University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

Specialized Propulsion Electronic Control System (SPECS)

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Approvals

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1. Problem Statement

In recent years small hobbyist jet engines have gained popularity within the US military as a possible propulsion solution for unmanned aerial vehicles (UAVs). By utilizing jet engines on UAVs, aircraft gain greater versatility in their mission capabilities. These small turbojets allow the aircraft to fly faster, carry more sensors or payload, and extend the range further than would be achievable with electric or piston motors. Instead of creating new UAV air-frames to fit new operational requirements, the United States Air Force is interested in modifying the existing R/C turbojet engines on their fleet of UAVs to enable these air-frames to achieve new mission objectives. The commercially available JetCat P90-RXi type R/C turbojet engine has primarily been used on small hobby jet aircraft projects. The stock engine was designed for operators lacking in-depth knowledge of jet engines or their operation. Due to this design, the stock engine does not allow for simple modification, such as an afterburner, without exceeding conservative safety limits which cause engine shutdown. Based on years of past experience, the proprietary electronics control unit (ECU), engine control module (ECM), and embedded software have limited the success of most hardware and software modifications to the engine [4] [5]. Additionally, the embedded software is inadequate for real-time monitoring of system parameters [6]. For these reasons, the ECU, ECM, and embedded software must be removed and replaced for a successful project.

The intent of SPECS is to expand the capability of the JetCat P90-RXi by designing, building, and validating a completely new ECU, ECM, and embedded software system that will address the issue of off-nominal operations and operator control causing the stock engine to shut down. The SPECS ECM will replace the stock ECM that is on-board the engine. Its purpose is to directly control engine components such as starter and fuel pump. The ECU will replace the external JetCat ECU, and will be a programmable microcontroller capable of interfacing with various GUI and running system profiles by commanding the ECM.

Figure 1. Application of the JetCat P90-RXi on an unmanned aerial vehicle.

The system will be validated through the creation of an engine simulator program that will model the performance of the engine with simulated sensor data. A test stand will be designed and manufactured for validation of electronics and engine component performance. A test assembly will be constructed to characterize the fuel pump flow rates and pressures. The system shall provide the operator with near real-time access with delays less than TBD seconds and control over fuel pressure, safety limitations, as well as RPM and Exhaust Gas Temperature (EGT). This solution will allow the JetCat P90-RXi engine to operate in a customized manner such that the overall operation can be changed without issues from the ECU. The operator will then be able to modify engine components or parameters chosen to increase the thrust to weight ratio without affecting the engine's ability to operate for a TBD amount of fuel. In doing so, current UAVs will become more mission flexible, able to fulfill a wider variety of new and future objectives, and capable of aiding our armed forces throughout ongoing operations.

2. Previous Work

The Air Force Research Laboratory (AFRL) began hosting the Aerospace Propulsion Outreach Program (APOP) in 2011 to fund student led development of modifications for small turbine engines. Each year the competition explores the viability of a different modification made to the JetCat family of microjets, with the hope of possible application to the Air Force's own small engine platforms. Since the program's inaugural year, the University of Colorado, Boulder (CU) has competed in five of these competitions. While each of these annual competitions had a unique design objective, a common dilemma that has arisen for multiple teams is the stock ECU for the JetCat P90-RXi. The provided ECU has hindered design attempts by providing a very limited operational window for testing and modification as any time the ECU receives any unusual signals from the engine, the engine is automatically shut down. The manufacturer does not wish to disclose proprietary design elements resulting in a barrier to project testing and implementation. Previous teams have encountered this obstacle, but have been unable to implement a successful user defined ECU.

In 2014, project MEDUSA attempted to modify the JetCat engine such that it was capable of running methane fuel instead of kerosene. The team designed a new ECU that was successful in collecting and interpreting sensor data from the engine, but unable to provide input to the engine to control performance. [10]

In 2015, project REAPER again attempted an ECU redesign. The objective of this project was to redesign the engine to take advantage of a recuperated cycle. After installing the modification it was determined that the ECU would prevent operational testing. The team attempted to design a new ECU that added the ability to collect intake parameters. A similar level of success was reached, with control input ability being a limiting factor.[11]

The most recent team to attempt to design a new ECU was the 2017 CU APOP competition team, ACES. Similarly to the previous two projects, the design objective given to them by AFRL required a modification to the ECU to ensure that the ECU would not force the engine to shut down when attempting a cold soak start. ACES developed a new ECU along with a new ECM that were capable of functioning at the extreme conditions of a cold start but struggled with integration of the ECU with the engine.[12]

In addition to projects undertaken by CU students on JetCat, numerous other projects have been undertaken by both undergraduate and graduate students intent on either building or modifying ECUs on comparable microjets. One such example came from a Czech team. The main objective of this project was the design and construction of an ECU for a JMP-TS-20 jet engine (an engine comparable in size to a P90-SXi). In this case, the ECU was intended to completely replace the aging APD-21 control unit. Ultimately their effort was successful and measurements were taken for the rpm, thrust, and temperature of the new starting process. The new ECU managed to perform the same function as the old one at a dramatic reduction in size.[13]

Another example of a similar project was detailed in a Turkish thesis submitted to the Middle East Technical University. This project centered around the creation of a mathematical model for a gas turbine engine using an AMT Olympus HP jet engine (another engine comparable in size to the JetCat family of engines). In the process of developing this model, an ECU was designed, constructed, tested, and evaluated. Ultimately a relatively accurate mathematical model was constructed and specific suggestions were given in the areas of gas turbine modeling, control, and ECU design.[14]

The SPECS team will mainly focus on the redesign of the ECU and ECM in order to allow the JetCat P90-SXi to operate under modified conditions to improve thrust-to-weight ratio without changing any engine structures. In order to evaluate theoretical models, the engine will need be to tested. To ensure the success of these tests multiple pieces of testing apparatus will need to be designed and manufactured.

3. Specific Objectives

The successful implementation of the project has been divided into multiple levels, each containing objectives that can be verified and quantified. This will enable our team to achieve steady progress while working toward higher levels of success. The level 3 success was designed to show the full operational capability of the new electronics and software system, while not being contingent on the JetCat engine actually operating. This was a deliberate decision to prevent the unpredictable operational nature of the engine from hindering functional goals. If this initial scope of the project is too ambitious, the focus can be reduced from the Level 5 goals to achieve lower levels and still demonstrate success in the project.

[7] [8] [9] [2]	**Electronics**	**Software**	**Modeling/Simulation/Test**
Level 1	Design an ECM prototype board that shall: Energize Starter, Igniter, and Fuel Pump Detect rotations per minute (RPM) input at 0 to 130,000 RPM Detect temperature input from 20 °C to 700 °C Operate Solenoid Valves	Provide UI for fuel pump and starter motor manual control Determine individual sensor poll rates to reduce processor overhead Interpret and record data from 6 channels (Load Cell, T_9, Pitot Tube, Fuel Pump, Hall Effect Sensor)	Use an idealized model to: Model stock engine thrust, P_9, T_9, T_4, and mass flow rate Provide static simulated data inputs from model (T_9, RPM) to test custom ECM response Manufacture test stand for safety validation of maximum RPM conditions
Level 2	Design an ECU prototype board that shall: Send a signal to ECM 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 Human Machine Interface (HMI) Mimic stock engine start-up sequence Interpret and record data from 8 channels (Load Cell, T_9, T_4, P_4, Pitot Tube, Fuel Pump, Hall Effect Sensor)	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 custom ECM and ECU response

Level 3	Control ECM through standalone ECU from an HMI during real-time processing operations Extend ECM sensor range to allow for expanded future capabilities to include: 130000 RPM to TBD RPM 700 °C - TBD °C	Determine fuel cutoff safety parameters Provide fully functional UI (feedback control functions, safety interlock set-point, and data collection) Implement UI in a simulated control environment	Provide dynamic simulated data inputs from model (T_9, RPM, T_4, P_4) to test custom ECM and ECU Perform Monte-Carlo Simulation to determine system sensitivity given TBD % variation
Level 4	Design custom ECU and ECM Integrate ECM onto JetCat engine Implement hall effect sensor daughter board to distribute sensor data collection	Implement UI on JetCat engine under nominal operating conditions Complete startup sequence	Manufacture test assembly using real components. Collect test data and compare to simulations.
Level 5		Run engine for 30 seconds with full throttle control Improve T/W ratio by TBD %	Conform model to actual operating parameters with $< TBD\%$ error

4. Functional Requirements

Accurate measurement of on-board systems is required to successfully design an engine control module. Fuel delivery will be modeled and tested extensively. Closed loop control based on engine RPM input will be used to adjust fuel pump output pressure. Control outputs will be required for the starter motor, ignition system, and fuel pump. Inputs from the RPM sensor and exhaust temperature will be measured and used to provide safety control limits for the engine during operation. Test equipment and associated hardware will need to be manufactured to verify proper functionality of each system before integration into the actual engine. In the functional diagram below, component configurations and descriptions of known limitations will be used to guide our research and design of the custom ECU/ECM.

4.1. Functional Block Diagram

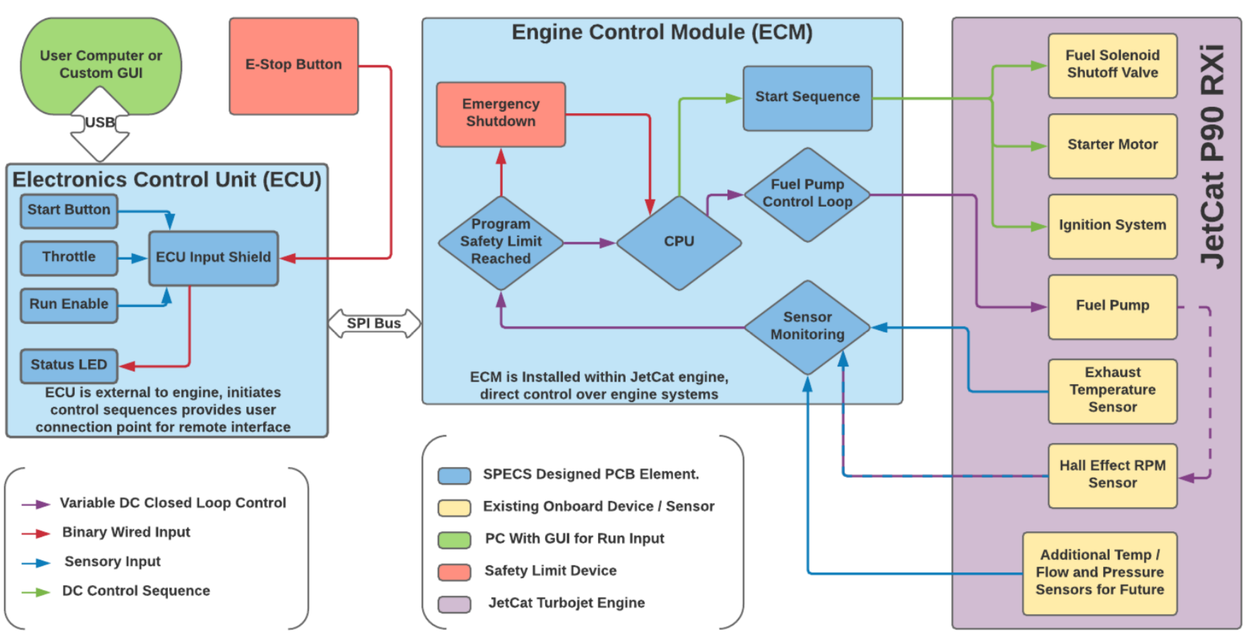

Figure 2. Electrical Systems Functional Block Diagram (ESFBD)

The electrical systems functional block diagram (ESFBD) starts at the computer uploading the critical operational code to the on-board the ECU. The ECM start sequence will engage starter, ignition system, fuel pump, and fuel shutoff solenoid. The ECU will be accompanied by a stackable shield, where user manual inputs and ECU communications to ECM are organized to a single data bus connection. The ECM takes inputs from the hall effect sensor which measures RPM, and a temperature sensor, measuring exhaust temperature. These inputs are then put through a closed loop control were the ECM drives the fuel pump to maintain program RPM.

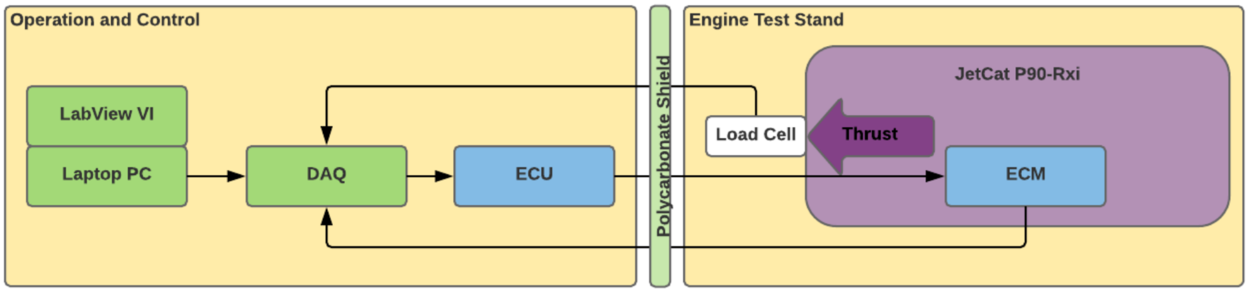

Figure 3. Testing and Control Functional Block Diagram (TCFBD)

The testing and control functional block diagram (TCFBD) shows the interaction between the test stand system developed in previous years and its integration into our control system. The engine is mounted on a static test stand equipped with load cells to measure the thrust being produced by the engine. This thrust data is sent to the computer and interpreted through LabView VI. The controls through the LabView VI interface will require a data acquisition unit (DAQ) for communication between the ECU and LabView VI.

4.2. Concept of Operations

Analysis of previous work has demonstrated that the tight, undefined parameters programmed into a proprietary controller results in the test engine becoming inoperable following even slight modification. By providing a controller with known inputs and outputs, the engine characteristics can be modeled and optimized in an iterative manner. Testing outside of standard operational parameters will provide insight into engine system dependencies and allow for user adjustments and tuning that would have normally resulted in a system shutdown. During this process, safety limits will remain in place as described in the engine users manual. Following sufficient testing and adequate data collection, limits will be analyzed to determine if performance can be safely increased through adjustment of predetermined limits. Figure 4 below shows the overall mission concept for the SPECS team control system, including future implementation.

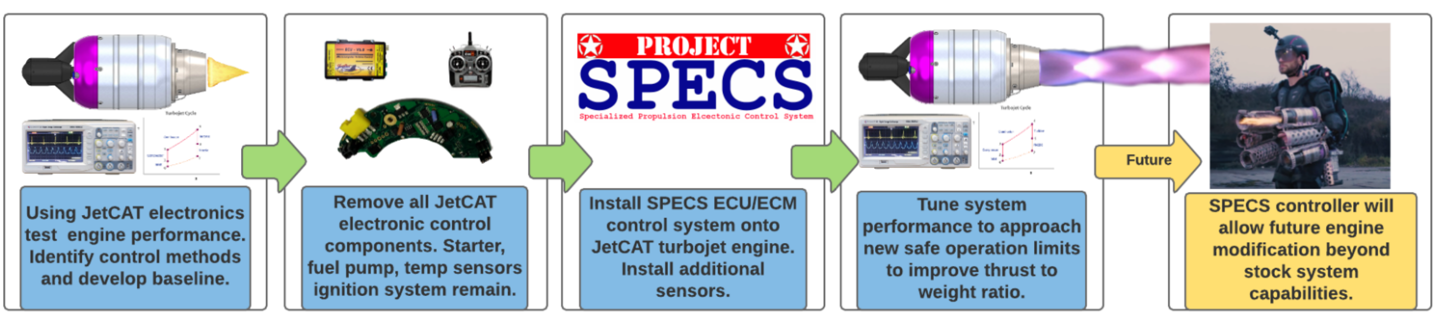

Figure 4. Mission Overview Concept of Operations

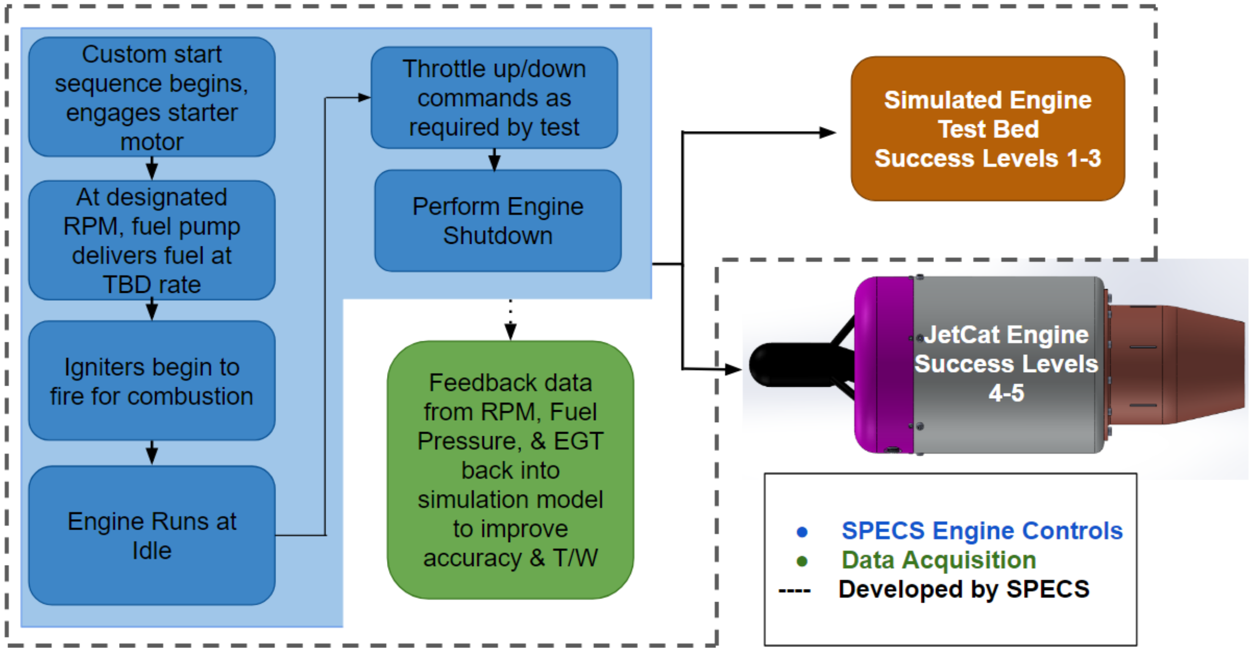

Figure 5. SPECS Ground Testing Concept of Operations

The concept of operations, in Figure 5, shows how the SPECS system will be implemented and tested, including various levels of success. Baseline data for the engine will be collected by installing and operating the engine on the test stand with stock components. After sufficient data collection all JetCat designed control hardware will be removed. The on-board starter, fuel pump, glow plug and exhaust temperature sensor will remain and be the basis for design on the new SPECS controller. The SPECS controller will include additional sensor inputs and control outputs that are user configurable. After installing the SPECS controller, refined measurements will be taken allowing the system to be tuned and approach new calculated safety limits while measuring thrust output. This will improve thrust to weight of the engine and provide clearly defined system performance parameters. Future projects will be able to freely design and test engine modifications without constraints of tightly defined fuel mapping or conservatively defined operational limitations.

5. Critical Project Elements

1. ECU/ECM - New engine electronics are required to continuously collect and report the state of the engine as well as perform start sequence as received from ECU. Furthermore, a new ECM will allow the team to modify the built in safety features that restrict the engine's performance and a new ECU will allow for user control of the engine.

2. Sensor Performance - The Hall Effect Sensor needs to accurately measure the RPM in order to provide accurate outputs and start the engine. The engine can rotate at 130k RPM and the Hall Effect sensor needs to sense and send data fast enough for the CPU to process the RPM. The sensed RPM will be compared to the ECU program set point value and will adjust fuel flow to match commanded RPM. In order to safely run the engine, additional sensing parameters will be added such as fuel pressure, fuel flow, and ambient temperature.

3. Engine - In order to both observe the system for modeling and later run for higher levels of success the engine must run successfully. The engine must withstand multiple tests without damage or failure of engine components which would incur a large financial burden. Finally, the engine must allow safe operation for the operator and observers.

4. Simulation - The model must produce simulated engine measurements as would be delivered by the ECM in order to test the software control of the engine. The data obtained from the model will then be used to characterize the safety limits of the engine.

6. Team Skills and Interests

Team Member Names	Associated Skills/Interests & Critical Project Elements
Matt Knickerbocker	Fluid Mechanics, Thermodynamics, 3D Modeling, Simulation, Systems Engineering Critical Project Element: Engine, Simulation, ECU/ECM
John Cutler	Thermodynamics, Modeling, Systems Engineering, Engineering Management Certificate Critical Project Element: Simulation, Systems Engineering
Dan Harthan	EE Major, Controls and DSP specialization , CAD/CAM. Critical Project Element: ECU/ECM
Daniel Castillo Oropeza	Business Minor, Electronics, Software, Finance, Website Critical Project Element: ECU/ECM
Madison Junker	Software (CSCI Minor), Algorithms, Controls Critical Project Element: ECU/ECM, Sensor Performance
Cedric Camacho	Taking microavionics, software Critical Project Element: ECU/ECM, Sensor Performance
Markus Fuernkranz	Modeling (FEM and CAD), Software, Electronics Critical Project Element: Simulation, Sensor Performance
Greg Frank	Avionics Technician, Flight Engineer, Thermodynamics, Structures, Manufacturing Critical Project Element: Engine, ECU/ECM
Yuzhang Chen	Manufacturing, Solidwork/Modeling, Electronics/Soldering(worked with Dale) Critical Project Element: Engine, Simulation
Preston FitzRandolph	Controls, Electronics, Systems Engineering, Testing & Safety Critical Project Element: Engine, Simulation, ECU/ECM
Samuel Piper	Certified LabVIEW Assoc. Developer, Thermodynamics, Turbo-machinery Operating Experience Critical Project Element: Engine, Sensor Performance

7. Resources

Critical Project Elements	Resource/Source
Engine	Test Facility: CU Energy Plant (303) 492-8432 Matt Rhode: Past project experience Trudy Schwartz: Past project experience Bobby Hodgkinson: Past project experience
ECU/ECM	Trudy Schwartz: Avionics/Electronics Bobby Hodgkinson: Electronics/JetCat experience
Sensor Performance	Bobby Hodgkinson: Extensive DAQ experience
Simulation	James Nabity: Professional propulsion experience

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