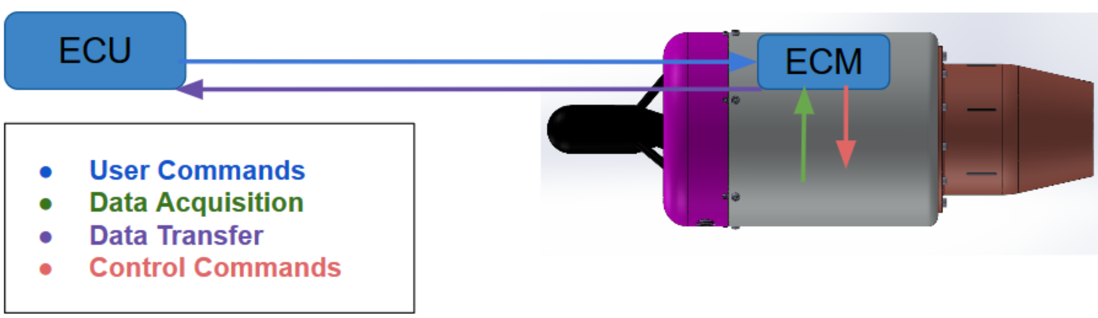

Figure 5. Theoretical split SPECS System

SPECS could also mimic the current JetCat architecture of a split ECU/ECM with an on-board ECM controlling most engine operations and a separate off-board ECU for user control. The benefit of this combination is the on-board ECM contains a simple fine tuned closed loop system for engine control, while the ECU is an off-board solution that is easily configurable to meet design or testing needs. This combination has the greatest flexibility and would provide reliable and stable control of the engine.

Table 3. Separate on-board ECM and off-board ECU.

Pros	Cons
Reduce flown weight	Heavier than completely offboard
High response time for ECM	Two separate Printed Circuit Board (PCB) components
High ability to control in flight from ECU	

Table 4. Separate on-board ECM and off-board ECU.

4.1.4. Conclusion

Based on the trade study in section 5.2, SPECS will be selecting the Split configuration. This configuration provides the best combination of fast accurate response and minimum on-board weight.

4.2. ECU Development Platform

There are many options for ECU development platforms that will work for this application. Integrated Development Environment (IDE) availability and user familiarity are critically important considerations for selection. This project intends to produce a Graphical User Interface (GUI) for user control and ease of use in future projects. This makes the selection of ECU heavily dependent on availability and relative complexity of development environments for the target users. Open source development software and free to use IDEs shall be considered for this application.

The controller boards associated with an IDE must be able to communicate with the ECM to receive sensor data and send commands to start, throttle, or shut down the engine. All options listed below meet the minimum computational standards needed for the project. Several options such as Raspberry Pi and similar boards are not considered because their level of performance is excessive for the desired application, needlessly adding cost and complexity to the design. The focus for selecting the development platform will be a combination of ease of application and adaptability for future use. The purpose of the SPECS ECU is to allow the user to modify engine control parameters on a regular and reoccurring basis, which requires heavy emphasis on usability.

4.2.1. Arduino

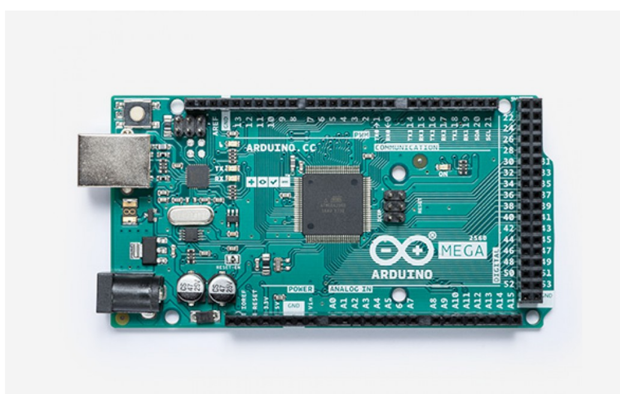

Figure 6. Arduino Mega 2560 Rev3

Arduino development boards come with a variety of capabilities and would allow SPECS easy and familiar access to a controller board with a range of I/O connections. The Arduino IDE allows the most accessible and familiar development platform for the controlling software, and there are many online support forums dedicated to education based applications of Arduino. There are several options for controller boards that meet the minimum requirements, such as the Arduino Mega which has 54 digital I/O pins and 12 analog input pins allowing the space needed for the desired sensor and user inputs. Several tools exist for the development of a GUI to display collected data such as Megunolink.

Table 5. Arduino Pros and Cons

Pros	Cons
Familiarity	Slower Processor
Intuitive IDE	Higher level approach
Many resources	

4.2.2. Mojo

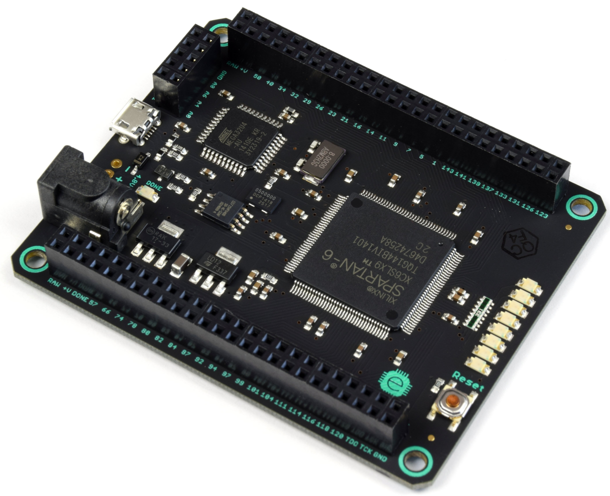

Figure 7. Mojo V3 FPGA

The Mojo development platform features a single controller board, the Mojo V3, with a field-programmable gate array or FPGA. This allows the user to program a controller completely from scratch. This means that the chip inputs and outputs are not constrained and can be configured for almost any useful application. This is particularly useful in applications where the hardware is continually changing or the controller needs to be re-configured on a continual basis to meet different design requirements. This intense customization comes at the cost of a more complicated programming environment and architecture for the board. The Mojo IDE is free to use and contains a broad assortment of signal processing tools, as well as a relatively intuitive user interface.

Table 6. Mojo V3 Pros and Cons

Pros	Cons
Speed	Difficulty
Flexibility	Cost

4.2.3. LPCXpresso

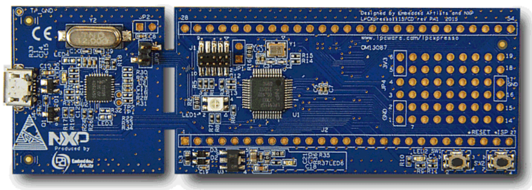

Figure 8. LPC1115 LPCXpresso board

NPX Semiconductors produces the LPCXpresso IDE for their ARM based controller boards. The boards are currently in use in the electrical engineering department for several classes and have instructors and other resources to aid with implementation. The IDE is significantly more complicated due to the wide assortment of processors and configurations that it is designed to accommodate. Programming language is C and assembly, but the file structure and application filter to enable/disable chip component properties adds development complexity. This additional complexity will increase design and troubleshooting time.

Table 7. LPCXpresso Pros and Cons

Pros	Cons
Speed	Minimal Support
Cost	Complex IDE
I/O Capability	Difficulty

4.3. T/W Increasing Modification

4.3.1. Custom Nozzle

The SPECS design team has the option to design and build its own nozzle to accelerate engine exit flow and thus increase thrust. In pursuing this particular design option, the SPECS design team will be able to apply the lessons learned from SABRE's[5] design and manufacturing experiences. However, the nozzle previously manufactured by SABRE is already available to the SPECS design team. With this nozzle the T/W ratio of the engine could be increased by at least 17%[2]. The SABRE nozzle was designed and manufactured to fit a JetCat P-90 RXi engine and accelerate airflow from subsonic speeds to supersonic speeds. In addition to the nozzle itself, SPECS also has direct access to the extensive documentation produced by SABRE. Nonetheless, SABRE was unsuccessful in producing the necessary conditions needed for this acceleration.

The use of a custom ECU/ECM will allow for the potential of increasing the performance of the engine. A determination of the approximate factor of safety used by the manufacturer will aid in the determination of the feasibility of this design. Assuming that a nominal sheet steel was used in the construction of the pressure vessel, modeled as a cylinder, and using the stock engine pressure ratio of 2.35, the stock engine is shown to have a factor of safety of ~2 using Equation 1. If the Air Force standard factor of safety for unmanned aerial vehicles of 1.3[17][18] is used instead, the ideal thrust improvement can be calculated. This calculation can be performed using standard atmospheric conditions and assuming the following: a Calorically Perfect Gas, ideal Brayton cycle, $V_o = 0$ m/s, an ideally expanded isentropic nozzle flow, a constant total pressure in the nozzle, and an axial compressor. Therefore, Eqs. 2 and 3 show that an exit Mach number of 1.58 (1038 m/s) could theoretically be achieved. This would allow a pressure ratio of 4.14. However, the stock temperature limitations on exhaust gas is 1073 K and a pressure ratio of 4.14 would require a static temperature above that limit. With the exhaust gas temperature limited to the stock value, a maximum pressure ratio of 3.73 is possible. This allows an exit Mach number of 1.51 (992 m/s), resulting in a theoretical maximum increase in thrust of 177%.

$$\sigma_H = \frac{PD}{t} \longrightarrow P = \frac{\sigma_H t}{D} \tag{1}$$

$$M_9 = \frac{V_9}{a_9} = \frac{V_9}{\sqrt{\gamma R T_9}} \tag{2}$$

$$F = \dot{m}_e V_e - \dot{m}_0 V_0 + (P_e - P_0) A_e \tag{3}$$

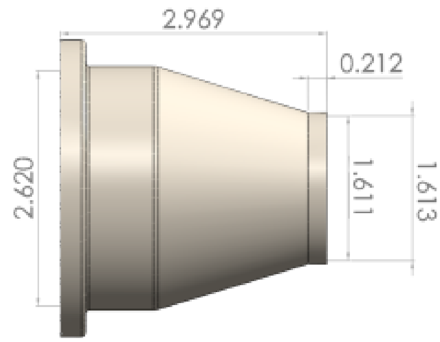

Figure 9. SABRE design nozzle

Table 8. Custom Nozzle pros and cons.

Pros	Cons
Theoretical thrust increase of 177%	Needs to be designed and manufactured
Will be designed for supersonic flow	Slight increase in weight
Similar design process documented extensively	

4.3.2. Water Injection

Another method to increase thrust is to integrate a water injection system into the engine. Documentation from NACA shows that even with a 0 m/s freestream velocity a 0.05 water-air ratio can increase the thrust of an engine by up to 30% on a dry day.[19] This can be done by spraying either water or a water-alcohol mixture into the compressor resulting in higher combustion chamber pressure. The higher mass flow combined with the higher chamber pressure will generate the higher thrust. Assuming that increase in thrust is primarily due to the increase in exhaust pressure and that the original nozzle ideally expanded the exhaust, an increase in total pressure of 144 kPa is possible according to Eq. 4. These assumptions involve a significant amount of error because a portion of the thrust increase is caused by the increased mass flow rate and the increase in exit velocity. Although the value is not exact, it does provide a baseline for estimation. Water injection can also be used in the combustion chamber but this will generate a lesser increase in thrust.

$$F = \dot{m}_e V_e - \dot{m}_0 V_0 + (P_e - P_0) A_e \longrightarrow \Delta F = \Delta P_t A_e \tag{4}$$

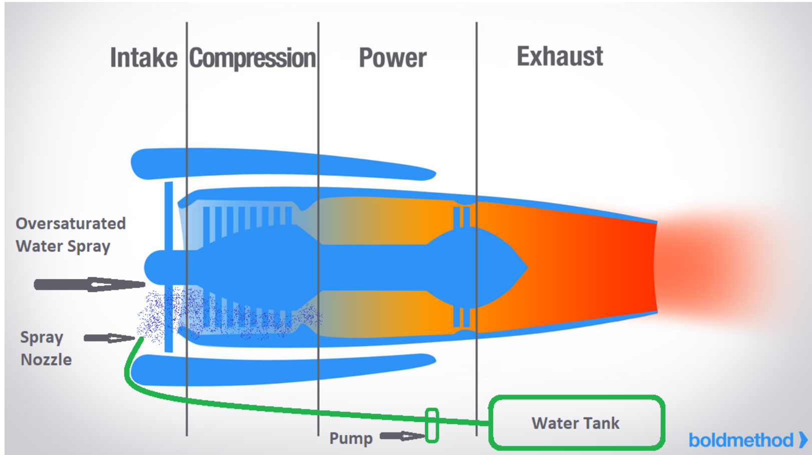

Figure 10. Example of Water Injection

Table 9. Water injection pros and cons.

Pros	Cons
Possible thrust increase of 30%	Utility dependent on ambient conditions
Only minor increase in weight	Turbine must be able to handle increased mass flow rate
Relatively easy to design compared to other options	

4.3.3. Afterburner

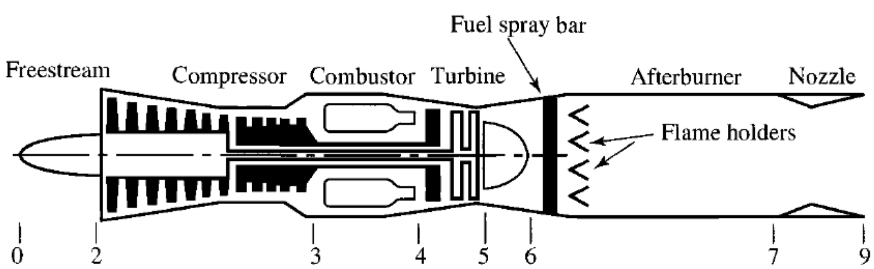

Figure 11. Example of an ideal afterburner

By implementing an afterburner into the JetCat engine, the SPECS design team can attain up to a 50% increase in thrust at the cost of a large increases in both weight and fuel consumption.[20] A CU team, DANTE, did a project on a similar engine for a faculty member in 2009. The goal of this project was to increase thrust by 50% without a decrease in the lift to weight ratio. Afterburners work by heating the exhaust gas, thus increasing enthalpy and generating higher exit velocity. This manner of thrust augmentation utilizes multiple parts; it requires fuel injectors, flame holders, an afterburner duct, and the requisite baffling. An example of such an implementation is the Pratt & Whitney J75 engine which could produce ~17,000 lbf without an afterburner and around 24,500 lbf with an afterburner weighing approximately 800 lbs[16]. With an afterburner this jet engine had a T/W ratio that is increased by 24.58% with a 44.12% increase in thrust itself. This jet engine core was used aboard the U-2C, F-105 Thunderchief, and the Boeing 707 in a modified form.

Pros	Cons
Possible thrust increase of up to 50%	Very large increase in weight
Extensively documented	Massive increase in fuel consumption
	DANTE apparatus unavailable
	Relatively complex
	Difficult to implement

Table 10. Afterburner pros and cons.

4.3.4. SABRE Nozzle and Water Injection

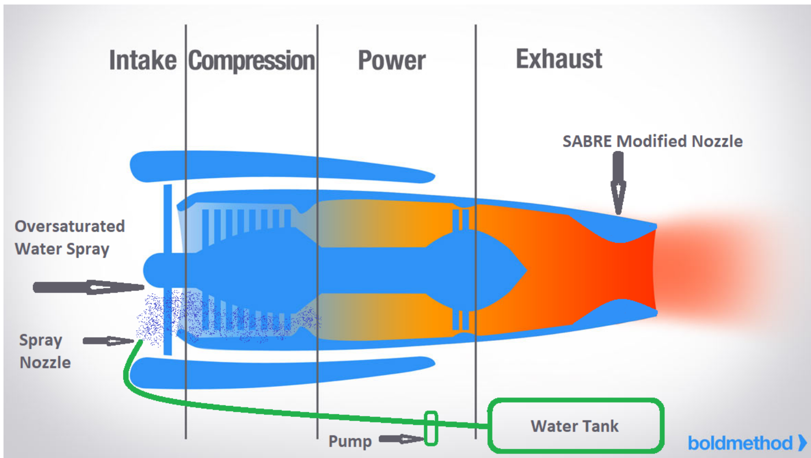

Figure 12. Example of Water Injection used with SABRE Nozzle

Building off the previous work of the SABRE team, the SPECS design team can solve the problem of inadequate turbine exhaust pressure experienced by the SABRE team by adding the capability of water injection to the P-90 RXi engine. As per NACA documentation, the addition of water injection allows for a higher compression ratio for the compression stage as well as decreased combustion chamber and exhaust temperatures which are both limiting factors in current engine performance. This option would necessitate the use of the SABRE nozzle to allow adequate time for design and testing of the water injection system, which will require additional modeling to verify safe engine operation. Extensive documentation from the SABRE team can be built upon by incorporating a more comprehensive system model which will determine the feasibility of achieving supersonic flow through the already proven nozzle. If time resources permit, other nozzle configurations can be considered where the flow can be ideally expanded depending on the final exhaust pressure that can be obtained using water injection.

Table 11. Nozzle/Water Injection pros and cons.

Pros	Cons
Possible thrust increase of 67%	Increase in weight
Ease of implementation	Increased fuel consumption
Extensively documented	Requires additional onboard water tank and pump

4.3.5. Turbine Modification

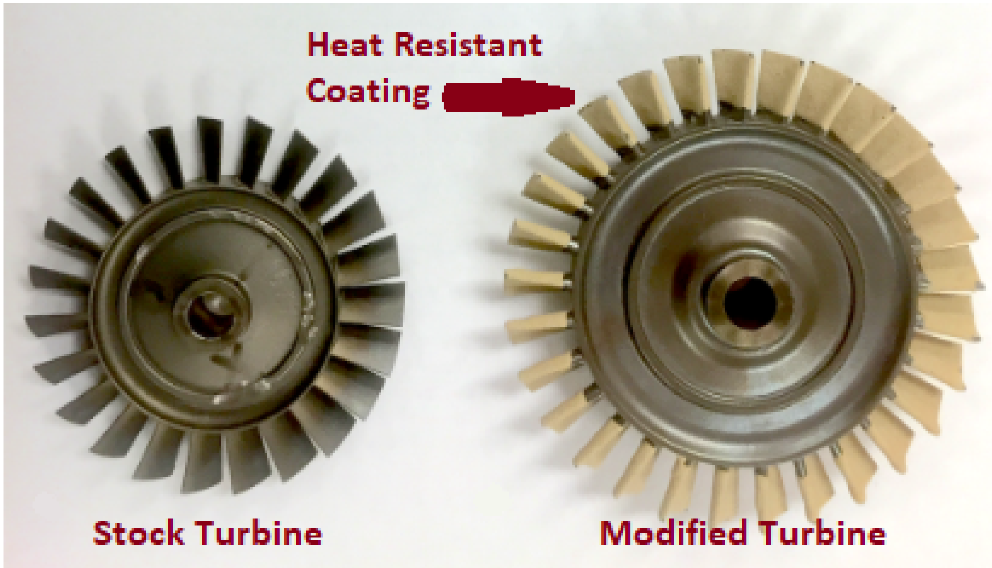

Figure 13. Example of a turbine stator modification

A modification to the turbine stage of the engine could allow for an increase in the temperature upstream of the turbine without exceeding the turbine temperature safety limits. The implementation of a turbine rotor cooling system through inlet air ducting through the blades themselves is one previously explored option among many. Previous work displayed a potential 5% increase in thrust through the incorporation of a turbine rotor cooling system.[15]

Table 12. Turbine Modification pros and cons.

Pros	Cons
Thrust increase of 5%	Not modular
	Theoretical increases not proven
	Potential to reduce thrust
	Difficult to define safety criteria

4.3.6. Compressor Modification

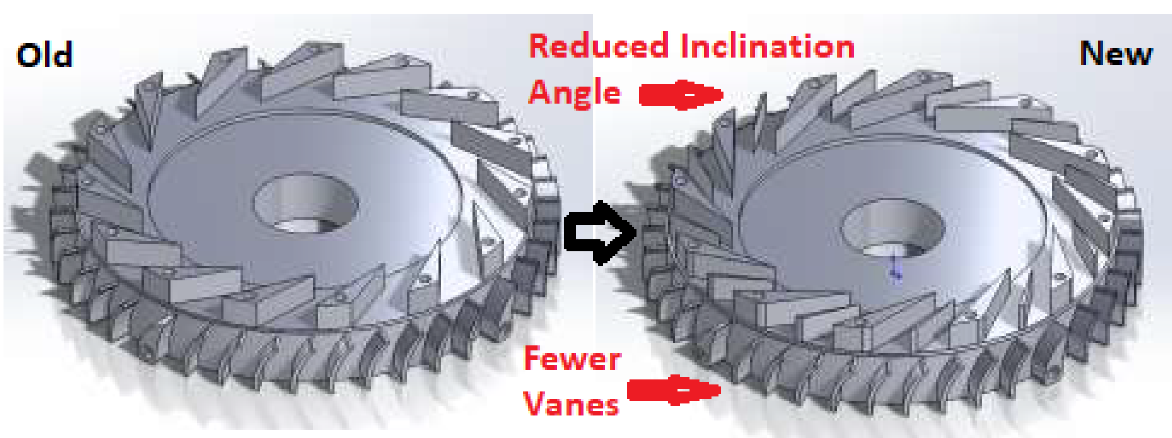

Figure 14. Example of a compressor diffusor modification

By redesigning the compressor, an improvement to the compression ratio or total pressure loss could be attained which would increase the thrust as well as potentially reducing the weight. Previous work on optimizing the compressor diffuser has shown total pressure loss decreases by as much as 7% (~5 kPa). This will have a predominant effect on efficiency but will also contribute to a small increase in thrust(~10 N). (Feldhacker, 2015, p. 5)

Table 13. Compressor Modification pros and cons.

Pros	Cons
Possible thrust increase of 11%	Not modular
	Complex modeling requirements

5. Trade Study Process and Results

5.1. Trade Study Methodology

5.1.1. Weighted Decision Matrix

In order to determine an objective set of criteria that would be used to judge the efficacy of a particular method, a decision matrix was assembled. A set of 10-15 criteria based on their effectiveness in accomplishing the goals of the trade was compiled and justifications for the use of each criteria was discussed by the team. Each member of the team then designated each criteria as either critical or non-critical to the success of the project and the criteria that received a cumulative score above a significant threshold was chosen as the critical criteria of that trade.
The weight assigned to each critical criteria was then designated by each member and any individual outliers were prompted for additional justification for the weight provided. After a consensus was reached on a weight to assign each critical criteria, the individual metrics were evaluated by their ability to meet the critical criteria using a Likert-like Scale to enable quantification of the qualitative elements of the scale.[21]

5.1.2. Proportional Likert Scale

A 5 tier Likert Scale, where a 1 or 5 denotes a very low or very high ability, respectively, to meet each critical criteria was used to evaluate the metrics. Through further team discussion, these scores were then scaled proportionally according to the criteria weights and summed to provide a cumulative total which designated its value as a solution. The quantitative elements of the scale were scored by assigning the integer value of the trade matrix while the qualitative elements were scored based off of the averages of the likert-like scale directly. The justification for each criteria is found in its applicable section below.

5.2. SPECS Configuration

5.2.1. Response Time

The on-board Hall effect circuit is particularly vulnerable to signal corruption at high engine RPM. Parallel runs of wires operating at high fluctuating voltages should be avoided wherever possible to provide the best signal integrity. The ability to quickly and accurately read RPM values will free up processing resources for data transmission and control signal generation. Best engineering practices are used to estimate anticipated system response.

5.2.2. Ease of Control

A simple and precise user interface is needed to control the engine reliably. Changing operational parameters should be an easy process that does not require the user to perform “work around” or require arduous procedures to make adjustments to an operating system.

5.2.3. Weight

The overall weight of SPECS controller will be similar to the stock ECU system. Project guidelines from the customer indicate that the engine weight will only include items physically present on the main engine assembly. System weight is based on if the configuration added or subtracted mass from the main engine assembly.

5.2.4. Trade Matrix

	1	2	3	4	5
Response Time (Weighted 37%)	Unsustainable response time	Much slower than stock ECU	Slower than stock ECU	Same speed as stock ECU	Faster than stock ECU
Ease of Control (Weighted 43%)	No functions available	Most functions available on engine	All functions available on engine	Most functions available at distance	All functions available at distance
Weight (Weighted 20%)	Much heavier than stock ECU	Heavier than stock ECU	Same weight as stock ECU	Lighter than stock ECU	Much lighter than stock ECU

Table 14. Rating Meaning

	Onboard	Offboard	Split
Response Time	4.3	2.2	4.1
Ease of Control	2.5	3.4	3.7
Weight	2.1	3.4	2.3
Total	3.0	2.9	3.6

Table 15. SPECS Configuration trade matrix.

5.3. ECU Development Platform

At this point in design, the IDE and support software is the most important aspect to consider for the ECM trade study. Each subset of micro controllers have many options that will satisfy the minimum computational requirements as they are currently defined. The metrics below are based on team experience and comfort with various platforms. Research has been done on availability and use-ability of software required to develop project systems. Results displayed below describe the metric and indicate how team members were asked to rate a system based on information provided from electrical team members.

5.3.1. Team Experience

The ECU is a critical element within the project. Being experienced with the platform will allow for smoother and more reliable development within the time available. The more the team must learn about the platform the longer progress will take. Weight and relative scores are determined by an individual users personal experience with the specific platform.

5.3.2. Compatibility

The stock engine has little compatibility to any modifications thus system compatibility with other devices is an important consideration due to the requirement for external input to control the engine. This rating is based on the ability to add additional devices or processes to the system without requiring excessive rework.

5.3.3. Development Time

The project must progress within the time given for the semester. This rating is a representation of confidence each member has in the application itself and that the objective can be completed as scoped. Weight and relative scores are determined by the average of individual user's confidence and experience with the associated IDE.

5.3.4. Data Acquisition Rate

The project has set goals for measuring and mapping system parameters. Data-sheets were reviewed for many options to ensure that solutions were available that meet minimum computational needs. This rating is based on the range of acquisition rates available for the boards encompassed by the development platform considered. A selection with a higher data acquisition rate would allow more complex computation during operation and may improve system reliability and accuracy.

5.3.5. Current Documentation

The more extensive the existing documentation of the development platform, the more resources are available to the team during development of the SPECS system. The quality and content of the documentation was also taken into account during the selection of the development platforms. Ratings indicate clarity and quality of easily located documentation for relevant micro controllers and support software.

5.3.6. Software Quality

The IDE and supporting software will play a critical role in aiding or hindering progress through development. This metric represents user confidence in the software capability and usability for the average user on the team. IDE experience and research into supplementary software options were analyzed at face value to determine that minimum requirements were met and to compare the ability of tools available to assist during development.

5.3.7. Trade Matrix

	1	2	3	4	5
Team Experience (Weighted 32%)	No experience	Some experience	Moderate experience	Great experience	Extensive experience
Compatibility (Weighted 7%)	Cannot accommodate desired sensors	Accommodates sensors with extensive configuration	Accommodates sensors with moderate configuration	Accommodates sensors with current configuration	Accommodates more than base sensors
Development Time (Weighted 24%)	Impossible before April 2019	> 80% of available time	60 – 80% of available time	40 – 60% of available time	20 – 40% of available time
Data Acquisition Rate (Weighted 8%)	Bare minimum speed to run engine	Able to run engine and process some additional sensors	Easily able to run engine and process additional sensors	Just able to run engine, process sensors, and produce GUI	Excess computational abilities to run engine, process sensors, and produce GUI
Current Documentation (Weighted 12%)	No documentation	Sparse documentation	Some documentation	Moderate documentation	Extensive documentation
Software Quality (Weighted 17%)	Extremely complicated	Complicated	Mediocre	Intuitive	Extremely intuitive

Table 16. Rating Meaning

	Arduino	Mojo	LCPXpresso
Team Experience	4.2	1.5	2.5
Compatibility	3.7	2.6	3.3
Development Time	4.0	2.1	2.8
Data Acquisition Rate	2.5	4.0	3.7
Current Documentation	4.5	2.5	3.1
Software Quality	4.1	2.7	3.5
Total	4.0	2.2	2.9

Table 17. SPECS ECU Development Platform trade matrix.

5.4. T/W Increasing Modification

5.4.1. Increased T/W Ratio

Improvement of T/W is the primary customer requirement and is central to any potential solution. The focus of increasing the T/W ratio is to generate more thrust is due to the number of options available to increase thrust while minimally affecting weight. This factor will measure how much the add-on system/equipment will impact the engine weight. This measurement will be an estimation based on current knowledge, research, and previous CU projects.

5.4.2. Development Time

The time-consuming modification design has to be taken into consideration since the SPECS design team is also focusing on building customized ECU and ECM. The limitation of time and human resources will result in a finite amount of work that can be done on those modifications. A design with reasonable complexity and manufacturing requirements needs to be developed, as well as a solution to the difficulty of assembling and integrating components.

5.4.3. Cost

Due to the financial limitation of a $5000 budget, the cost of modifications needs to be taken into account. Even though previous CU design teams' ECU and ECM are available, the customized electronics need to be completely redesign to fulfill SPECS project's requirements. With previous lessons learned from the SABRE team, there is a risk of melting the ECM board, and the cost of replacing it will be around $500 not including any customized components that will be installed. A budget of $2000 needs to be saved for a new JetCat P90-RXi engine in case of any fatal damages done to the engine.

5.4.4. Modularity/Ease of Implementation

The defining characteristic of any potential solution desired by the AFRL is that it be 'bolt-on' as much as possible, meaning that the solution can be quickly added as a modification to an existing engine with minimal redesign of the engine components. This criteria is inherently subjective in nature as there is always the potential for a particularly creative design that allows a complex engine modification to be done with minimal effort.

5.4.5. Safety

The safety requirement of the modification is the ability to run the engine within its material limits such as the pressure limit inside combustion chamber, the maximum exhaust temperature that the nozzle can tolerate, etc. The manual operation is also considered a part of safety since any modifications have the potential of changing engine start sequence, and any incorrect operations may cause engine to shut down or, even in worse scenario, to explode or catch on fire. This scenario could result in permanent damage to the engine or to surrounding people.

5.4.6. Current Documentation

Besides the time to manufacture, integrate, and test the components, the support of thorough and well-written documentation on any past or similar projects will reduce the difficulty of the modifications implementation. A modification with sufficient documentation would allow for an easier and quicker installation.

5.4.7. Trade Matrix

	1	2	3	4	5
Increase T/W Ratio (Weighted 38%)	Limited theoretical and no experimental data showing possible improvement	Limited theoretical and experimental data showing possible improvement	Extensive theoretical and limited experimental data showing possible improvement	Extensive theoretical and limited experimental data directly applicable to P90-Rxi engine showing improvement	Extensive theoretical and experimental data directly applicable to P90-Rxi engine showing improvement
Cost (Weighted 9%)	Estimated Cost > 75% of budget, very high risk of additional expenses being incurred	Estimated Cost > 50% of budget, high risk of additional expenses being incurred	Estimated Cost > 25% of budget, moderate risk of additional expenses being incurred	Estimated Cost > 15% of budget, mild risk of additional expenses being incurred	Estimated Cost < 15% of budget, no risk of additional expenses being incurred
Development Time (Weighted 21%)	Extremely time-consuming, will not finish on time	Highly time-consuming, unlikely to finish on time	Moderate time-consuming, can finish on time	Little time-consuming, likely to finish ahead of time	Not time-consuming, will finish ahead of time
Current Documentation (Weighted 15%)	A single source	Little documentation	Moderate documentation	Substantial documentation	Extensive documentation from both CU teams and academia
Modularity/Ease of Implementation (Weighted 9%)	Extremely difficult	Highly difficult	Moderately difficult	Little difficult	Not difficult 'Bolt-On' Solution
Safety (Weighted 8%)	Safety limitations unlikely to be determined	Safety limitations may be poorly defined	Safety limitations documented but difficult to determine	Safetly limitations simply defined	Safety limitations predefined by stock engine parameters

Table 18. Rating Meaning

	Custom Nozzle	Water Injection	Afterburner	SABRE Nozzle and Water Injection	Turbine Modification	Compressor Modification
Increase T/W Ratio	4	2.8	2.4	3.9	1.4	2.4
Cost	2.6	2.7	2.1	2.5	2.4	2.3
Development Time	3.3	2.3	1.6	2.3	2	1.8
Current Documentation	3.7	1.6	3	2.5	1.8	1.6
Modularity/Ease of Implementation	4.3	2.8	2.5	2.8	2.6	1.5
Safety	3.4	2.9	1.4	3.3	2.4	2.5
Total	3.7	2.5	2.2	3.1	1.9	1.9

Table 19. T/W Increasing Modification Trade Study

6. Selection of Baseline Design

6.1. SPECS Configuration

Visible in Table 15, the split configuration has the highest cumulative score. This configuration is common throughout the RC world for many of the same reasons explored in the trade study. Having a responsive controller to drive the engine, and the freedom of on off engine platform for control and development make the split configuration the best choice.

6.2. ECU Development Platform

The Arduino platform and IDE has been selected as the SPECS development platform. Other options provided finer control or faster processing, but Arduino has many offerings that will meet the minimum computational needs with a user friendly and familiar IDE. The widespread use of Arduino in education has resulted in thriving support communities and easy to use add-ons for GUI development and control loop tuning. Team members can dive straight into development, saving time and resources.

6.3. T/W Increasing Modification

It is evident from Table 19 that the custom nozzle achieves the highest average score. In addition there is an extensive amount of resources on supersonic nozzles. This includes the SABRE team documentation and their actual testing model which will support the SPECS design team's fundamental development on nozzle design. Along with a highest theoretical maximum thrust increase of 177%, a custom nozzle is recognized as the most appropriate design choice.

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7. Appendix A

JetCat P90-RXi Stock Startup Sequence[8]

1. The turbine is spun up via the starter to 2000-2500 RPM.
2. The glow plug is activated and is preheated for 5 seconds.
3. The starting fuel valve opens and starts to pulse fuel into the chamber.
4. The speed of the turbine is kept constant until the combustion chamber is preheated to about 120 °C.
5. The main fuel valve is opened and fuel starts to be injected into the chamber.
6. The turbine accelerates to idle RPM and then the starter disengages.
7. The turbine RPM will progressively be increased to approximately 55,000 RPM and then will be automatically stabilized to idle speed.
8. The turbine will now be kept at idling speed until the throttle stick has also been brought back to idle position. If this is done, the turbine thrust can now be specified by the pilot.