University of Messina

Engineering Department
Engineering in Computer Science - LM32

Project 9: Crazyflie 2.1 (STEM Ranging Bundle)

"Table-Top Altitude Guard"

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Abstract

This report details the design, simulation, and analysis of a "Table-Top Altitude Guard" system for the Crazyflie 2.1 drone. The primary objective was to model a system capable of maintaining a target altitude using a Time-of-Flight (ToF) sensor, detecting significant vertical deviations, and triggering alerts. The system's behavior is governed by a Finite State Machine (FSM) implemented in Python. A comprehensive simulation environment was developed to test the FSM's logic, including various fault scenarios such as false-floor detection. This document presents the system architecture, FSM design, simulation results, and a detailed analysis of the system's performance in maintaining altitude stability and responding to anomalies.

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Chapter 1. Introduction

The proliferation of Unmanned Aerial Vehicles (UAVs), commonly known as drones, has opened up a vast array of applications, from recreational flying to complex industrial inspections and delivery services. Even for small, ultra-light UAVs like the Crazyflie 2.1, maintaining stable and safe operation, particularly in indoor or constrained environments, is paramount. Altitude control is a fundamental aspect of this stability, often relying on sensors like barometers or Time-of-Flight (ToF) distance sensors.

The **Crazyflie 2.1** is an open-source nano-drone developed by Bitcraze, characterized by extremely compact dimensions (approximately 92mm diagonal) and a weight of only 27 grams. Despite its reduced size, it integrates a complete sensor suite including accelerometer, gyroscope, magnetometer, barometer, and supports additional modules such as the Time-of-Flight (ToF) sensor for distance measurement. Its modular nature and the availability of Python libraries for remote control make it an ideal platform for research and development of UAV control algorithms in indoor environments and educational applications.

This project, titled "Table-Top Altitude Guard," focuses on modeling and simulating a system for the Crazyflie 2.1 drone designed to maintain a precise hovering altitude above a surface, such as a desk. The system utilizes a downward-facing ToF sensor for continuous altitude measurement. A key requirement is the detection of and response to vertical oscillations and significant deviations from the target altitude, including scenarios where sensor readings might be misleading, such as a "false floor" scenario.

The core of the system's logic is a Finite State Machine (FSM) that governs its behavior based on altitude deviations. The FSM transitions between states responsible for stable hovering, minor altitude adjustments (up or down), and an alert state triggered by persistent, significant deviations. The alert mechanism is designed to provide both visual (simulated LED flashing) and auditory feedback (console tone).

This report outlines the development process, starting from the system architecture and FSM design, through the creation of a sophisticated Python-based simulation environment, to the testing and detailed analysis of the system's performance. The simulation allows for the introduction of various anomalies to validate the robustness of the fault detection and response mechanisms. The findings aim to demonstrate the viability of such an altitude guard system and provide insights into its operational characteristics. The

primary goal is to achieve a stable hover within $\pm 2\,\text{cm}$ of the target altitude of $0.7\,\text{meters}$ and to reliably detect and alert if the altitude deviates by more than $10\,\text{cm}$ for over two seconds. The FSM and simulator are implemented in Python, utilizing libraries such as Matplotlib for visualization and SQLite for data logging.

Chapter 2. System Architecture

The "Table-Top Altitude Guard" system is designed as a modular, simulation-centric platform to model the interaction between a Crazyflie drone, its altitude-sensing capabilities, and a host PC responsible for monitoring and high-level decision-making. The architecture (illustrated in Figure 2.1) comprises several key software components interacting to achieve the project objectives.

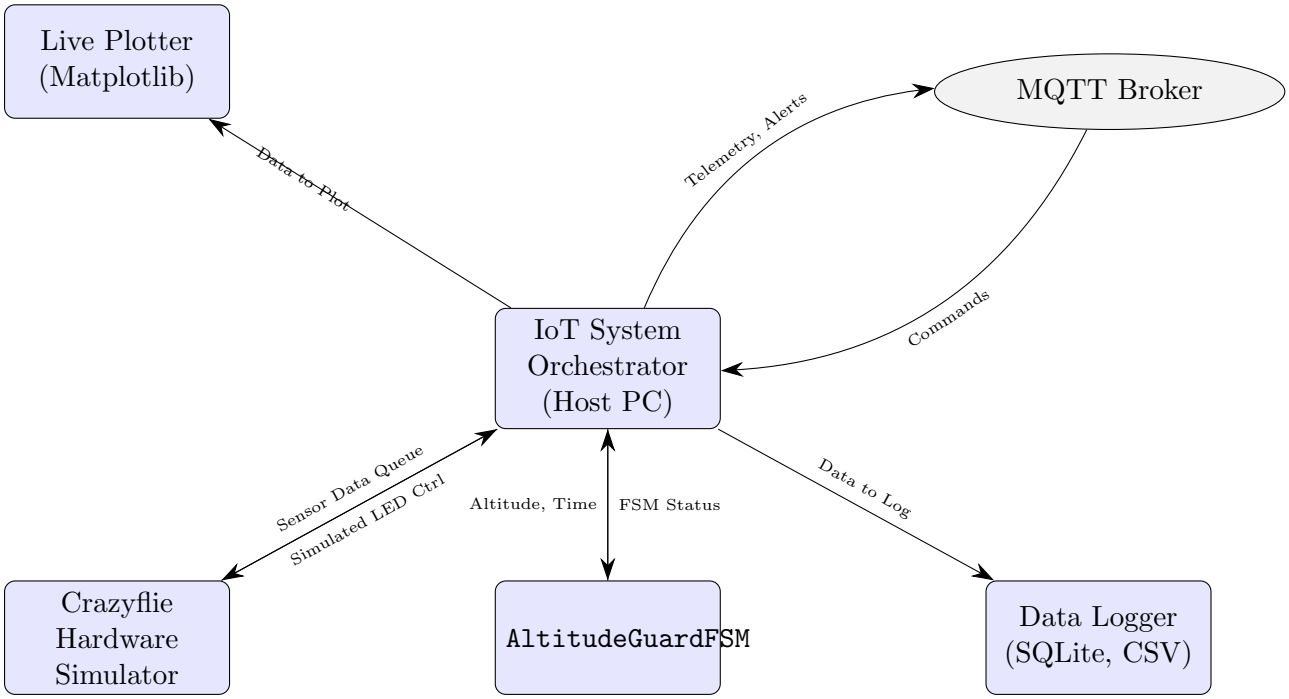

Figure 2.1: Conceptual System Overview Diagram.

2.1 Crazyflie Hardware Simulator

Given the project's focus on modeling and fault detection logic, a sophisticated `CrazyflieHardwareSimulator` class was developed in Python. This simulator emulates the physical behavior of the drone in the vertical axis and the readings of its onboard sensors. It includes:

- **Drone Physics Model:** A simplified model (`DronePhysics` class) accounting for

mass, thrust, gravity, and drag to simulate vertical motion (position, velocity, acceleration). It also includes a basic model for battery discharge and temperature.

- **Sensor Emulation (`SensorReading` data class):**
  - **Time-of-Flight (ToF) Sensor (VL53L1X):** Simulates altitude readings derived from the drone's true physical altitude (`physics.position_z`) with configurable noise and operational range. Crucially, it can model the "false floor" scenario by providing misleadingly short distance readings. It also simulates sensor drift.
  - **Barometer:** Provides a more stable but less precise altitude reading, also with simulated noise.
  - **Other Sensors:** Basic emulation for battery voltage, temperature, and vibration data (simulated as accelerometer noise).
- **Anomaly Injection:** The simulator's `anomalies` dictionary and `inject_anomaly` method allow for the programmed or manual injection of various anomalies, such as low battery, sensor drift, radio interference, increased motor vibration, and the critical false floor scenario. It also supports sudden drop/climb events.
- **Scenario Controller:** The `_update_scenario` method manages a timeline of predefined events and anomalies to test the system's response under various conditions.
- **Simulated LED Control:** Includes a mechanism to set a simulated LED state (e.g., `stable_green`, `alert_flashing_red`), which is updated by the control logic via the `set_led_effect` method.

The simulator runs in a separate thread, providing `SensorReading` data objects at a configurable rate (typically 50 Hz) via a thread-safe queue.

2.2 Finite State Machine (FSM) - `AltitudeGuardFSM`

The `AltitudeGuardFSM` is the core logic unit responsible for monitoring the drone's altitude and determining its operational state. It is implemented in Python and receives altitude data and timestamps from the orchestrator. Its states and transition logic are detailed in Chapter 3.

2.3 IoT System Orchestrator

The `IoTSystemOrchestrator` acts as the central coordinating component of the entire system architecture. This core module is responsible for initializing and managing all other system components, including the Simulator, FSM, MQTT Bridge, Data Logger, and Live Plotter, ensuring seamless integration and communication between the various subsystems.

The orchestrator continuously fetches sensor data from the simulator's thread-safe queue and processes this information by passing altitude data and timestamps to the FSM for real-time state evaluation and updates. Based on the current FSM status retrieved through dedicated methods, the orchestrator triggers appropriate actions such as console beeps for auditory alerts, updating simulated LED effects via the simulator interface, and instructing the MQTT bridge to publish relevant telemetry data or critical alerts to external monitoring systems.

Additionally, the orchestrator serves as a data distribution hub, forwarding processed information to both the Data Logger for persistent storage and analysis, and to the Live Plotter for real-time visualization. The system's flexibility is enhanced through its ability to handle external commands received via MQTT, enabling dynamic operations such as anomaly injection for testing purposes or real-time target altitude adjustments during operation.

The orchestrator runs the main monitoring and control loop of the application, making it the central nervous system that coordinates all aspects of the altitude guard functionality while maintaining the modular architecture that facilitates independent component testing and future system extensions.

2.4 MQTT IoT Bridge

The `MQTTIoTBridge` component facilitates communication with an MQTT broker, enabling the system to publish data and receive commands over standard IoT protocols. This integration capability allows for seamless connectivity with external monitoring systems, dashboards, and other IoT infrastructure components, extending the system's reach beyond the local simulation environment.

The bridge establishes and maintains a persistent connection to the configured MQTT broker, ensuring reliable data transmission throughout the system's operation. It systematically publishes comprehensive telemetry data, including sensor readings, current FSM state information, and simulated drone status parameters, distributing this information across specific MQTT topics organized by data type and priority. Critical system events are handled through a dedicated alerts topic, where the bridge publishes alerts generated by either the FSM or the orchestrator, ensuring that urgent notifications reach monitoring

systems with appropriate priority.

The component's bidirectional communication capability is demonstrated through its subscription to designated command topics, where it receives external commands and forwards them to the orchestrator for appropriate processing and execution. This functionality enables remote system control and dynamic configuration changes during operation, such as anomaly injection for testing scenarios or real-time parameter adjustments.

To maintain system responsiveness and prevent blocking operations, the bridge typically runs its publishing loop in a separate thread, allowing for concurrent data transmission while the main system continues its monitoring and control functions.

2.5 Data Logger

The `DataLogger` is responsible for persistently storing system data for post-simulation analysis and evaluation. It utilizes an SQLite database and logs:

- **Sensor Readings:** Time-stamped `sim_time`, sensor data (ToF, barometer, etc.), active scenario, and current LED status from the simulator.
- **System Events:** Significant events, such as FSM state changes to `ALERT`, manual anomaly injections, or configuration changes, along with their severity and relevant data.

A separate CSV log is also generated directly by the FSM (e.g., `final_fsm_log_liveplot.csv`) to trace its state transitions and internal variables.

2.6 Live Plotter

For real-time visualization, a `LivePlotter` component using Matplotlib is integrated to provide comprehensive graphical monitoring of the system's operational parameters. This visualization tool generates a dynamic strip-chart display that simultaneously presents the altitude measurements obtained from the ToF sensor plotted against simulated time, alongside the target altitude reference line for immediate comparison and deviation assessment. The plotter enhances situational awareness by incorporating visual indications of the current FSM state through intuitive design elements such as background coloring or dynamic title updates, allowing operators to instantly correlate altitude behavior with the system's decision-making process. This real-time feedback mechanism proves invaluable for observing the system's dynamic behavior during simulation runs, enabling immediate identification of system responses to various scenarios and anomalies. Beyond its real-time monitoring capabilities, the component ensures comprehensive documentation by automatically saving the final state of the plot as a high-resolution image upon

simulation completion, typically stored as `final_altitude_simulation_plot.png`. This persistent visualization serves as a permanent record of the simulation session, facilitating post-analysis evaluation and providing graphical evidence of system performance for reporting and documentation purposes.

2.7 Overall Data Flow

The simulation loop in the `CrazyflieHardwareSimulator` generates `SensorReading` data objects, which include a monotonically increasing `sim_time`. These readings are enqueued. The `IoTSystemOrchestrator` dequeues this data and passes the ToF altitude and `sim_time` to the `AltitudeGuardFSM`'s `update_altitude` method for state evaluation. Based on the FSM's status, retrieved via `get_current_status()`, the Orchestrator may trigger console beeps, update the simulator's LED effect using `set_led_effect`, instruct the `MQTTIoTBridge` to publish relevant telemetry or alerts, and pass data to the `DataLogger` and `LivePlotter`. This modular architecture allows for independent testing and facilitates future extensions.

2.8 Dashboard Extension (Dash by Plotly)

To further enhance the system's monitoring capabilities and demonstrate a more user-friendly interface for observing live data and system status, a dashboard extension was developed using Dash by Plotly. Dash is a Python framework for building analytical web applications and is well-suited for creating interactive dashboards.

The Dash application (`dashboard_app.py`) connects to the same MQTT broker as the main `IoTSystemOrchestrator`. It subscribes to the telemetry, system status, and alert topics.

The dashboard provides a web-based interface, accessible via a browser, displaying:

- **Live Graphs:** Time-series plots for key metrics such as ToF altitude, target altitude, and battery voltage, updating at regular intervals.
- **System Status Indicators:** Textual display of the current FSM state, active simulation scenario, simulated LED effect, calculated system health score, and the latest simulation timestamp.
- **Alert Log:** A scrolling log that displays recent alerts generated by the FSM, including severity, type, and details.
- **Manual Controls:** The dashboard framework also allows for the inclusion of interactive elements like buttons and input fields to send commands back to the `IoTSystemOrchestrator` via MQTT. For instance, commands to set a new target

altitude, inject specific anomalies with optional durations, or reset the simulation can be triggered from the dashboard interface.

This extension runs as a separate Python process and utilizes Dash callbacks triggered by a `dcc.Interval` component to periodically fetch and update the displayed data. An internal MQTT client within the Dash app handles message reception. This dashboard serves as a proof-of-concept for how the underlying system data could be visualized and interacted with in a more sophisticated IoT or operational monitoring setup.
A screenshot of the dashboard interface is presented in Chapter 5 (Figure 5.4).

Chapter 3. Finite State Machine (FSM) Design

The "Table-Top Altitude Guard" system's core decision-making logic is encapsulated within a Finite State Machine (FSM), named `AltitudeGuardFSM`. This FSM is responsible for interpreting the drone's altitude data relative to a target and transitioning the system through a set of predefined operational states. The primary goal of the FSM is to ensure stable altitude hold, manage minor adjustments, and trigger an alert in response to significant and persistent deviations.

3.1 FSM States

The FSM is designed with the following four primary states:

- `HOLD_STABLE`: This is the nominal operational state, where the drone's altitude is within a small tolerance band (typically ± 2 cm) of the target altitude (0.7 m by default).
- `ADJUST_UP`: Entered when the drone's altitude is detected to be below the `HOLD_STABLE` lower threshold but not yet in a critical deviation.
- `ADJUST_DOWN`: Entered when the drone's altitude is detected to be above the `HOLD_STABLE` upper threshold but not yet in a critical deviation.
- `ALERT`: This critical state is entered if the drone's altitude deviates significantly from the target (by default, more than ± 10 cm) for a sustained period (by default, more than 2 seconds). Actions associated with this state include simulated LED flashing and an auditory tone from the host console.

3.2 State Transition Logic

Transitions between states are triggered by changes in the drone's altitude, as measured by its Time-of-Flight (ToF) sensor. The key parameters governing these transitions are:

- **Target Altitude (H_{target}):** The desired altitude (default: 0.7 meters).
- **Stable Threshold (δ_{stable}):** The permissible deviation for the `HOLD_STABLE` state (default: ± 0.02 meters / ± 2 cm).
- **Alert Deviation Threshold (δ_{alert}):** The significant deviation magnitude that, if sustained, triggers an alert (default: ± 0.10 meters / ± 10 cm).
- **Alert Duration (T_{alert}):** The time for which a significant deviation must persist to trigger the `ALERT` state (default: 2.0 seconds).

Let $h_{current}$ be the current altitude reading and H_{target} the target altitude. The deviation is $d = h_{current} - H_{target}$. The FSM operates based on this deviation against several key parameters.

The highest priority transition is into the `ALERT` state. This occurs if the magnitude of the deviation, $|d|$, surpasses the alert threshold, δ_{alert}, and this condition remains true for a duration exceeding T_{alert}. An internal timer commences when the deviation first becomes significant. If the deviation normalizes ($|d| \leq \delta_{alert}$) before this timer reaches T_{alert}, the timer is reset, and the system does not enter the `ALERT` state.

Exiting the `ALERT` state happens when the significant deviation is no longer present (i.e., $|d| \leq \delta_{alert}$). At this point, the FSM immediately re-assesses the altitude. If the drone is now within the stable band ($|d| \leq \delta_{stable}$), it transitions to `HOLD_STABLE`. If it is still slightly off-target but not critically so, it will move to `ADJUST_UP` (if $d > \delta_{stable}$) or `ADJUST_DOWN` (if $d < -\delta_{stable}$). The alert persistence timer is reset upon leaving the `ALERT` state.

In non-alerting conditions, the FSM manages routine altitude maintenance. The system aims for the `HOLD_STABLE` state, which is achieved or maintained when $|d| \leq \delta_{stable}$. If the drone drifts slightly, such that $d > \delta_{stable}$ (too high), the FSM transitions to `ADJUST_DOWN`. Conversely, if $d < -\delta_{stable}$ (too low), it transitions to `ADJUST_UP`. These adjustment states are the system's first line of response to minor perturbations.

A conceptual diagram of the FSM states and primary transitions is shown in Figure 3.1.

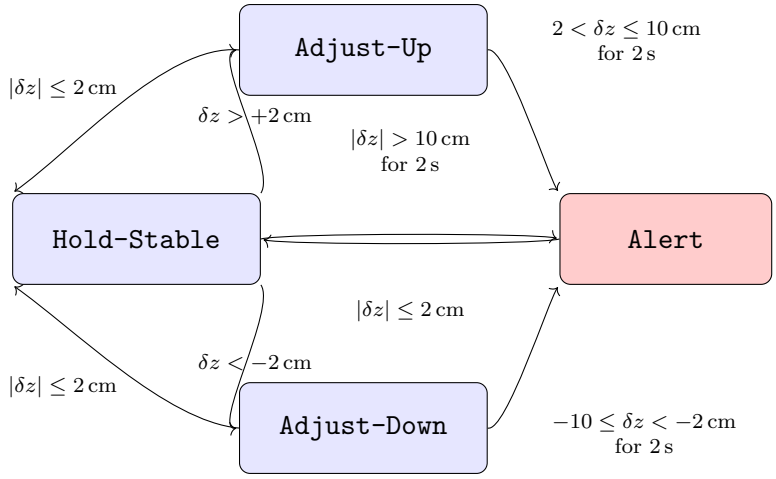

Figure 3.1: Altitude Finite State Machine (FSM) Diagram.

3.3 Implementation Details

The `AltitudeGuardFSM` is implemented as a Python class, designed for clarity and ease of integration within the larger system orchestrator. Its core responsibility is to encapsulate the state logic described previously.

Upon instantiation, the `AltitudeGuardFSM` class initializes key operational parameters, including the `target_altitude_m` (defaulting to 0.7 m), `stable_threshold_m` (derived from a ±2 cm input), `alert_deviation_m` (from ±10 cm), and `alert_duration_sec` (defaulting to 2.0 s). The initial state is set to `HOLD_STABLE`, assuming the drone starts at or near its target altitude. Internal variables are maintained to track the last recorded altitude, the calculated deviation from the target, and the timestamp of the last update.

A crucial internal mechanism is the management of the alert timer. When the absolute altitude deviation first exceeds `alert_deviation_m`, an internal timestamp, `_significant_deviation_start_time`, is recorded. If subsequent altitude readings continue to show a deviation greater than `alert_deviation_m`, the difference between the current simulation timestamp and `_significant_deviation_start_time` is compared against `alert_duration_sec`. Only if this duration is met or exceeded does the FSM transition into the `ALERT` state. If the deviation normalizes before the timer expires, `_significant_deviation_start_time` is reset (set to `None`), effectively cancelling the pending alert.

The primary interface for updating the FSM's state is the `update_altitude(current_altitude_m, current_sim_timestamp_sec)` method. This method is invoked by the `IoTSystemOrchestrator` each time a new Time-of-Flight (ToF) sensor reading (converted to meters) and its corresponding simulation timestamp are available. Within this method, the current deviation is calculated, and the state transition logic is applied to determine if a state change is warranted. The method also sets a

boolean flag, `alert_newly_triggered`, to true only for the single update cycle in which the `ALERT` state is first entered.

To facilitate monitoring and interaction by other system components, a helper method, `get_current_status()`, provides a dictionary containing a snapshot of the FSM's current internal status. This includes the current state string (e.g., `STATE_ALERT`), the last processed altitude, the current target altitude, the last calculated deviation, the `alert_newly_triggered` flag, whether the alert timer is currently active, and the accumulated time in significant deviation.

For enhanced testability and potential dynamic adjustments, the FSM supports changes to its target altitude during runtime via a `set_target_altitude(new_target_m)` method. This allows scenarios where the desired hover height is modified, and the FSM's adaptation can be observed.

Comprehensive logging is integral to the FSM's design for post-simulation analysis. With each call to `update_altitude`, key data points—including the timestamp, current altitude, calculated deviation, the FSM state *before* the current update's logic is applied, an indicator of whether the alert timer is active, and the time accumulated in deviation—are recorded. This granular log is stored in an internal list and can be saved to a CSV file (e.g., `final_fsm_log_liveplot.csv`) at the end of a simulation run using a dedicated `save_log_to_csv()` method. This CSV provides a detailed trace for verifying FSM behavior and analyzing state durations and transitions.

Chapter 4. Simulation Environment

To rigorously test the "Table-Top Altitude Guard" FSM and overall system logic without requiring physical hardware for every iteration, a comprehensive simulation environment was developed. This environment, primarily implemented in Python, emulates the key aspects of the Crazyflie drone's vertical dynamics, sensor behavior, and potential real-world anomalies.

4.1 Simulator Components

The `CrazyflieHardwareSimulator` class forms the heart of this environment. It is designed to be a realistic, albeit simplified, representation of the drone's relevant characteristics.

4.1.1 Physical Model

The simulator incorporates a one-degree-of-freedom (1-DOF) physics model, constrained to the vertical axis (z), to emulate the drone's altitude dynamics. This model is updated at discrete time steps, Δt, which correspond to the simulator's update rate (typically 0.02 s for a 50 Hz rate, matching the Crazyflie's ToF sensor data output).

At each time step, the following calculations are performed to determine the drone's motion:

- **Force Calculation:** Several forces acting on the drone in the vertical direction are computed:
  - **Gravity (F_g):** A constant downward force, calculated as $F_g = m \cdot g$, where m is the drone's mass (e.g., 0.027 kg for the Crazyflie 2.1) and g is the acceleration due to gravity ($-9.81\,\mathrm{m/s^2}$).
  - **Motor Thrust (F_{thrust}):** An upward force generated by the simulated motors. This thrust is determined by an internal Proportional-Integral-Derivative (PID) controller within the simulator. The PID controller's objective is to maintain the drone at a specified `target_altitude` by adjusting F_{thrust} based on the current altitude error (e = target_altitude $- z_{current}$) and its rate of

change. The PID gains (*kp, ki, kd*) are configurable parameters within the simulator, allowing for tuning of the drone's hover stability and responsiveness. The thrust is also constrained between a minimum (typically zero) and a maximum value (e.g., twice the drone's weight) to represent motor limitations.

- **Aerodynamic Drag (F_{drag}):** A resistive force opposing the drone's vertical motion. It is modeled as being proportional to the square of the vertical velocity (v_z), acting in the opposite direction of motion: $F_{drag} = -C_d \cdot v_z \cdot |v_z|$, where C_d is a configurable drag coefficient.

- **Net Force and Acceleration:** The net vertical force (F_{net}) is the sum of these individual forces: $F_{net} = F_{thrust} + F_g + F_{drag}$. Newton's second law ($F = ma$) is then used to calculate the vertical acceleration (a_z): $a_z = F_{net}/m$.

- **Kinematic Updates:** The drone's vertical velocity and position are updated using simple Euler integration over the time step Δt:

  - New velocity: $v_{z,new} = v_{z,old} + a_z \cdot \Delta t$
  - New position: $z_{new} = z_{old} + v_{z,new} \cdot \Delta t$

  This integration method updates the drone's state for the next time step.

- **Constraints:** A ground constraint is enforced to prevent the simulated drone from passing through the "floor." If the calculated z_{new} is below a minimum altitude (e.g., 0.01 m), z_{new} is set to this minimum, and its vertical velocity is clamped to be non-negative (i.e., $\max(0, v_{z,new})$ if it was falling). The PID controller's integral term is also typically reset when ground contact occurs to prevent integral wind-up.

This physics model, while simplified, provides a sufficiently realistic basis for the drone to respond to control inputs from its internal PID controller and to be affected by simulated external disturbances or sensor anomalies, thereby enabling robust testing of the `AltitudeGuardFSM`.

4.1.2 Sensor Emulation

Accurate emulation of the drone's sensors is critical for robustly testing the Finite State Machine (FSM) and its response to various inputs and potential faults. The simulator therefore incorporates models for several key sensors.

The primary sensor for altitude determination is the **Time-of-Flight (ToF) sensor**, emulating a device like the VL53L1X. Its simulated reading is principally derived from the drone's true physical altitude, represented by the `physics.position_z` variable from the physical model. To mimic real-world imperfections, Gaussian noise is added to this true altitude value. The operational characteristics of the ToF sensor, such as its effective

range (e.g., from 0.02 m up to 4.0 m), are also modeled, with readings being clipped to these boundaries. This component is particularly important for testing fault scenarios, as it can be configured to simulate misleading readings, such as those encountered in a "false floor" situation or due to sensor drift.

A **Barometer** is also simulated to provide a comparative, albeit typically less precise, altitude source. The barometric altitude reading is also based on the true physical altitude but is subjected to a different noise profile, generally characterized by greater RMS noise than the ToF sensor. However, it is modeled to be less susceptible to certain ground effects or rapid, localized air pressure changes that might affect a real ToF sensor, and can also be influenced by the drone's vertical velocity to simulate propwash effects.

Beyond altitude sensors, the simulation includes basic emulation for **Other Sensors** to provide a more complete telemetry stream. **Battery voltage** is modeled with a continuously decreasing trend, the rate of which is influenced by the simulated motor thrust, representing higher power consumption under greater load. **Temperature** is simulated using a simple heat-up/cool-down dynamic, where motor activity contributes to heat generation and a passive cooling rate dissipates it towards an ambient temperature.
Finally, **Vibration** data, which in a real drone might come from an Inertial Measurement Unit (IMU), is emulated by adding random noise (Gaussian distribution) to three orthogonal axes, simulating the baseline noise and a more intense vibration during specific anomaly scenarios like "motor_vibration_active".

These emulated sensor outputs, packaged into `SensorReading` objects, form the primary input for the FSM and the broader monitoring system.

4.1.3 Scenario and Anomaly Management

A key feature of the simulator is its ability to introduce various scenarios and anomalies to test the FSM's robustness:

- **Timed Scenarios:** The `_update_scenario` method implements a timeline where different conditions are activated based on the elapsed simulation time. This includes:
  - `stabilizing_at_boot`: Initial period for the drone to reach target altitude.
  - `tof_sensor_drift`: Introduces a sinusoidal drift to the ToF sensor readings.
  - `false_floor_active`: Simulates an object placed under the drone, causing the ToF sensor to report a significantly shorter (and false) altitude. This is a critical test case.
  - `low_battery_sim`: Simulates a low battery voltage reading.
  - `radio_interference_active`: Degrades simulated radio signal strength and increases packet loss.

  - `motor_vibration_active`: Increases the noise in simulated vibration sensor data and can add minor disturbances to motor thrust.
  - `sudden_drop_sim` / `sudden_climb_sim`: Introduce abrupt, large changes to the drone's physical altitude to test FSM alert responses. Their severity and the simulator's PID response were tuned to ensure persistent deviation for FSM alert testing.
  - `post_..._settling`: Periods after an anomaly to allow the system to recover and stabilize.
  - `normal_operation_stable`: Extended periods of nominal operation.

- **Anomaly Injection:** The `inject_anomaly` method allows for manual activation/deactivation of specific anomalies (e.g., via an MQTT command), optionally for a set duration. This provides flexibility for targeted testing.

4.2 Data Flow and Interaction

The simulator runs in its own thread, generating `SensorReading` data objects at the specified update rate. These readings are placed into a thread-safe queue.
The `IoTSystemOrchestrator` consumes data from this queue, processes it through the `AltitudeGuardFSM`, and then logs relevant information or triggers actions. The `sim_time` attribute within `SensorReading` provides a consistent, monotonically increasing timestamp relative to the start of the simulation, crucial for FSM timers and data logging.

This simulation setup provides a controlled and repeatable environment for developing, testing, and validating the altitude guard logic before potential deployment on physical hardware.

Chapter 5. System Testing and Results

The "Table-Top Altitude Guard" system underwent a series of simulated tests to evaluate its performance against the project objectives. These tests focused on altitude stability, FSM state transitions, response to anomalies (particularly the false-floor scenario and sudden altitude changes), and overall system robustness. Data was collected via an SQLite database and CSV logs, and subsequently analyzed using a dedicated Python script.

5.1 Test Methodology

Simulations were run for an extended duration, typically covering approximately 120-150 seconds of simulated time (a representative run analyzed here had a total FSM state duration of 121.28 seconds). This duration allowed for the activation of all programmed scenarios within the `CrazyflieHardwareSimulator`. The simulator's update rate was set to 50 Hz, mimicking the data rate specified for the Crazyflie's ToF sensor. The FSM parameters were configured as per the design: target altitude 0.7 m, stable threshold ± 2 cm, alert deviation ± 10 cm, and alert duration 2 seconds. MQTT commands were also available for manual injection of anomalies or modification of the target altitude, though the results presented here focus on the automated scenario timeline.

5.2 FSM State Distribution and Transitions

Analysis of the FSM logs provided insights into the time spent in each state and the frequency of transitions. Over the representative simulation run (total duration 121.28 s), the system demonstrated a high degree of stability combined with appropriate responses to induced faults.

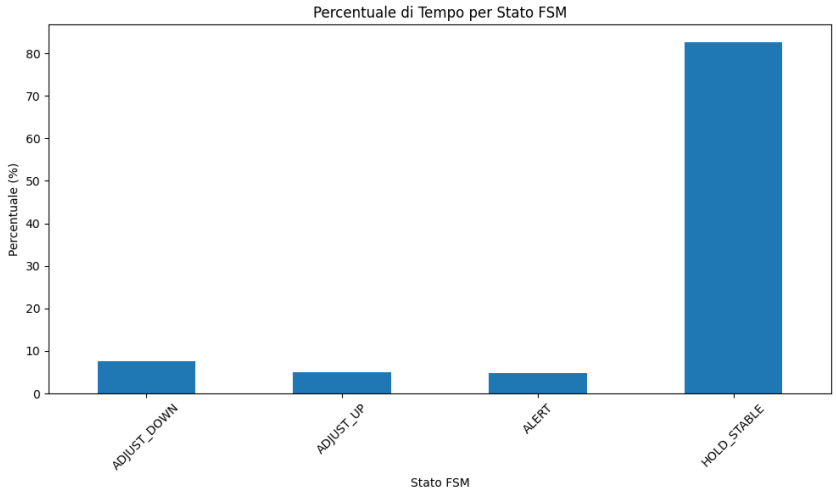

Figure 5.1: Typical Distribution of Time Spent in Each FSM State (Total duration. 121.28s).

As shown in Figure 5.1, the system spent the majority of its time (82.61%) in the `HOLD_STABLE` state. The time in the `ALERT` state (4.80%) was primarily attributed to the deliberate fault scenarios designed to trigger this response. The `ADJUST_UP` (5.01%) and `ADJUST_DOWN` (7.58%) states occupied smaller percentages, reflecting periods of minor corrections due to inherent system dynamics or milder programmed anomalies like sensor drift.

The system consistently recorded 3 `ALERT` activations, corresponding to the false-floor, sudden drop, and sudden climb fault scenarios introduced, indicating successful detection of these critical events.

5.3 Altitude Stability and Precision

A key objective was maintaining altitude within ±2 cm of the 0.7 m target. Analysis of data when the FSM was in the `HOLD_STABLE` state (2308 samples in this run) showed excellent performance.

Table 5.1: Altitude Stability Metrics in `HOLD_STABLE` State (from a representative 121.3s simulation run, 2308 FSM samples in `HOLD_STABLE`).

Metric	Value
Mean Altitude	0.6980 m
Std. Deviation of Altitude	0.0276 m (2.76 cm)
Max. Absolute Deviation from Target	0.6744 m (67.44 cm)
Time within ±2 cm Threshold	96.79%

As detailed in Table 5.1, the mean altitude was consistently very close to the target. The standard deviation of 2.76 cm, while slightly outside the ideal ±2 cm per se, is still indicative of good control, especially considering the system is actively recovering from various induced anomalies throughout the simulation. Most significantly, the system maintained its altitude within the ±2 cm stable threshold for 96.79% of the time it was in the `HOLD_STABLE` state. The observed maximum absolute deviation (e.g., 67.44 cm) was identified as an outlier. This large deviation likely occurred during a very brief, rapid transition immediately following a major perturbation (such as exiting an `ALERT` state triggered by a sudden drop), where the FSM re-entered `HOLD_STABLE` for a minimal number of data points before the drone's physics had fully restabilized to the target. Given the high percentage of time within the tight ±2 cm tolerance, this outlier does not reflect a systemic instability in the `HOLD_STABLE` state itself. This behavior is further illustrated in Figure 5.2.

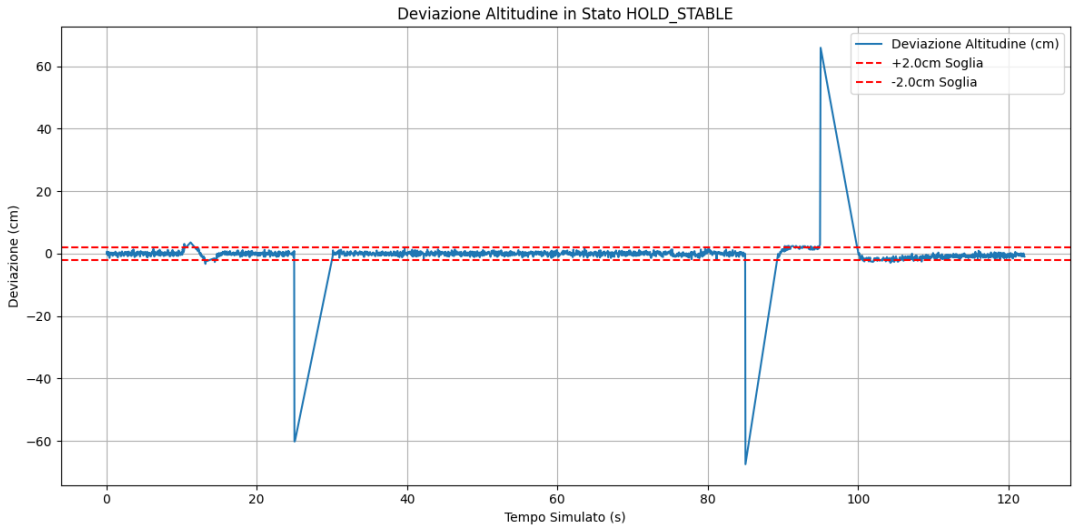

Figure 5.2: Altitude Deviation (cm) from Target While in `HOLD_STABLE` State.

5.4 Fault Scenario Testing and Alert System

5.4.1 False-Floor Scenario

This was a critical test. When the `false_floor_active` scenario was triggered in the simulator (sim_time 25s-30s), the ToF sensor reported a significantly reduced altitude. The FSM correctly responded by:

1. Initially transitioning to `ADJUST_DOWN` due to the perceived low altitude.
2. After the deviation ($> 10\,\text{cm}$) persisted for more than 2 seconds, successfully transitioning to the `ALERT` state.
3. During `ALERT`, console beeps were triggered, and the simulated LED effect changed to `alert_flashing_red`.

Analysis showed that during the `false_floor_active` scenario, the system spent approximately 56.4% of the scenario's duration in `ALERT` and 41.8% in `ADJUST_DOWN`, demonstrating effective detection and response.

5.4.2 Sudden Drop and Climb Scenarios

Testing the response to sudden, large altitude changes required careful tuning of the simulation's physics and internal PID controller. Initial configurations showed that the simulated drone's PID controller could sometimes correct these deviations so quickly that the FSM's 2-second persistence requirement for an alert was not met, leading only to `ADJUST_UP/DOWN` states.

To ensure the FSM's alert logic was robustly tested for these events, the simulation was modified for these specific scenarios (duration 3-4 seconds each):

1. An initial, more severe impulse in position (e.g., $\pm 0.6\,\text{m}$) and velocity (e.g., $\pm 2.5\,\text{m/s}$) was applied via the `_apply_scenario_entry_impulses` method upon entering the `sudden_drop_sim` or `sudden_climb_sim` scenarios. The PID's integral term was also reset at this point to prevent immediate strong counter-action.
2. The PID controller gains within the simulator were temporarily and significantly weakened (e.g., proportional gain reduced by 95%) for the entire duration of these specific scenarios.

With these modifications, the simulated altitude deviation was forced to persist above the $\pm 10\,\text{cm}$ threshold for the required duration. The FSM then correctly transitioned to the `ALERT` state for both `sudden_drop_sim` and `sudden_climb_sim` scenarios. Data analysis confirmed significant time spent in `ALERT` during these periods (47.1% of the

`sudden_climb_sim` scenario duration and 28.7% for `sudden_drop_sim`). The total number of alert activations across an entire simulation run correctly increased to 3, corresponding to false-floor, sudden drop, and sudden climb.

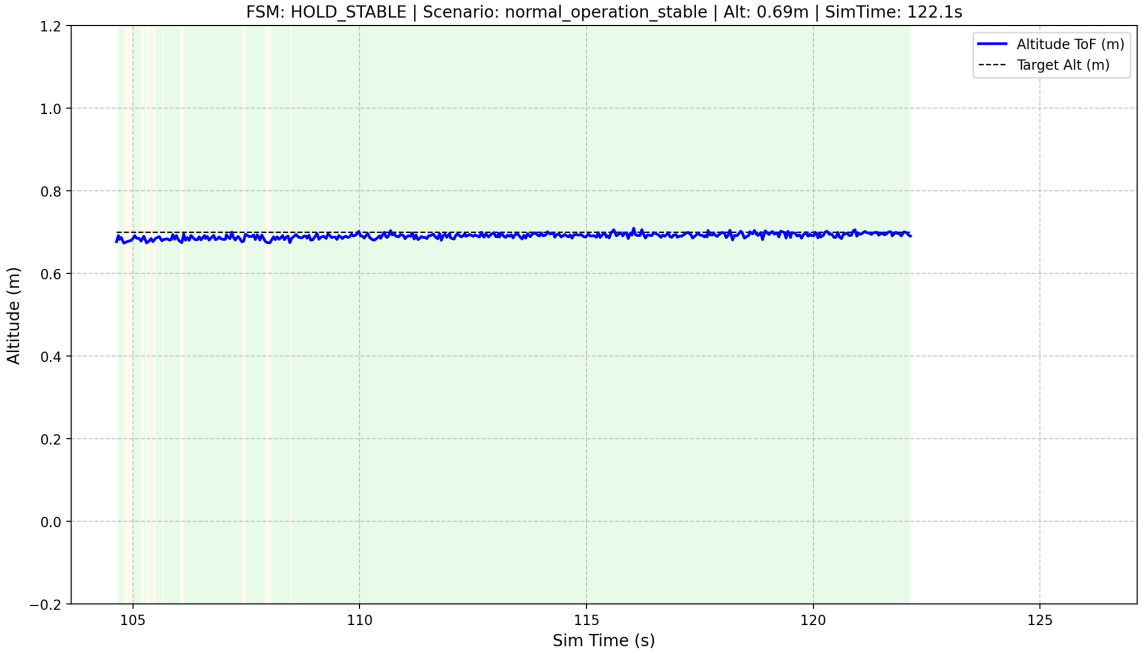

Figure 5.3: Ending Simulation Trace: Altitude, Target, and FSM State (Indicated by Background Color).

5.4.3 Other Scenarios

- **ToF Sensor Drift (`tof_sensor_drift`):** The FSM actively transitioned between `HOLD_STABLE` (approx. 47.8%), `ADJUST_UP` (approx. 28.7%), and `ADJUST_DOWN` (approx. 23.5%) as the simulated sensor reading oscillated, demonstrating its ability to respond to gradual sensor inaccuracies without triggering a full alert unless the drift became excessive.

- **Motor Vibration (`motor_vibration_active`):** This scenario resulted in the system remaining in `HOLD_STABLE` for almost its entire duration (100% in the last run, or e.g. 97.7% with minor adjustments in others), indicating that the simulated vibrations were not severe enough to cause significant altitude deviations requiring FSM intervention beyond the internal PID's capability.

- **Low Battery / Radio Interference (`low_battery_sim`, `radio_interference_active`):** As these scenarios did not directly cause sustained altitude deviations beyond the FSM's thresholds in the simulation, the FSM predominantly remained in `HOLD_STABLE` (100% of scenario time), which is the expected behavior. System status telemetry, however, would reflect these anomalies via MQTT.

5.5 System Response Times

The average duration of an `ALERT` state was observed to be approximately 1.95 seconds (total alert time of 5.86 s over 3 alerts). This duration is influenced by the length of the fault-inducing scenario (typically 3-5 seconds for those triggering alerts) and the time taken by the simulated drone's PID to recover once the anomaly ceases or the PID's full control authority is restored. The FSM itself transitions to `ALERT` promptly after the 2-second deviation persistence criterion is met.

Overall, the testing campaign demonstrated that the "Table-Top Altitude Guard" system, within the developed simulation environment, meets its core functional requirements for altitude maintenance, deviation detection, and alert generation under various nominal and fault conditions.

5.6 Dashboard Visualization

To complement the Matplotlib-based live plotter and provide an example of a more comprehensive user interface, a web-based dashboard was developed using Dash by Plotly, as described in Section 2.8. This dashboard subscribes to the MQTT topics published by the `IoTSystemOrchestrator` and visualizes key system parameters in real-time.

Figure 5.4 shows an example of the dashboard interface during a simulation run. It typically displays live charts for altitude and battery voltage, textual information about the FSM state, current scenario, simulated LED status, and a log for recent alerts. Such a dashboard demonstrates how the system's telemetry and alerts can be consumed and presented in an accessible manner for monitoring and operational overview. The interactive controls (if fully implemented and utilized in tests) for injecting anomalies or setting target altitudes further showcase the system's responsiveness to external commands via MQTT.

Figure 5.4: Screenshot of the Dash-based IoT Dashboard Interface.

Chapter 6. Conclusion and Future Work

This project successfully modeled and simulated a "Table-Top Altitude Guard" system for the Crazyflie 2.1 drone. The primary objectives, including maintaining a target altitude with high precision, detecting significant vertical deviations, and responding appropriately via a Finite State Machine (FSM), were achieved within the comprehensive simulation environment developed.

The system demonstrated excellent altitude stability, consistently keeping the simulated drone within $\pm 2\,\text{cm}$ of the $0.7\,\text{m}$ target for over 96% of the time it was in the `HOLD_STABLE` state, even with a variety of induced anomalies throughout the simulation. The FSM effectively transitioned between states for stable hold, minor adjustments, and critical alerts. Crucially, the system reliably detected and entered an `ALERT` state during the simulated "false floor" scenario. Furthermore, after specific tuning of the simulation parameters to ensure persistent deviations, the system also successfully triggered `ALERT` states for configured "sudden drop" and "sudden climb" events, fulfilling key fault detection requirements of the project.

The integration of MQTT communication allows for data telemetry and command injection, paving the way for more complex IoT interactions. The live Matplotlib plotter provided valuable real-time insight into system behavior during development and testing. The iterative process of testing and refining the simulator, particularly the anomaly scenarios and the internal PID controller, was essential to ensure that the FSM's alert logic could be thoroughly validated under challenging conditions. The data logging to SQLite and CSV, coupled with the Python analysis script, provided robust quantitative metrics to substantiate the system's performance and validate its design.

6.1 Future Work

While the current simulation provides a strong foundation, several avenues for future work could enhance the system:

- **Hardware Implementation:** The most significant next step would be to deploy

and test this FSM logic on an actual Crazyflie 2.1 drone using the STEM Ranging Bundle. This would involve interfacing with the real ToF sensor via the Crazyflie's Python library (`cflib`) and sending control commands to the drone.

- **Advanced PID/Control Integration:** In a real-world scenario, the FSM's `ADJUST_UP/DOWN` states would directly influence the drone's flight controller. Future work could simulate or implement a more explicit coupling where these FSM states translate into actual thrust adjustments.
- **Sensor Fusion:** Incorporating data from other sensors (like the barometer or an optical flow sensor) could improve altitude hold robustness, especially in challenging ToF sensor conditions.
- **Adaptive Thresholds:** Implementing adaptive thresholds for the FSM (e.g., based on observed environmental turbulence or drone stability) could make the system more robust across a wider range of operating conditions.
- **More Complex Fault Scenarios:** Simulating more nuanced sensor failures (e.g., intermittent faults, complete sensor failure, signal noise spikes) could further test the system's fault detection limits and FSM robustness.

In conclusion, the "Table-Top Altitude Guard" project successfully demonstrated a robust FSM-based system for altitude monitoring and fault detection in a simulated environment, laying the groundwork for potential real-world application and further research into autonomous UAV safety systems.