Course Project Report

Authors

```
- Bhamidipati Srinath Dhatre             2023122002

-  GV Dheeraj Sai                        2023122007
```

Objective

- This project aims to design and implement a transition controller for a VTOL UAV within the ROS2 PX4 framework and Gazebo simulation. The controller ensures a stable transition from VTOL to fixed-wing mode by adjusting elevon control and propulsion parameters. Performance is evaluated using flight data, including accelerations, angular rates, and gyro readings, with video analysis supporting the findings.
- Before implementing the transition logic, controllers for fixed-wing and quadcopter modes are designed and validated. Performance is analyzed using flight data and video documentation.

Introduction

- Vertical Takeoff and Landing (VTOL) aircraft combine the capabilities of traditional fixed-wing airplanes with rotor-based systems, allowing them to operate in constrained environments without requiring runways. Among VTOL configurations, hybrid VTOLs feature both rotor-based propulsion for hover and conventional aerodynamic surfaces for forward flight, enabling efficient long-range operations while retaining the flexibility of vertical takeoff and landing.

Need for Hybrid VTOLs

- Hybrid VTOLs address key limitations in conventional UAV designs. Multirotors offer precise control and hover capability but are limited by endurance and range. Fixed-wing UAVs, while highly efficient in cruise flight, require runways for operation and lack stationary maneuverability. A hybrid VTOL configuration merges these benefits, making it suitable for applications like aerial surveillance, cargo transport, and autonomous operations in areas with limited infrastructure.

Introduction to Fixed-Wing and Quadcopter Control

- Fixed-wing UAVs rely on controllers that regulate airspeed and altitude by managing control surfaces like elevons and throttle. These controllers ensure aerodynamic efficiency and stability during flight. In contrast, quadcopters achieve precise position control and trajectory tracking using feedback mechanisms that manage rotor thrust and attitude adjustments, allowing them to hover and maneuver in confined spaces.

Challenges in Transitioning Between Modes

- The transition from VTOL to fixed-wing flight introduces several complexities. One major challenge is ensuring adequate airspeed before aerodynamic surfaces generate sufficient lift, preventing stall conditions. Improper timing or insufficient thrust can lead to instability or loss of control. Conversely, transitioning from fixed-wing to VTOL mode requires carefully managed deceleration to avoid abrupt retardation forces that could exceed the aircraft's structural limits. Smooth acceleration control ensures stable hover entry without excessive stress on propulsion systems.

Methodology

Fixed Wing Controller

1. Outer Loop Controllers (Flight Path Control)

- The **altitude controller** regulates the UAV's vertical position by adjusting the pitch angle θ.
- The **heading controller** manages directional control by adjusting the roll angle ϕ\phi.
- These controllers take desired altitude (h desired) and desired heading (ψ desired) as inputs and compute the necessary attitude adjustments.

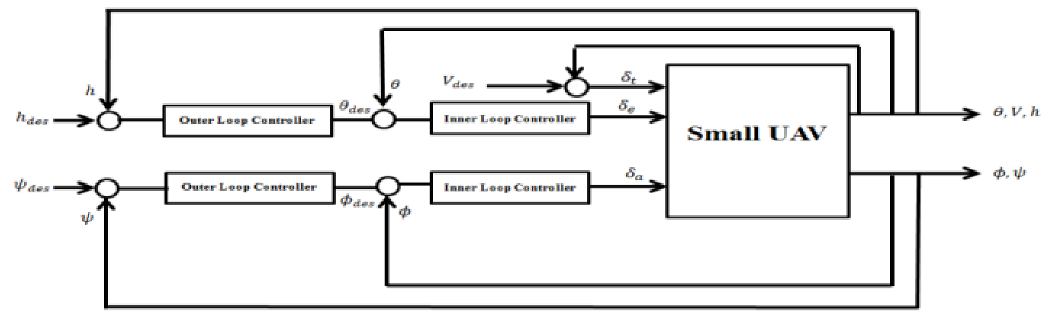
2. Inner Loop Controllers (Attitude Control)

- The **pitch controller** ensures the UAV maintains the commanded pitch angle θ, controlling the **elevator deflection** (δe).
- The **roll controller** ensures stability in banking maneuvers by adjusting the **aileron deflection** (δa).
- These inner loop controllers refine the aircraft's attitude based on the outputs from the outer loop.

3. Fixed-Wing UAV Behavior

- The UAV receives **desired airspeed** (V desired), elevator (δe), and aileron (δa) inputs.
- The aircraft then outputs real-time state variables: **pitch angle** θ, airspeed V, altitude h, roll angle ϕ, and heading ψ.
- The closed-loop system ensures stable navigation and precise control over both altitude and heading.

Control Scheme



Alternative controller for fixed wing UAV

Total Energy Control System (TECS) in Fixed-Wing UAVs

TECS provides a sophisticated approach to controlling **both airspeed and altitude** simultaneously, a challenge due to the coupled effects of pitch and throttle on UAV dynamics. This system transforms the control problem into an **energy-based formulation**, allowing independent regulation of total energy and energy balance.

1. Why TECS is Needed for Dual Setpoints

Traditional controllers struggle when managing **airspeed and altitude** together because:

- Increasing **pitch angle** raises altitude but reduces airspeed.
- Increasing **throttle** raises airspeed but also lifts altitude due to increased lift.
- Both **pitch and throttle affect altitude and speed**, making direct control difficult.

By expressing control inputs as **energy quantities**, TECS separates:

- **Total energy (kinetic + potential energy), controlled via throttle**.
- **Energy balance (trade-off between airspeed and altitude), controlled via pitch**.

2. TECS Control Architecture

TECS operates through **two primary loops**:

Total Energy Control Loop

- Determines **overall energy state** by summing kinetic and potential energy.
- Uses **throttle** as the primary actuator to **increase or decrease total energy**.
- Ensures the UAV maintains a target energy level, balancing climb rates and airspeed.

Energy Balance Control Loop

- Adjusts the UAV's energy distribution between **altitude and airspeed**.
- Uses **pitch angle** to transfer energy between speed (kinetic) and altitude (potential).
- Ensures a stable energy ratio, avoiding excessive altitude loss or speed reduction.

These loops work **independently yet in coordination**, simplifying simultaneous control of **airspeed and altitude**.

3. TECS Implementation and Dependency on Attitude Control

Since TECS relies on pitch control, **proper tuning of the attitude controller** is essential:

- The **fixed-wing attitude controller** operates using a **cascaded loop method**.
- The **outer loop** computes attitude errors and generates rate commands via a P-controller.
- The **inner loop** regulates angular rates using a **PI-controller**, ensuring smooth acceleration control.
- Control surface effectiveness varies **with airspeed**, so airspeed scaling is applied.

If airspeed sensors are unavailable, gain scheduling is disabled, resulting in an **open-loop controller**.

4. TECS in VTOL Transitions

- During **VTOL to fixed-wing transition**, TECS ensures gradual acceleration to prevent stall.
- During **fixed-wing to VTOL transition**, TECS manages retardation smoothly by controlling energy dissipation via pitch and throttle.
- In **hybrid VTOL aircraft**, TECS facilitates a seamless switch between hover and cruise modes by modulating energy levels dynamically.

Quadcopter

1. Cascaded Control Structure

Multicopter control is structured in a **cascaded manner**, meaning multiple nested controllers operate sequentially. Each **inner loop controller** stabilizes fundamental UAV dynamics, while **outer loop controllers** refine higher-level movement.

2. Outer Loop: Position & Velocity Control

These controllers manage high-level motion, such as **position hold, trajectory tracking, and hovering**.

Position Controller (P Controller)

- Determines how far off the UAV is from the desired position.
- Generates a **velocity command** to correct positional errors.
- Uses a simple **P gain** (`MPC_XY_P` and `MPC_Z_P`) to control movements in horizontal and vertical axes.
- The commanded velocity is **saturated** (limited) to prevent excessive movement.

Velocity Controller (PID Controller)

- Takes the **position error** and converts it into an acceleration command.
- Uses **Proportional (P), Integral (I), and Derivative (D)** gains to regulate speed.
- The integrator has an **anti-reset windup (ARW)** to prevent instability.
- Acceleration is **not directly saturated**, but thrust is later limited through tilt constraints.

3. Inner Loop: Attitude & Angular Rate Control

These controllers refine **rotation stability** and ensure the UAV responds smoothly to flight commands.

Attitude Controller (P Controller)

- Converts **desired attitude (quaternions)** into rate commands.
- Uses a **P gain** for attitude stabilization (`MPC_ATT_P`).
- Commands are **saturated** to prevent excessive rotation rates.

Angular Rate Controller (PID Controller)

- Takes attitude commands and computes precise **rotational acceleration** needed.
- Uses **K-PID control** with:
  - **P gain** for immediate response.
  - **I gain** for long-term drift correction.
  - **D gain** with a **low-pass filter (LPF)** to prevent noise amplification.

- Output limits (-1 to 1) prevent excessive control effort.

4. IMU Pipeline (Sensor Processing)

Sensors provide real-time feedback, processed through multiple filtering stages:

- **Gyro readings** → Calibration → Bias removal → **Notch Filter** (`IMU_GYRO_NF0_BW`) → **Low-Pass Filter** (`IMU_GYRO_CUTOFF`).
- **Filtered angular velocity** feeds into P and I controllers.
- **Filtered angular acceleration** feeds into the D controller (`IMU_DGYRO_CUTOFF`).

This ensures smooth control inputs with **minimal noise interference**.

5. Thrust and Attitude Conversion

Velocity controllers generate acceleration commands, which are then converted into **thrust and attitude setpoints**:

1. Compute **required vertical thrust** (`thrust_z`).
2. **Saturate thrust_z** (`MPC_THR_MAX`) to prevent overload.
3. Compute **horizontal thrust** using

6. Challenges in VTOL Transitions

When switching from **VTOL to fixed-wing flight**, key control challenges arise:

- **Stalling Risk:** The UAV must **build sufficient airspeed** before relying fully on aerodynamic lift.
- **Thrust Overshoot:** Incorrect deceleration can cause a **hard drop** during transition.
- **Acceleration Limiting:** When switching **from fixed-wing to VTOL**, the UAV must carefully slow down while avoiding excessive retardation forces.

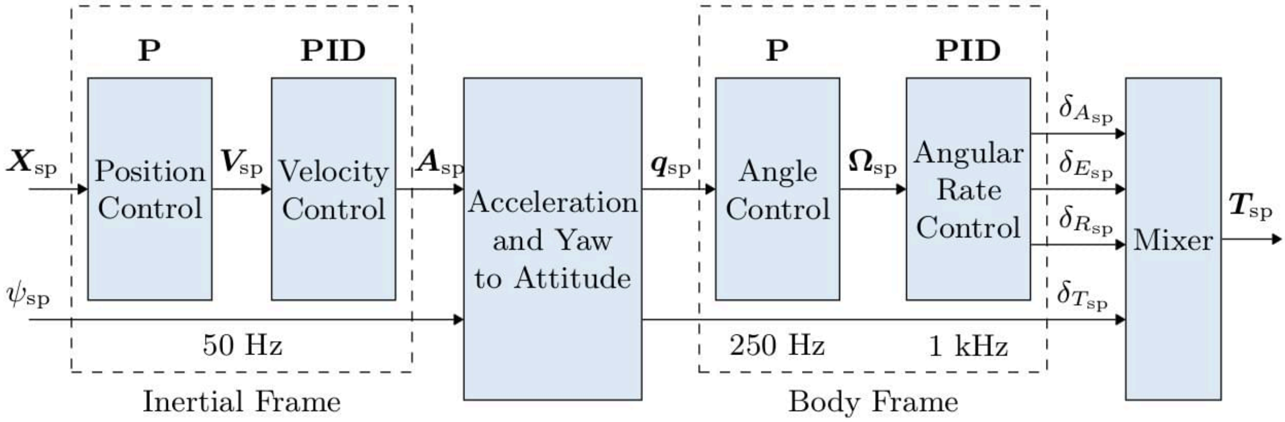
Modifying the **velocity controller's feedforward tuning** and implementing **adaptive thrust scaling** can help mitigate these issues.

7. Integration into VTOL Transition Control

Your **transition controller** will need to:

1. Gradually **bypass multicopter position control** while engaging **fixed-wing attitude control**.
2. Monitor **airspeed thresholds** before committing to aerodynamic lift.
3. Use **thrust scaling** to smoothly decelerate when switching back to VTOL mode.

This ensures the UAV **maintains stability** while transitioning between flight modes.



VTOL Controller

1. VTOL Attitude Controller: Switching & Blending Logic

The **VTOL Attitude Controller** acts as the **central switching mechanism**, determining which control loops are active:

- **In pure VTOL mode** → Multicopter control logic dominates.
- **In pure fixed-wing mode** → Fixed-wing control logic handles attitude and rate stabilization.
- **During transition** → Both controllers interact, ensuring smooth blending.

Virtual Inputs & Mode-Based Control

- Some control inputs are **ignored** depending on the VTOL mode.
- In **tilt-rotor & standard VTOL**, the **fixed-wing attitude controller** generates rate setpoints, which are distributed to actuators via separate **rate controllers**.
- In **tailsitter configurations**, the **multicopter attitude controller remains active** during transition.

The output consists of **separate torque and thrust commands** for both:

- **Multicopter actuators (rotor thrust adjustments)**
- **Fixed-wing actuators (ailerons, elevators, rudders)**

These are processed within an **airframe-specific control allocation class**, ensuring correct actuator mixing.

2. Airspeed Scaling in VTOL Control

Airspeed significantly affects actuator effectiveness, requiring **airspeed scaling in control gains** for optimal performance.

Effects of Airspeed on Control Surfaces

- **Higher airspeed → Greater aerodynamic force generation** (torques from control surfaces).
- **Lower airspeed → Reduced effectiveness** (actuator authority diminishes).
- Without airspeed scaling, a controller tuned for **cruise speed** might **overreact at high speeds** or **underperform at low speeds**.

3. Scaling Methods for PI & Feedforward (FF) Controllers

- **Static Torque (PI) Scaling** → Adjusts control outputs proportionally to **IAS^2** (Indicated Airspeed).
- **Rate (FF) Scaling** → Adjusts control based on **TAS** (True Airspeed), compensating for roll damping effects.

Final Scaling Equations

- **PI Controller Output Scaling** → Scaled with **IAS^2**
- **FF Controller Output Scaling** → Scaled with **TAS**

These adjustments ensure **consistent attitude control performance across different airspeeds**.

4. VTOL Transition Challenges

- **VTOL to Fixed-Wing** → Requires **gradual airspeed buildup** to prevent stall.
- **Fixed-Wing to VTOL** → Requires **controlled deceleration** to avoid instability due to excessive retardation.

To manage these transitions:

- The **attitude controller blends rate setpoints** across both configurations.
- **Pusher motor ramping** ensures smooth acceleration during VTOL → fixed-wing transition.
- **Thrust modulation** prevents abrupt changes during fixed-wing → VTOL transition.

5. Tuning Recommendations

- **Tune attitude controllers** at a balanced airspeed between **stall & max speed**.
- **Ensure high-quality airspeed measurements**, as errors degrade performance.
- **Use FW_AIRSPD_TRIM** for optimal controller tuning reference.

3. Simulation Setup & Flight Tests

Gazebo Simulation Setup

The transition controller for the VTOL UAV was tested in **Gazebo**, a physics-based simulation environment integrated with **ROS2 PX4**. The UAV model was configured with a hybrid VTOL airframe, including fixed-wing aerodynamic surfaces and multicopter propulsion.

Key simulation parameters:

- **Aerodynamic modeling**: Simulated lift, drag, and moment coefficients for fixed-wing flight.
- **Actuator dynamics**: Integrated elevon control and motor response timing.
- **Environmental conditions**: Wind disturbances and turbulence were added for robustness testing.

Flight scenarios were defined to evaluate:

1. **VTOL takeoff**, hover stabilization, and transition initiation.
2. **Fixed-wing cruise performance** post-transition.
3. **Reverse transition from fixed-wing to VTOL**, assessing deceleration handling.

ROS2 PX4 Configuration

The UAV's control logic was implemented using **ROS2 PX4**, ensuring real-time execution and modularity in system design.

- **PX4 Firmware**: Configured for hybrid VTOL transitions.
- **ROS2 Nodes**:
  - **Position and velocity tracking** for flight phase monitoring.
  - **Attitude control commands** via custom ROS2 topics.
  - **Logging mechanisms** for real-time data capture.

The **adaptive sliding mode controller (ASMC)** was integrated with **PID stabilization layers** for precise airspeed and attitude regulation during transitions.

Flight Data Logging

Data collection was essential to validate transition performance. The following telemetry streams were recorded:

1. **Linear Accelerations**: Captured via onboard IMU, analyzing transition-induced forces.
2. **Angular Rates**: Logged from gyroscope readings to observe roll, pitch, and yaw dynamics.
3. **Gyro Readings for Transition Phases**: Identified stability characteristics during mode switching.

Data visualization was handled using **PlotJuggler**, enabling real-time plotting for debugging and refinement of transition logic.

Would you like me to expand on any specific subsections or adjust the technical depth?

also explain with this what plug in for aerodynamics is

Aerodynamics Plugin in Gazebo for VTOL Simulations

The **Aerodynamics Plugin** in Gazebo is crucial for simulating realistic flight behavior for VTOL aircraft, particularly in transitioning between **multicopter and fixed-wing modes**. It models aerodynamic forces and moments, allowing for accurate flight dynamics in the simulation.

1. Role of the Aerodynamics Plugin

- **Simulates Lift & Drag:** Enables realistic interactions of the airframe with airflow, crucial for fixed-wing flight.
- **Handles Control Surface Effects:** Computes how elevons, rudders, and ailerons generate forces for maneuvering.
- **Implements Wind Disturbances:** Adds environmental factors to test controller robustness.
- **Supports Airspeed Scaling:** Adjusts control effectiveness based on velocity.

In **PX4-based VTOL simulations**, this plugin is integrated with **Gazebo's physics engine**, ensuring that forces from **thrust, aerodynamics, and gravity** are correctly applied.

2. Key Parameters in the Plugin

- **Lift coefficient (CL)** → Determines how much lift is generated based on airspeed and angle of attack.
- **Drag coefficient (CD)** → Models air resistance affecting forward motion.
- **Moment coefficients (Cm)** → Used for rotational effects (pitch, yaw, roll).
- **Air density (ρ)** → Adjusted for altitude variations.
- **Control surface effectiveness (δ)** → Defines how much ailerons, elevators, and rudders impact flight dynamics.

These parameters influence how the **VTOL transition controller** adapts during mode switching, ensuring proper stabilization.

3. Implementation in PX4 & ROS2

- **Gazebo SDF models** → Contain aerodynamic properties for the UAV.

- **PX4 airframe configuration** → Defines flight dynamics for both multicopter and fixed-wing controls.
- **ROS2 topics** → Monitor aerodynamic forces and adjust control gains dynamically.

For **your VTOL transition project**, incorporating an **aerodynamics plugin** ensures realistic behavior during **airframe rotation, propulsion modulation, and lift-off dynamics**.

Results & Flight Test

Simulation Setup & Flight Tests

Flight Testing in ROS2 Gazebo & PX4

The transition controller was implemented and tested in a **ROS2 PX4 simulation environment** within **Gazebo**, evaluating its performance across different flight phases. The UAV model was configured for **VTOL to fixed-wing transitions**, with emphasis on control blending, stability, and airspeed regulation.

Key aspects of the flight test include:

- **VTOL Takeoff & Hover Stability** → Ensuring reliable position control using multicopter logic.
- **Transition Phase** → Gradual engagement of fixed-wing dynamics, monitoring airspeed buildup to prevent stall.
- **Fixed-Wing Cruise** → Assessing elevon effectiveness and throttle modulation.
- **Reverse Transition to VTOL** → Managing retardation forces for smooth deceleration.

All flight tests were conducted **within ROS2 PX4 using Gazebo's aerodynamic models**, ensuring realistic dynamics.

Simulation

The simulation Video link : https://drive.google.com/file/d/1ZKha2m71GoqK3qdksNrv-DZdhDnwKqr3/view?usp=sharing

Sadly, there is error in the software stack which inhibits the topic recording, resulting in no graphical data.