Univeristy of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018
Project Definition Document

REcuperating Advanced Propulsion Engine Redesign (REAPER)

Approvals

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I. Problem or Need

The JetCat P90-RXi is part of a class of miniature turbojet engines that are used in small unmanned air vehicles (UAV). Due to the intelligence and reconnaissance missions of many military UAV's, the aircraft must have excellent endurance and range characteristics in order to enter a target area and loiter while gathering the necessary mission intelligence. Hobbyists also desire long flights with more range, which is mostly limited by fuel and engine functionality. Another growing industry is delivery of packages by UAV. Deliveries are more practical with UAV's that have more powerful engines that can carry high loads over longer distances.

Traditionally, small UAV's have utilized electric or piston propeller propulsion systems due to their high efficiency and low specific fuel consumption. Turbojets improve speed and altitude flight envelops, but inherently have high specific fuel consumption. A recuperative turbojet engine has decreased specific fuel consumption while maintaining benefits of turbojet propulsion. A recuperating device takes waste heat from the turbine exhaust gases and transfers it to the incoming combustion chamber air, effectively decreasing the amount of fuel needed to heat the air. A successful recuperating turbojet engine would increase range, altitude, and speed performance for small UAV's. The aim of the REAPER project is to model, implement, and verify a recuperative system integrated into JetCat P90-RXi engine for increased efficiency from baseline tests.

II. Previous Work

Research on increasing engine efficiency through recuperation has been conducted for a number of years, however has yet to be implemented effectively. One similar and current application for use of a recuperator to increase efficiency is with gas turbine engines.[1] Although there are few sources directly related to recuperating a turbojet, there are many that are related enough to apply to the current project.

The 2014-2015 University of Colorado senior project team MEDUSA worked with the JetCat P90-RXi turbine, making modifications based on the requirements set for their specific project.[2,3] MEDUSA's goal was to convert the engine to run on methane fuel. They worked to develop a new engine control unit (ECU), maintain the existing kerosene lubrication system and minimize performance losses. The MEDUSA project will be a good resource due to their work with the same engine used project REAPER.

The only recuperative gas turbine based systems currently in mass use are relatively large and heavy land or sea based turboshaft machines intended for power generation. For instance, the Capstone C200 is a 200kW class recuperative microturbine with an operational efficiency of 33% and over 10 million operational hours.[4,5] While the operational turbines validate the use of recuperation to improve the efficiency of gas turbines, the design choices used to make them do not closely correlate with design choices for a small UAV powerplant due to materials, size, and weight. In particular, the ground-based power generation turbines can use large, heavy recuperators meant to maximize heat recovery which are unsuited for the weight and volume constraints of small UAVs.

While there are no small recuperated turbines in mass use (defined as turbines with a power output less than 10 kW), several researchers have conducted feasibility studies and even constructed prototype small recuperated engines. One proposed all ceramic 7.5kW microturbine for power generation would have a overall chemical power to electrical power efficiency of 40%.[6] Another proposed 4 kg, 3 kW recuperated engine specifically designed to act as turboprop for a small to medium size UAV, obtained a recuperator effectiveness of 84% and a overall efficiency of 19%.[7,8] While the microturbines represent a much more closely related design space (significant consideration was given to volume and weight), they diverge from the current project in two main ways. First, all proposed microturbines are shaft-work devices (i.e. engine is used to drive a shaft), not flow work devices (e.g. turbojets or turbofans). Second, the microturbines used or proposed the use of cutting-edge or near future ceramic components that allow the engines to operate at higher temperatures resulting in greater efficiency gains.

III. Specific Objectives

In order to generate a goal for the effectiveness of the recuperator, the team examined the previously mentioned 3 kW UAV micro-turbine design to determine appropriate values for average heat-transfer coefficients then applied the NTU heat exchanger sizing method.[8–11] The effectiveness of a heat exchanger is defined as the ratio of the temperature rise of the cold flow divided by the maximum temperature difference of the hot and cold flow. Based on the analysis, the team found that a viable range of heat exchanger effectiveness was between 11% and 14% depending on the configuration of the exchanger. Ultimately, the team choose a design goal of 13% effectiveness for the recuperator. Using engine performance values found by previous projects, a value of 13% effectiveness will correspond to a 10% decrease in thrust specific fuel consumption.

To reach level two success, the engine must run for 120 seconds. Sixty seconds is needed for the engine to stabilize, so 120 seconds allows a period of time to measure the recuperator performance on the engine operating at steady-state conditions. To reach level three success, the engine must be brought up and run at full throttle with the recuperator integrated. Based on tests from previous years, a full test at full throttle requires 4 minutes, so this level will be successful when full throttle is reached with the recuperator integrated.

To attain these goals, the REAPER team will create a computerized thermal model of a recuperator and use this model to guide the design and fabrication of the physical recuperator. There are three levels of increasing success for the REAPER project, as defined in Table 1. Level 1 addresses minimum success, while Level 3 defines full success. The increasing levels of success are designed as steps along the process to achieving a fully functional recuperation engine that meets all requirements (success level 3).

Various tests will be performed during the academic year to determine functionality, compliance to requirements, and success level, with full engine tests occurring at Boulder Municipal Airport. After the class and academic year are over, the project will finish by testing the recuperator-engine design at the Wright-Patterson Air Force Base with the Air Force Research Labs.

Success Level	Project Description	
	Simulation	Recuperator/Engine
Level 1	• First order, one-dimensional, steady state engine thermal modeled with recuperator design integrated • Predicted efficiency and thrust from model meets recuperator effectiveness (13%), thrust specific fuel consumption reduction (10%), and thrust reduction (10%) requirements	• Recuperator designed and manufactured • Recuperator tested with engine analog at dimensionally scaled steady-state, full-throttle operating conditions without a critical failure
Level 2	• Thermal model includes transient performance • Predicted recuperator effectiveness, specific fuel consumption, and thrust from model continue to meet requirements	• Recuperator integrated to reroute engine exhaust heat • Engine starts and runs at at full throttle for 120 seconds with the integrated recuperator, with recuperator effectiveness at or above 13%
Level 3	• CFD model of the recuperator developed with effectiveness matching actual recuperator test data by 25%	• Engine with integrated recuperator runs continuously for full throttle range • Engine with integrated recuperator meets effectiveness (13%), thrust reduction (10%), thrust specific fuel consumption reduction (10%), and mass increase (50%) and volume increase (100%) requirements • Engine runs at full throttle, with recuperator integrated, for at least 4 minutes

Table 1: REAPER Success Levels

IV. Functional Requirements

The concept of operations (ConOps) within the modified jet engine is shown in Fig. 1. Starting at the labeled point 1, the engine will perform nominal start up procedures to reach idle. Then the throttle control will be increased (point 2) to full throttle, where the recuperator will achieve maximum effectiveness (see engine blow out). The addition of the recuperator by REAPER serves to reroute waste exhaust heat back into the engine, after the compressor, to preheat the intake air prior to combustion. Preheating improves the efficiency of the engine by requiring less fuel burn to reach the same exit temperature. At maximum throttle, temperature, RPM, and TSPC data will be gathered by the ECU (point 3). At the end of engine run, data will be transferred to a computer for analysis (point 4).

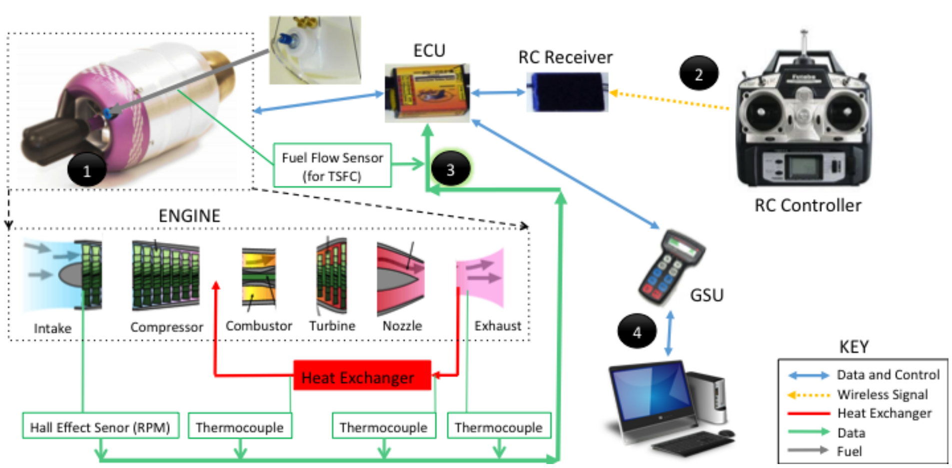

Figure 1. Concept of Operation

The functional block diagram (Figure 2) goes into more detail about the system interactions. Items that existed prior to project REPEAR are boxed in black; green boxes indicate items that will be purchased to ensure engine functionality; yellow boxes are components that will need to be modified or created to achieve comprehensive success.

Starting at the engine, exhaust heat will be diverted to pre-heat air entering the combustor via a heat exchanger.

Moving clockwise (to gold blocks), the fuel flow rate sensor will be integral measuring thrust specific fuel consumption (TSPC) for engine efficiency. In order to control the fuel flow rate to keep exhaust temperature below 700°C, the ECU will need to be modified. On the peripherals, the RC Controller will send throttle commands to the receiver while the engine sensor package and data handling gather data on the engine performance during a test.

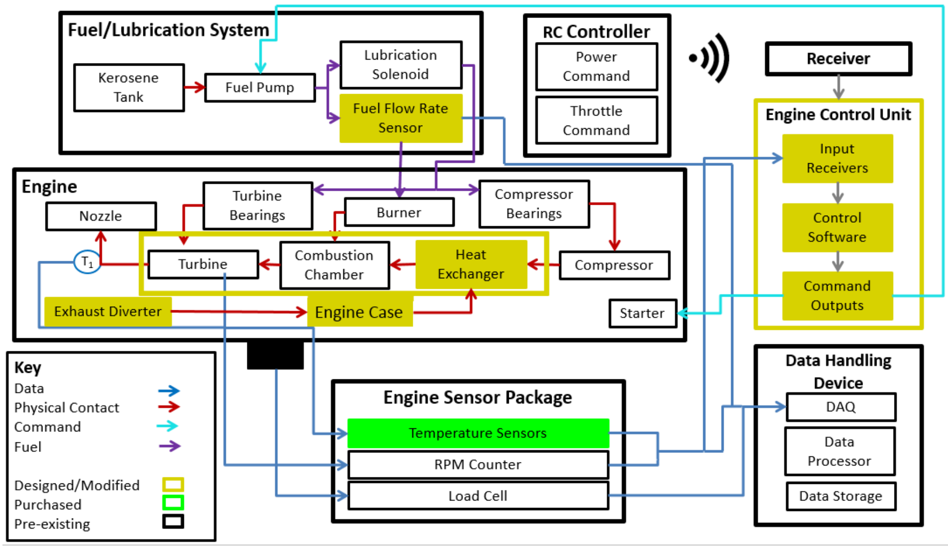

Figure 2. Functional Block Diagram (FBD)

V. Critical Project Elements

1. Recuperator

1.1. Material and Manufacture - To effectively transfer the heat from the engine's exhaust to the front of the combustor, precise manufacturing will be required to create a working recuperator. Material selection will be important due to operation temperatures, and the material and manufacturing may be expensive. Additionally, since the recuperation system will likely change the shape and size of the engine, modifications may need to be made to the test stand to accommodate these changes.

1.2. Engine Integration - The engine used for this project is very difficult to keep operational once internal modifications have been made. Integration of the recuperator will have to be carefully performed. Modifications may have to be made to electronics as well to keep the engine from shutting down due to the change in temperature at the combustion chamber and exhaust exit.

2. Engine

2.1. P90-RXi - The engine being used in the project is notoriously hard to run after modifications have been made. To test the recuperator and verify the project's higher levels of success, the engine must be kept in operable condition. The efforts to keep the engine operational may include repair or replacements costs.

2.2. ECU - The engine control unit (ECU) is required to operate the engine. In order to run the engine and gather data, the group will have to work with the ECU from the manufacturer or modify the ECU designed by the MEDUSA group from last year's senior projects (since it is designed to run on methane instead of kerosene). These boards will need to be altered or created. This is the component that has caused the most problems for senior projects in years past, and thus is one of the most risky aspects of the project.

3. Simulation

3.1. Heat Transfer Model - In order to predict the effectiveness of the recuperator, development of a computer-based a thermal model of the recuperator interfacing with the engine or with an engine analog is required. Data from these simulations will drive the design of the recuperator.

4. Logistics

4.1. JetCat - The JetCat company has been known to difficult to get information from. As a result, other methods of learning more about the engine may have to be use instead of direct contact. Hardware may also have to be purchased from or fixed by JetCat with a significant lead time and cost.

4.2. Testing and Personnel - Engine test runs will be performed at the Boulder Airport, necessitating transport of people and equipment to the test site. Matt Rhode or Bobby Hodgekinson may also need to be present.

VI. Team Skills and Interests

The team member skills and interests pertaining to the critical project elements (CPE) are outlined in Table 2.

CPE	Team Member(s) and associated skills/interests
Recuperator	Carolyn- Experience in machine shops, took materials Kevin G. - Works in engineering production; Deals with many different materials David - Some experience from Freshman projects, highly interested in manufacturing process Andrew - CAD design, geometric dimensions & tolerances, and measurement systems analysis
P90 RXi Engine	Peter - Machining and Embedded system experience. Jacob - Interest in engine design and manipulation/machining Becca - Interest in engine functionality and some experience with embedded systems.
ECU	Peter - Embedded system and coding experience Kevin H - coding/CSCI and interest Becca - Embedded system/PCB design experience and coding knowledge
Simulation	Kevin G. - CAD, Matlab, and Simulink experience Carolyn- Some Solidworks Experience, Matlab David - Some experience in SolidWorks, Matlab, and SimuLink. Jacob - Experience Matlab and SimuLink. Kevin B. - CAD and CFD experience, Matlab and Simulink use for modeling
Testing	Carolyn- Wrote test procedure & worked in clean room Kevin G. - Work experience with creating and following engineering procedure Peter - Labview and electrical experience Jacob - LabView and testing procedure experience Kevin B. - Internship experience writing and running integration test procedures Andrew - Created production testing procedures; measurement systems analysis

Table 2: Team Skills and Interests to Mitigate Critical Design Elements

VII. Resources

Table 3 outlines the resources available to mitigate the risk of the critical design elements. Although the list of available resources here is not all inclusive, these resources will provide invaluable to achieving success for project REAPER.

CPE	Resource/Source
Recuperator	• Michael J. Vick - Naval Research Lab; research with recuperating jet engine • Ryan Starkey - Previous experience working with JetCat engines and propulsion systems • James Nabity - Previous experience with propulsion systems and jet engines • Matt Rhode - Manufacturing knowledge; experience with alterations to the P90RXi engine • Bobby Hodgekinson - Experience with alterations P90RXi engine and manufacturing
P90RXi Engine	• Ryan Starkey - Worked with JetCat and other jet engines and propulsion systems • Matt Rhode - Manufacturing knowledge; experience with alterations to the P90RXi engine • Bobby Hodgekinson - Experience with alterations P90RXi engine and manufacturing • MEDUSA Team - Experience with and knowledge about JetCat P90RXi engine
ECU	• Trudy Schwarts & Bobby Hodgekinson - Extensive work with EDU redesign from 2014-2015 MEDUSA project and general electronics/software knowledge • MEDUSA Team - Resigned ECU for P90RXi engine; knowledge and hardware will help
Simulation	• Ryan Starkey - Propulsions knowledge; work withe previous high fidelity engine models • COMET Engine Model - Very high fidelity engine model developed for 2013-2014 senior project course that could provide a good baseline for creating a simulation
Testing	• Ryan Starkey - Experience with JetCat engines and tests at the Boulder Airport • BAC Lab - Test stand and sensors available for use to characterize engine performance • GoJett - Worked with BAC Lab test set up and can provide extra help during testing • Matt Rhode - Many engine tests; assistance with safe and smart testing

Table 3: Resources Available to Mitigate Critical Design Elements

References

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