Design of a Turbojet for UAV Applications

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Motivation and Objective

Motivation

- The motivation behind creating a virtual turbojet engine model and its control mechanism for UAV applications stems from the rapid growth of UAV usage across multiple sectors.
- UAVs are gaining popularity in many fields for example: in the defense sector, disaster relief, environmental monitoring, and logistics.
- These operations need UAVs with high flight performance, exact control, and the capability to adjust to different situations, all depending on the propulsion system that is good in performance and reliability.

Objective

- Assess and contrast PI and Fuzzy Logic Control systems.
- Identify the most effective method for achieving stability and responsiveness in engine control.
- Develop a virtual turbojet model in simscape and simulation of essential performance characteristics of different components in the virtual model.

Turbojet and Its Working

- **Definition:** Turbojet is a gas turbine engine that generates thrust by expelling exhaust gases at high speed.

A turbojet engine basically a type of gas turbine engine that run in the sequence as follows:

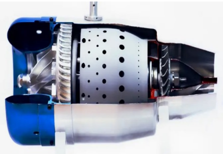
- Air is compressed, increasing its pressure and temperature.
- Compressed air is mixed with fuel and ignited in the combustion chamber.
- The combustion process increases the energy and momentum of the exhaust.
- The exhaust transfers its kinetic energy to the turbine, which powers the compressor via a shaft.
- The exhaust exits through the nozzle at high velocity, producing thrust.

Turbojet and UAV Applications

Turbojet Engines used for UAVs around the world:

BQM-167A
Single Spool
4 stage Axial Compressor
Single stage Turbine
Annular Combustor

Max. Thrust = 5.7K



TJ90 Micro Turbojet
Single-stage radial compressor
Single-stage axial turbine
Annular combustor

Max Thrust = 900N

PTAE-7 Turbojet Engine
4-stage axial compressor
Single-stage turbine
Annular combustor

Max Thrust = 3.27KN

Klimov(VK-1) Turbojet
Centrifugal Compressor
9 combustors
Axial Turbine

Max Thrust = 26.5 kN

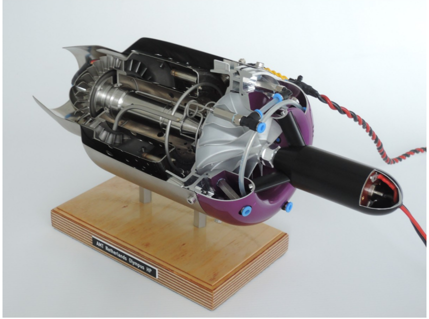
Teledyne CAE J69
centrifugal Compressor
Annular combustor
Single stage Turbine

Max Thrust = 3.9 kN

Real World Turbojet Model Used for Our Project

AMT Olympus HP

- **Thrust:** 250 N
- **Fuel used:** Kerosene
- **Configuration:**
  - Centrifugal Compressor,
  - An annular-type combustion chamber,
  - A single-stage axial turbine
- **Max. rotational speed :** 108 [krpm]



Overview Of the work

- **Mathematical Model of Turbojet**

In this project, first of all, we wrote a Matlab code with the help of mathematical equations of different components of a turbojet. Then we applied control algorithms like PI and Fuzzy logic control to this virtual model of turbojet and compared the result outputs of both controllers.

- **Simscape Model of Turbojet**

We also developed a Simscape model with the help of built-in blocks of components of a gas turbine engine. We add the dual PID controller to control speed and temperature to produce desired thrust values. We feed the default values of parameters as given in Matlab and generate the compressor map.

Flowchart

Flowchart of the Engine Working

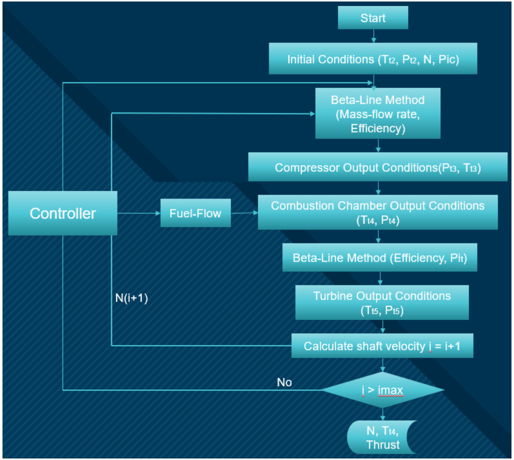


Figure 1: Flowchart of Engine Working

Engine Model

Purpose: Develop a mathematical model to understand the engines behavior and transient response.

All components mathematical models were developed by using physical rules and empirical data.

Thermodynamic properties of combustion gases and air were calculated using variation of temperature.

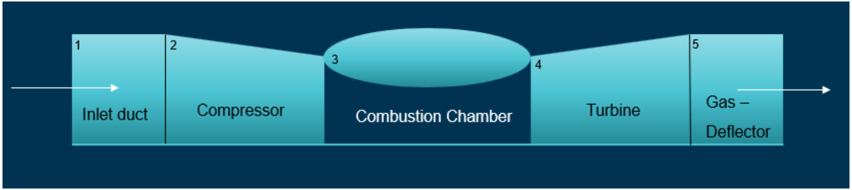


Figure 2: Engine Block Diagram

Compressor Model

- Modeled using the Beta Line Method, which utilizes compressor maps to determine pressure ratios and efficiency based on shaft speed and corrected mass flow rate.
- Beta Line Method (fig.3) used to digitize the compressor map (Basically an interpolation technique).

$$T_{t3} = T_{t2} + \frac{T_{t2}}{\eta_c} \cdot \left[\left(\frac{P_{t3}}{P_{t2}} \right)^{\frac{\gamma a - 1}{\gamma a}} - 1 \right] \quad (1)$$

$$\dot{m}_C = f(N, \pi_c) \quad (2)$$

$$\eta_c = g(N, \pi_c) \quad (3)$$

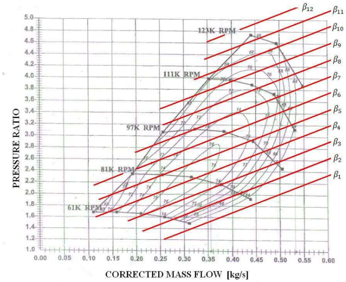


Figure 3: Compressor Map for Beta Line Method

Combustion Chamber Model

- Nonlinear equations based on mass and energy conservation laws, solved using the Runge-Kutta method for dynamic response.
- A Proportional-Integral (PI) controller is used to adjust fuel mass flow for stable combustion.

$$\frac{dP_{t4}}{dt} = \frac{P_{t4}}{m_{comb}} \cdot \left(\dot{m}_c + \dot{m}_{fuel} - \dot{m}_T\right) + \frac{P_{t4}}{T_{t4} \cdot c_{vmed} \cdot m_{comb}} \cdot \Big[\dot{m}_c \cdot c_{pair} \cdot T_3 - \dot{m}_T \cdot c_{pgas} \cdot T_{t4} + Q_f \cdot \eta_{comb} \cdot \dot{m}_{fuel} - c_{vmed} \cdot T_{t4} \cdot \left(\dot{m}_c + \dot{m}_{fuel} - \dot{m}_T\right)\Big] \tag{4}$$

$$\frac{dT_{t4}}{dt} = \frac{\dot{m}_C \cdot c_{pair} \cdot T_3 - \left(\dot{m}_C + \dot{m}_{fuel}\right) \cdot c_{pgas} \cdot T_{t4} + Q_f \cdot T_{t4} \cdot \dot{m}_{fuel}}{c_{vmed} \cdot m_{comb}} \tag{5}$$

Turbine Model

- Receives high-energy gas from the combustion chamber, converting this energy to mechanical work to drive the compressor.
- Modeled with performance maps, efficiency, and conservation equations, allowing accurate calculation of exit conditions and power produced for the work balance.

$$T_{t5} = T_{t4} + T_{t4} \cdot \eta_t \cdot \left[1 - \left(\frac{P_{t5}}{P_{t4}} \right)^{(\gamma_g - 1)/\gamma_g} \right] \tag{6}$$

$$\dot{m}_T = f(N, \pi_T) \tag{7}$$

$$\eta_T = g(N, \pi_T) \tag{8}$$

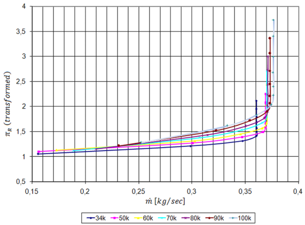


Figure 4: Turbine Map

PI Controller

Overview of PI Controller Design:

- PI controller is designed to regulate a process variable based on its setpoint and manipulated variable.
- **Proportional Control (P):** Provides an immediate response to the error. The larger the error, the stronger the response, controlled by the proportional gain, K_p
- **Integral Control (I):** Accumulates past errors over time to correct any remaining steady-state error. The integral gain, K_i, helps to fine-tune the control for consistent long-term accuracy.

Advantages and Limitations:

- **Advantages:** Easy to implement and performs well under stable conditions and predictable disturbances.
- **Limitation:** Slower to settle in non-linear operating conditions. Can exhibit minor overshoot and stability issues, especially when dealing with non-linear changes in the system, such as in variable thrust requirements for UAVs.

PI Controller

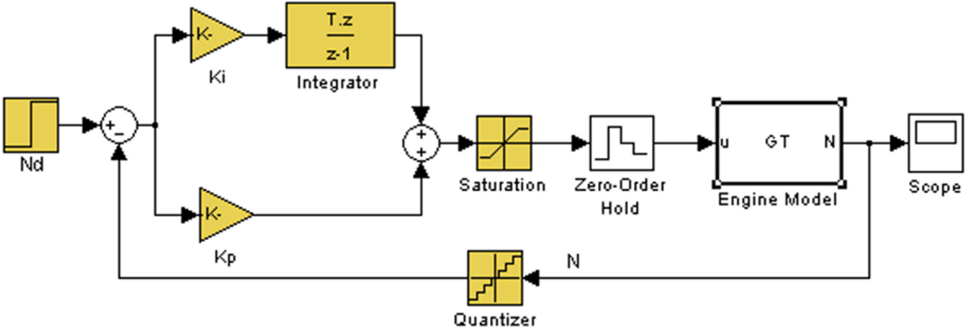


Figure 5: PI Controller

Fuzzy Logic Controller(FLC)

Overview of FLC Design:

- Fuzzy Logic is a form of logic that can deal with degrees of truth rather than binary true/false values.
- The FLC uses linguistic rules ("If-Then" rules) to determine the control actions, providing more flexibility and stability for the turbojet engines thrust control.

Advantages of Fuzzy Logic Control:

- Handles Nonlinearities
- Reduced Overshoot
- Enhanced Stability

Fuzzy Logic Controller

- **Fuzzification:** Converts input values (error in thrust and rate of change of error) into fuzzy values based on membership functions.
- **Rule Base:** Contains a set of If-Then rules ("If error is large and increasing, then increase fuel flow moderately").
- **Inference Mechanism:** Determines which rules are active based on current conditions and generates fuzzy output.
- **Defuzzification:** Translates fuzzy outputs back into precise control actions, such as adjusting fuel flow rate.

Fuzzy Logic Controller

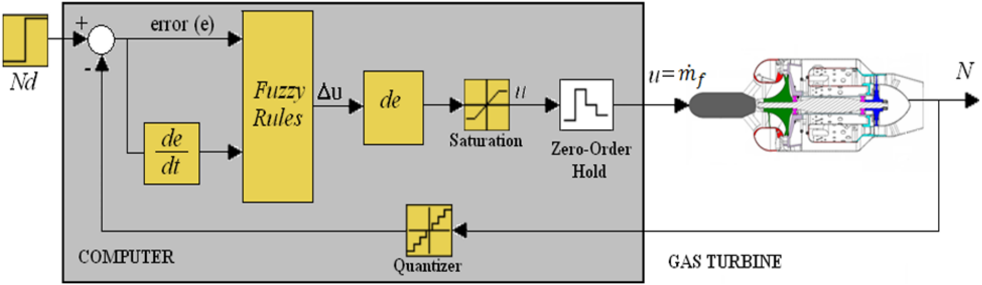


Figure 6: Fuzzy Logic Controller

Results

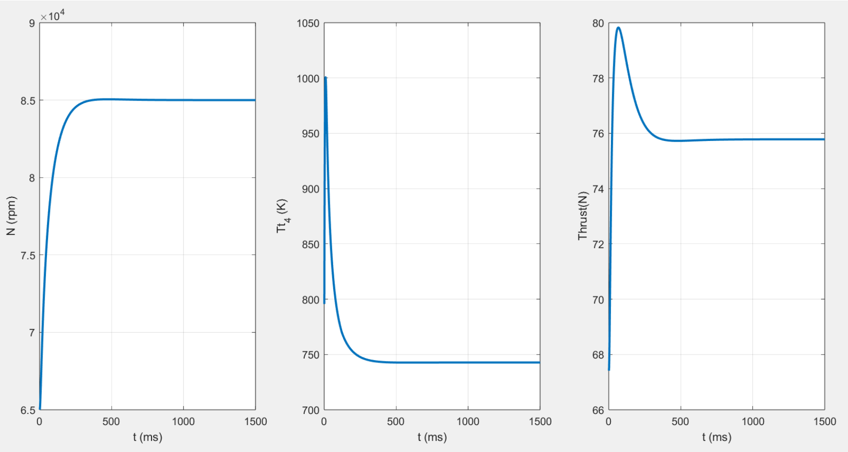


Figure 7: PI controller Results

Results

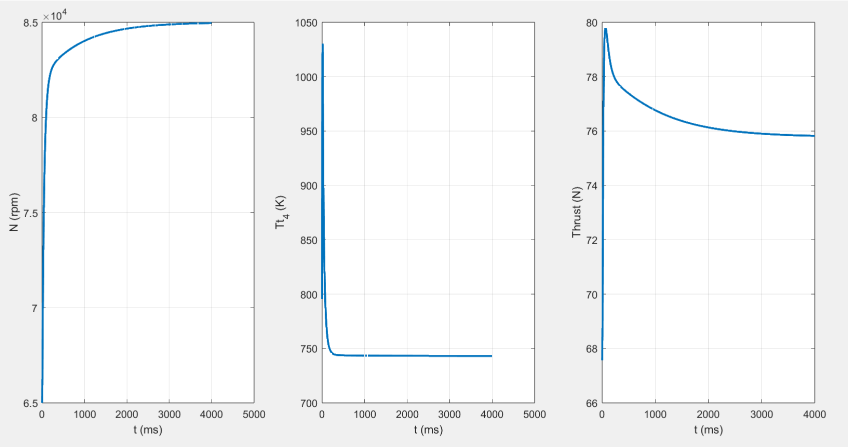


Figure 8: Fuzzy Logic Controller Results

Simscape Model of Engine

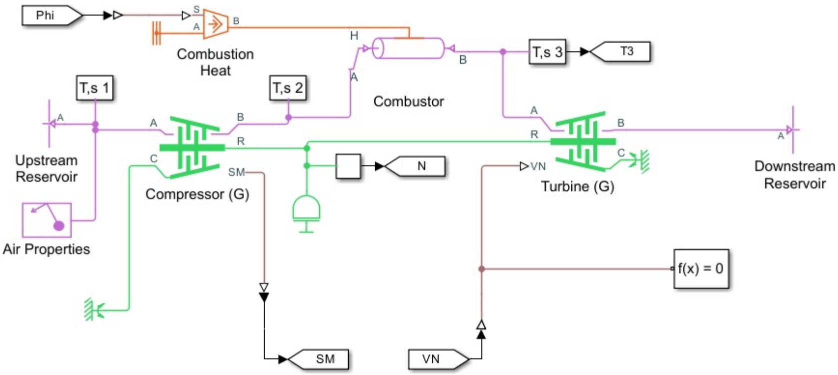


Figure 9: Turbojet Simscape Model

Simscape Model of Engine

- The model incorporates a dual-PI controller system. The Speed Regulator PI adjusts the shaft speed(N) to match a desired setpoint Nsp.
- By coordinating these two PI controllers, the model achieves precise thermal control, with the speed control feeding into temperature control for enhanced stability.
- Temperatures are measured at the inlet and outlet of each component.
- This streamlined representation focuses on temperature control through shaft speed adjustments, avoiding the complexity of additional operating scenarios.

Results

Interpreting the Map

- At lower RPMs, the map shows a limited range of mass flow and pressure ratio.
- As the RPM increases (moving up the blue speed lines), the compressor achieves higher pressure ratios and larger corrected mass flows.
- Efficiency tends to peak in a certain region of the map and falls off as you move closer to the choke or surge lines.

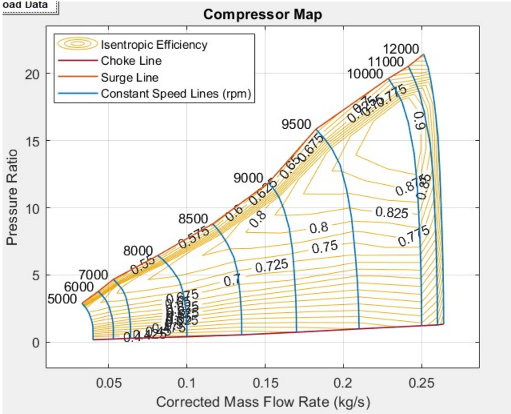


Figure 10: Compressor Map

Results

Air Properties: Compressor Exit

- Enthalpy: 871.4 KJ/Kg
- Pressure: 1.654e+06 pa
- Temperature: 729 k
- Density: 7.856 Kg/m3
- Specific Heat Capacity: 1.085 KJ/Kg

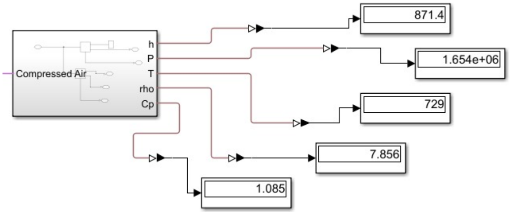


Figure 11: Properties of air at compressor outlet

Results

Combustor Outlet or Turbine Inlet

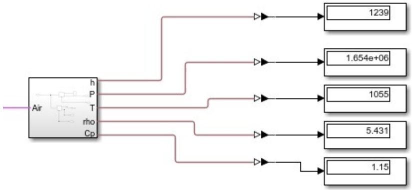


Figure 12: Properties of air at Combustor Outlet or Turbine Inlet

Turbine Outlet

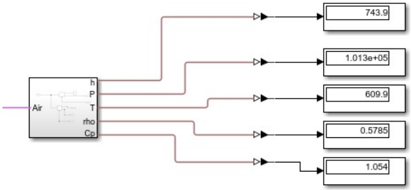


Figure 13: Turbine Outlet

Conclusions

- Fuzzy Logic Control proved superior, offering reduced overshoot, faster settling, and better handling of nonlinearities compared to the PI Controller.
- The findings highlight the effectiveness of adaptable, rule-based control strategies in complex propulsion systems.
- We successfully developed and evaluated a virtual model of a turbojet engine tailored for UAV applications.
- With the Simscape Model, we can check the performance of different components of the jet engine without a real prototype.

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Thank you!