Conceptual Design Report

Flying Hand

Aerial Manipulator for Non Destructive Testing



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Contents

1 Project Description **1**

2 Use Case **1**

3 System-Level Requirements **3**
3.1 Mandatory Functional Requirements . . . 4
3.2 Mandatory Performance Requirements . . . 4
3.3 Mandatory Non-Functional Requirements . . . 5
3.4 Desirable Functional Requirements . . . 5
3.5 Desirable Performance Requirements . . . 5

4 Functional architecture **5**
4.1 System Inputs and Outputs . . . 6
4.2 Core Functional Blocks . . . 6

5 System and Subsystem Level Trade Study **7**
5.1 System-Level Trade Study: Non Destructive Testing (NDT) Method . . . 7
5.2 Subsystem Level Trade Study 1: Drone Platform . . . 8
5.3 Subsystem Level Trade Study 2: Manipulator Arm . . . 9

6 Cyberphysical architecture **10**

7 Subsystem Description **11**
7.1 Communication . . . 11
7.2 Sensing . . . 12
7.3 Localization . . . 12
7.4 Navigation . . . 13
7.5 Hover Stably . . . 14
7.6 Manipulation . . . 14
7.7 Perform NDT . . . 14

8 Project Management **15**
8.1 Work plan and tasks . . . 15
8.1.1 Hardware . . . 16
8.1.2 Software . . . 17
8.2 Schedule . . . 17
8.2.1 Key Milestones . . . 18
8.3 System validation demonstrations . . . 20
8.3.1 Spring Validation Demo (SVD) . . . 20
8.3.2 Fall Validation Demo (FVD) . . . 20
8.4 Responsibilities . . . 21
8.5 Provisional parts list and budget . . . 21
8.6 Risk management . . . 21

References **23**

1 Project Description

Non-Destructive Testing (NDT) is a critical component of preventive asset maintenance for large-scale industrial infrastructure such as transmission towers, pipelines, storage tanks, and industrial facilities. Despite its importance, current NDT practices remain constrained by high inspection costs, operational downtime, limited access to complex geometries, and significant safety risks for human inspectors. Many inspection tasks require scaffolding, rope access, or shutdown of critical systems to facilitate operator task, making frequent inspection costly and disruptive.

To address these challenges, this project proposes **Flying Hand**, an aerial robotic manipulation system designed to perform **contact-based non-destructive testing** on hard-to-reach industrial assets. By combining a multirotor aerial platform with a robotic manipulator arm and a contact-based NDT end-effector, Flying Hand enables targeted inspection without interrupting ongoing operations or exposing personnel to hazardous environments.

Flying Hand is designed as an operator-deployed yet autonomously executing inspection system. A trained operator manually pilots the drone to a designated Area of Interest (AOI) using a ground control station. Upon arrival, the operator identifies the specific Point of Interest (POI) directly from the real-time video feedback at the ground control station. From this point onward, the system autonomously plans and executes precise arm motions to position the end-effector onto the selected POI, maintains stable contact during data acquisition, and relays inspection data back to the ground station.

The primary objective of this project is to design and implement an aerial robotic inspection system capable of performing multiple high-precision contact-based NDT measurements within a single flight while maintaining stability under realistic environmental disturbances such as wind. Specifically, Flying Hand aims to achieve up to five contact-based NDT measurements per flight, reducing inspection time, cost, and risk while laying the foundation for future fully autonomous aerial inspection systems.

2 Use Case



Figure 1: Operator manually flies Flying Hand to the area of interest (AOI)

To illustrate the intended operation of the Flying Hand system, this section presents a representative use case drawn from common industrial inspection scenarios.

A maintenance team prepares for a routine inspection of an industrial structure, such as a chimney or a similar large asset, while normal facility operations remain uninterrupted. Traditional inspection methods would require

scaffolding, rope access, or partial shutdown of the facility, increasing cost and operational disruption. Instead, the team deploys the Flying Hand system from a staging area near the asset.

A trained operator initializes the system, which consists of a ground control station, remote controller, and the Flying Hand aerial robot, and performs standard preflight checks. Once initialization is done, the operator manually flies the Flying Hand toward the structure using the remote controller while monitoring video streamed from the onboard cameras. As the drone approaches the area of interest on the structure, the operator uses the onboard camera to survey the structure, identify potential regions of interest, and plan an efficient inspection sequence.



Figure 2: Flying hand autonomously performs contact-based NDT at the point of interest (POI)

Once done surveying, using the ground control station interface, the operator selects a specific point of interest directly on the video feed. At this stage, control is shifted from manual navigation to autonomous manipulation.

After the point of interest is selected by the user, Flying Hand autonomously plans a collision-aware arm trajectory and guides the end-effector toward the selected point of interest on the structure's surface. The system establishes controlled contact between the contact-based NDT probe and the asset while actively compensating for disturbances such as wind. Throughout the measurement process, the aerial platform and manipulator work in coordination to maintain stable end-effector contact, ensuring consistent data acquisition.

Once contact is established, the NDT sensor performs the inspection while measurement data is recorded onboard and transmitted to the ground control station in real time. This immediate feedback allows the maintenance team to assess inspection results as they are collected. If additional inspection points are required, the operator manually repositions the drone to another area of interest and selects a new point of interest from the video feed. The autonomous manipulation and inspection sequence is then repeated. After completing the scheduled inspection cycle, the operator manually flies Flying Hand back to the launch area.

By enabling rapid, contact-based inspection without disrupting ongoing operations or exposing personnel to hazardous environments, Flying Hand provides maintenance teams with timely, actionable inspection data. This allows potential issues to be identified early and maintenance activities to be planned proactively, reducing downtime, cost, and safety risk compared to conventional inspection methods.

3 System-Level Requirements

Our system-level requirements began with identifying the fundamental challenges of performing contact-based NDT using an aerial robotic system. Through multiple iterations of discussion with the CMU AirLab aerial manipulation team and external domain users familiar with NDT processes, we refined the high-level goals and operational constraints of the Flying Hand system. These insights were organized into an Objective Tree, which helped structure the problem into clear functional objectives, performance expectations, and non-functional considerations. By evaluating these objectives against our available resources, technical feasibility, and team expertise, we consolidated them into a focused and achievable set of system-level requirements. The following tables summarize the resulting mandatory and desirable functional, performance, and non-functional requirements that will guide the design and validation of the Flying Hand system.

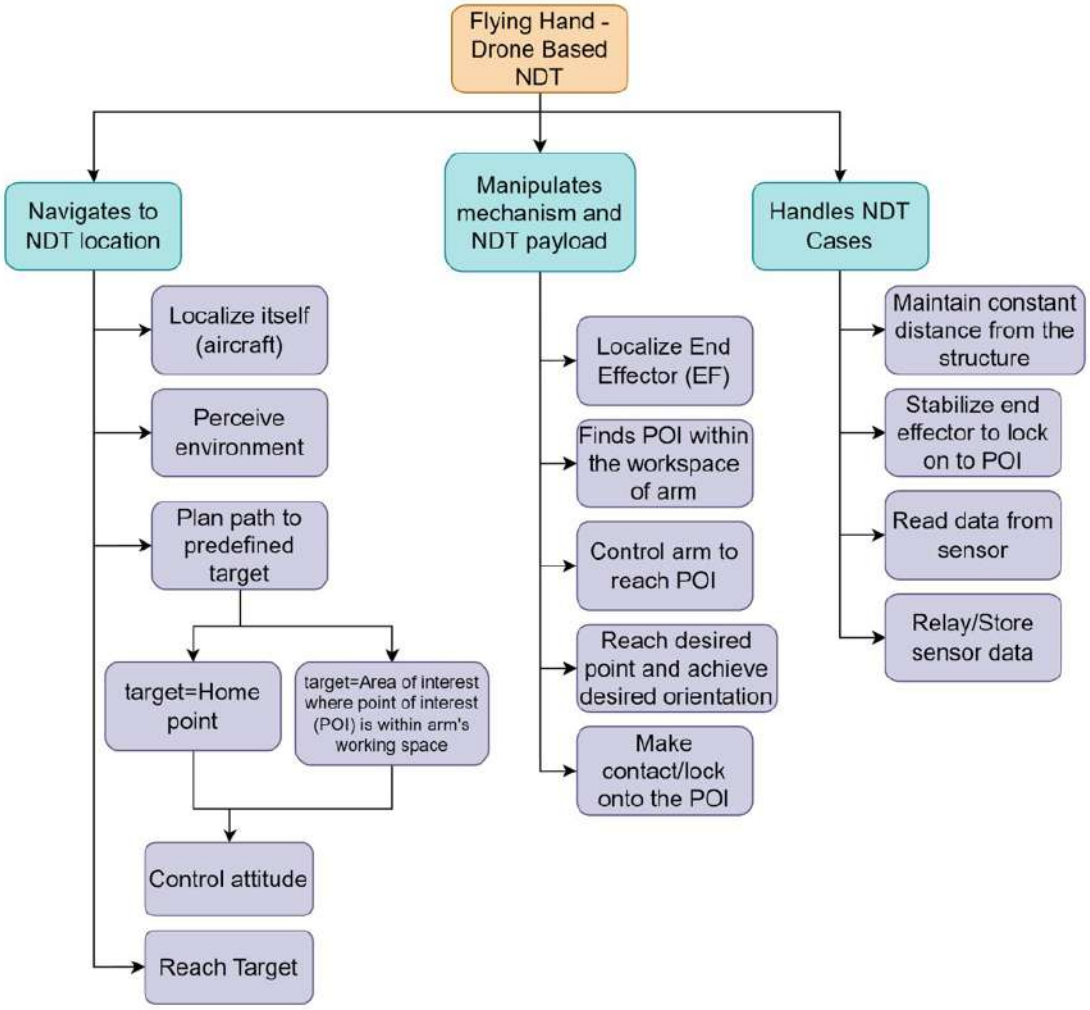


Figure 3: Objective Tree

3.1 Mandatory Functional Requirements

Table 1: Mandatory Functional Requirements

ID	Description
M.F.1	The system shall sense the surrounding environment.
M.F.2	The system shall localize its own pose relative to the environment.
M.F.3	The system shall allow an operator to manually pilot the Flying Hand to an Area of Interest (AOI).
M.F.4	The system shall provide real-time visual feedback to the operator.
M.F.5	The system shall allow the operator to define a Point of Interest (POI) from the video feed.
M.F.6	The system shall autonomously plan arm motion to reach a selected POI.
M.F.7	The system shall manipulate the end-effector to establish contact with the POI.
M.F.8	The system shall maintain stable end-effector contact during NDT execution.
M.F.9	The system shall perform contact-based non-destructive testing.
M.F.10	The system shall store and relay NDT data to the ground station.
M.F.11	The system shall execute a fail-safe response upon loss of communication.

3.2 Mandatory Performance Requirements

Table 2: Mandatory Performance Requirements

ID	Metric
M.P.1	The system shall sense the environment within the range of 0.5–4 m[1] from the Flying Hand.
M.P.2	The system shall localize its position with an error of at most 5 cm under nominal conditions.
M.P.3	The Flying Hand shall navigate at speeds up to 1 m/s during manual flight.
M.P.4	The system shall detect a POI from a distance of at least 0.6 m.
M.P.5	The system shall maintain end-effector positioning accuracy within ± 10 cm during contact-based NDT.
M.P.6	The system shall maintain stable contact under wind disturbances up to 3 m/s.
M.P.7	The system shall complete at least 5 NDT measurements in a single flight.
M.P.8	The system shall relay data to the ground station with latency not exceeding 100 ms.
M.P.9	The system shall execute a fail-safe response within 1 s of communication loss.

3.3 Mandatory Non-Functional Requirements

Table 3: Mandatory Non-Functional Requirements

ID	Description
M.N.1	The system shall be modular to allow rapid probe or end-effector replacement.
M.N.2	The total take-off mass shall not exceed 15 kg.
M.N.3	The system shall be operable by a trained operator with minimal setup time.
M.N.4	The system shall store NDT data in standard reusable formats.
M.N.5	The system shall operate in temperatures from $-5°$C to $40°$C and humidity up to 95%.

3.4 Desirable Functional Requirements

Table 4: Desirable Functional Requirements

ID	Description
D.F.1	The system may employ deep learning to identify points of interest.
D.F.2	The system may adapt manipulation strategies based on surface characteristics.
D.F.3	The system may have autonomous capability in controlling Flying Hand to the area of interest instead of manual teleoperating.

3.5 Desirable Performance Requirements

Table 5: Desirable Performance Requirements

ID	Metric
D.P.1	The system may perform more than 5 NDT measurements in a single flight.
D.P.2	The system may maintain contact stability under wind disturbances exceeding 3 m/s.
D.P.3	The system shall maintain end-effector positioning accuracy within $\pm$ cm during contact-based NDT.

4 Functional architecture

The functional architecture describes what the Flying Hand system does, independent of any particular hardware or software implementation. It is derived from the system use cases and functional requirements.

Figure 4 illustrates the main functional blocks and information flows for the aerial NDT mission. The system is bounded on the left by system inputs and on the right by system outputs. At the top, a Communicates function provides the bidirectional information link between the Flying Hand platform and the ground station, as well as internal messaging between functional blocks.

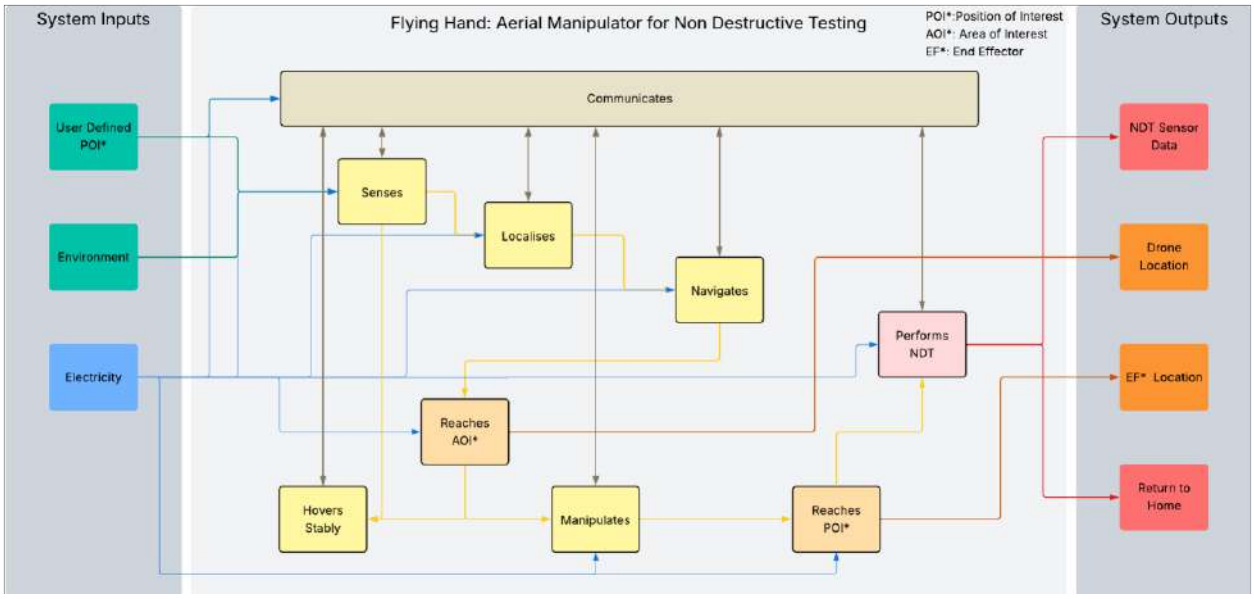


Figure 4: Functional Architecture

4.1 System Inputs and Outputs

System inputs include:

- **User-defined POI / mission plan:** Operator-specified points or areas of interest (POI/AOI), inspection waypoints, and mission parameters provided via the ground station.
- **Environment:** The external world in which the drone operates, including terrain, obstacles, wind, ambient lighting, and the inspected structure itself.
- **Electricity:** Energy supplied by the onboard power system, enabling all sensing, computation, actuation, and communication functions.

System outputs include:

- **NDT sensor data:** Raw and processed inspection measurements suitable for storage, post-processing, and maintenance decision-making.
- **Drone location:** The estimated pose of the drone in a global or mission-referenced frame, for logging, supervision, and safety monitoring.
- **End-effector location:** The estimated pose of the manipulator end-effector relative to the inspected structure, used for quality assurance and to verify coverage of POIs.
- **Return to home:** Confirmation that the system has safely returned to its starting location and ended the mission.

4.2 Core Functional Blocks

Within these boundaries, the Flying Hand functional architecture is decomposed into the following major functions:

- **Communicates:** Exchange commands and telemetry between the drone and the ground station throughout the mission. Distribute mission updates to internal modules and relays status, NDT results, and safety information back to the operator. Support both high-level supervisory control and low-latency feedback channels needed for safe operation.
- **Senses:** Acquire data from exteroceptive sensors observing the environment and inspected structure, as well as proprioceptive sensors measuring drone and arm states. Provide processed observations that feed into Localizes, Navigates, and manipulation functions. Implement filtering and basic quality checks to ensure robustness to noise and environmental disturbances.
- **Localizes:** Estimate the state of the drone in a global or mission frame by fusing onboard sensor data. Determine the relative location of AOIs and POIs with respect to the drone and manipulator workspace. Output state estimates and uncertainty bounds to Navigates, Reach AOI, and Reach POI to enable accurate positioning.
- **Navigates:** Plan and update the drone's trajectory from launch to the AOI, and between multiple inspection waypoints, using mission goals from Communicates and state estimates from Localizes. Generate feasible reference paths that respect vehicle dynamics, keep safe separation from obstacles, and maintain appropriate stand-off distance to the structure. Command low-level motion control functions to follow these paths at speeds compatible with inspection accuracy and safety.
- **Hovers stably:** Maintains a stable flight condition when the drone is near the inspected structure and the arm is actively manipulating. Rejects disturbances to keep the platform within an allowable position and attitude envelope. Provides a quasi-static base on which the manipulator can reliably reach the POI and perform NDT.
- **Reaches AOI:** Refines the drone's position and orientation to bring the AOI into the manipulator's workspace while respecting safe distances to the structure. Uses feedback from Senses and Localizes to close the loop on the desired inspection pose.
- **Manipulates:** Plan and execute arm joint motions that move the end-effector from a neutral configuration to a configuration capable of reaching the POI. Enforce joint limits, collision avoidance with the drone and structure, and dynamic constraints so as not to destabilize the platform. Coordinate with Hovers stably to manage coupling between arm motion and vehicle attitude.
- **Reaches POI:** Perform the fine positioning of the end-effector relative to the POI, based on local sensing and localization feedback. Achieve the required contact force, orientation, and positioning accuracy specified by the NDT technique. Signal readiness to the Performs NDT function once the POI is correctly reached.
- **Performs NDT:** Execute the selected NDT procedure according to mission parameters. Collect, time-stamp, and organize NDT measurements along with associated location and configuration metadata. Stream NDT results to the ground station via Communicates or stores them onboard for later retrieval.
- **Return to Home:** After completing inspection tasks, return to preset position.

5 System and Subsystem Level Trade Study

To determine the optimal system architecture for Flying Hand, we conducted a multi-level trade study. This analysis progressed from high-level system selection for performing Non-Destructive Testing (NDT) to specific subsystem selections for the drone platform and manipulator arm.[2]

5.1 System-Level Trade Study: Non Destructive Testing (NDT) Method

The initial system level trade study compared four distinct methods for performing NDT tasks: human inspectors, wheeled wall-climbing robots, arm-mounted legged robots, and arm-mounted aerial robots.

Selection Criteria was based on eight weighted criteria, with the top priorities being:

- **Workspace Reachability (20%):** Defined as the ability to access the workspace thoroughly.
- **Safety (15%):** The minimization of fatality risks or injuries during the NDT process.
- **Time Efficiency (15%):** The total time required for preparation (e.g., scaffolding) and execution.

		Non Destructive Testing (NDT) Methods			
		Human	Wheeled Wall-Climbing Robot	Arm Mounted Legged Robot	Arm Mounted Aerial Robot
					
Value Ratings 1: Inadequate 2: Tolerable 3: Adequate 4: Good 5: Excellent					
Criteria	**Weighting**	**Value(1-5)**			
Workspace Reachability	20%	2	3.5	1	5
Safety	15%	1	5	5	5
Time Efficiency	15%	2.5	4	4	5
Operational Cost	15%	1	2	3	4
Task Versatility	10%	2.5	2	2	4
Dexterity	10%	5	2.5	3.5	4
Robustness to Uncertainty	10%	5	3	3	2.5
Environment Tolerance	5%	1	3.5	3	2.5
Weighted Average	**100%**	**2.375**	**3.275**	**3**	**4.275**

The Arm-Mounted Aerial Robot achieved the highest weighted average score of 4.275/5. It excelled in workspace reachability because it can access structures thoroughly without physical contact or supporting infrastructure, significantly improving safety and efficiency. Based on this analysis, the Arm-Mounted Aerial Robot was selected as the system-level solution.

5.2 Subsystem Level Trade Study 1: Drone Platform

Following the system selection, we evaluated potential aerial platforms. Candidates included standard Quadcopters, Hexacopters (e.g., Phoenix/Hexsoon 650), Fully-Actuated Omnidirectional frames (e.g., DIM100), and a Modified Tarot X6 configuration.

Key Selection Criteria for the platform included:

- **Degrees of Freedom (20%):** Critical for the vehicle's ability to orient the NDT instrument against a surface.
- **Payload Capacity (15%):** Ensuring sufficient thrust to carry the manipulator and sensor suite.
- **Ease of Reconstruction (15%):** The ability to repair or rebuild the system quickly after potential accidents.

		Platform				
		Quadcopter		Hexacopter	Fully-Actuated	Omni-Directional
		Pheonix (Hexsoon 650)	DJI M100	Tarrot X6	Modified Tarrot X6	
Value Ratings 1: Inadequate 2: Tolerable 3: Adequate 4: Good 5: Excellent						
Criteria	**Weighting**	**Value(1-5)**				
Degrees-of-freedom	20%	2	2	2	**4.5**	5
Payload Capacity	15%	3	3.5	4.5	**3.5**	2
Ease of Reconstruction	15%	4	4	4	**4**	1
Autopilot Firmware Support (open-source)	15%	5	5	5	**5**	2
Control Complexity	15%	5	5	5	**4**	3
Flight Time	10%	2	3	4	**3**	2
Cost	5%	5	5	5	**5**	2
Size	5%	5	4.5	4	**4**	4
Weighted Average	**100%**	**3.65**	**3.8**	**4.025**	**4.125**	**2.7**

The Modified Tarot X6 achieved the highest weighted score of 4.125/5. It balances the high payload and redundancy of a hexacopter with the dexterity of a fully actuated system, while remaining easy to reconstruct due to the availability of standard parts. Construction feasibility revealed that fully actuated performance could be achieved by modifying a standard Tarot X6 frame. By altering the motor orientation on this widely available hexacopter frame, we can achieve 6-DOF capabilities without the complexity of a custom build. The Modified Fully-Actuated Tarot X6 was selected as the drone platform.

5.3 Subsystem Level Trade Study 2: Manipulator Arm

The final trade study focused on the robotic arm required to position the NDT sensor. We evaluated 2-DOF, 3-DOF, and 4-DOF configurations.

Key Selection Criteria for the arm included:

- **Flexibility in Workspace (35%):** The ability to reach specific points with the desired attitude.
- **Arm Weight (20%):** Crucial for maintaining flight time; heavier arms require more counter-thrust from the drone.
- **Cost (15%) and Complexity:** More components generally correlate with higher cost and control difficulty.

		Arm		
		2 DOFs	3 DOFs	4 DOFs
Value Ratings 1: Inadequate 2: Tolerable 3: Adequate 4: Good 5: Excellent				
Criteria	**Weighting**	**Value(1-5)**		
Flexibility in Workspace	35%	2	**4.5**	5
Arm Weight	20%	5	**4.5**	3
Cost	15%	5	**4.5**	2.5
Control Complexity	10%	5	**4**	2.5
Payload Capacity	10%	4	**3**	3
Ease of Construction	10%	5	**4.5**	3.5
Weighted Average	**100%**	**3.85**	**4.3**	**3.625**

The 3-DOF arm achieved the highest weighted average of 4.3/5. It represents the optimal trade-off, providing sufficient dexterity for full-scale NDT tasks while maintaining a manageable weight profile to maximize flight time. The 3-DOF arm is the selected design for the final system. However, to mitigate risk and allow for incremental validation of the flight platform, implementation will be phased:

- **Phase 1 (Spring Semester):** A static, protruding stick with an NDT probe end-effector will be used for validation.
- **Phase 2 (Fall Semester):** The fully actuated 3-DOF arm will be integrated to provide the necessary dexterity for complex surface NDT.

6 Cyberphysical architecture

The cyberphysical architecture of our aerial manipulation system is illustrated in Figure 5.

At the top level, the platform communicates through multiple channels. HereLink telemetry with MAVLink is used for data transmission between the drone, ground station, and onboard computer. A 2.4 GHz RC controller provides manual control when needed, while Wi-Fi enables inter-drone communication and debugging. Physical wiring is used for internal onboard data exchange. Together, these communication interfaces ensures that sensing, navigation, and testing modules remain synchronized throughout flight operations.

Beneath the communication layer, the system is structured into several major functional components.

First, the drone perceives the environment using a suite of sensors, including an RGB-D camera, IMU, downward-facing RGB and LiDAR units, and RTK for high-precision positioning. These sensors collectively provide depth information, motion cues, and accurate altitude and localization data.

Next, the system performs target localization through deep-learning-based detection, while the drone's pose is computed using visual-inertial odometry. This dual-localization strategy enables accurate estimation of both the target's position and the UAV's relative pose with respect to the Area of Interest (AOI) and Point of Interest (POI).

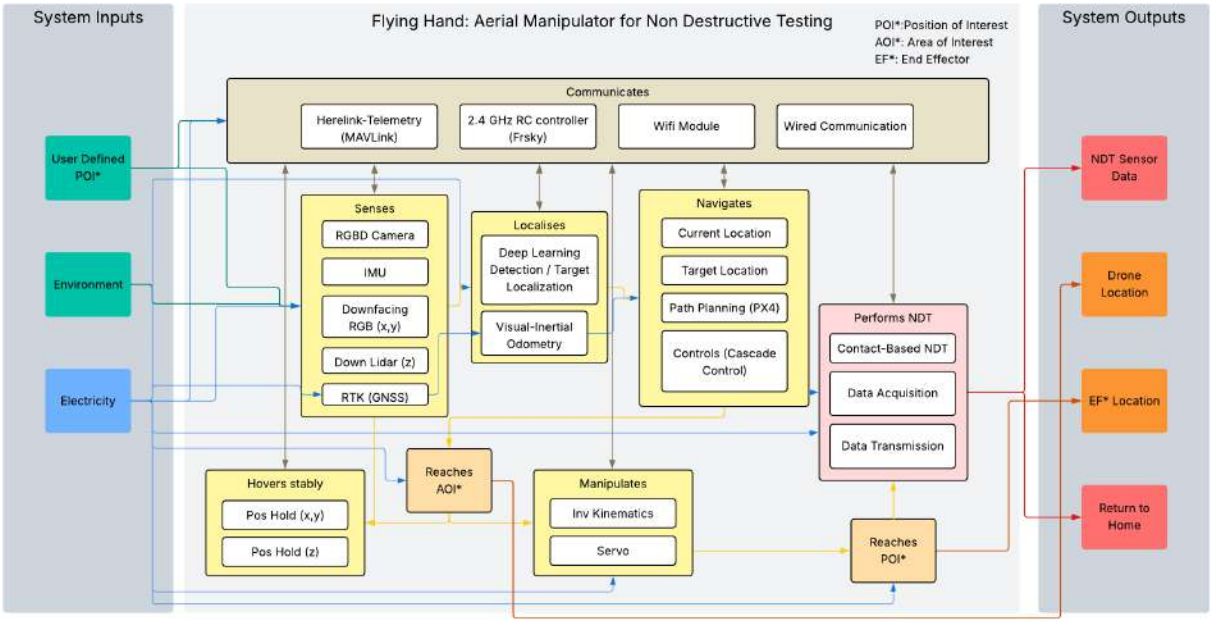


Figure 5: Cyberphysical Architecture

The navigation module then processes this information to generate motion commands. It determines the current state and goal state, plans an appropriate flight trajectory using PX4's control framework, and ensures stable maneuvering through a cascaded control structure.

In parallel, the hovering subsystem maintains precise position hold in both horizontal and vertical axes, ensuring stability during inspection and manipulation tasks.

Upon reaching the AOI, the manipulation subsystem activates. Using inverse kinematics and servo-based actuation, it positions and orients the end effector with high precision to align with the inspection surface.

Finally, the system executes Non-Destructive Testing (NDT) procedures, including contact-based NDT, data acquisition, and data transmission. The resulting inspection data are transmitted back to the ground station for monitoring and analysis.

In summary, the integrated architecture enables the system to sense, localize, navigate, manipulate, and communicate seamlessly, supporting contact based Non Destructive Testing (NDT) operations.

7 Subsystem Description

7.1 Communication

The communication subsystem serves as the link between the aerial platform, the ground station, and the onboard computer.

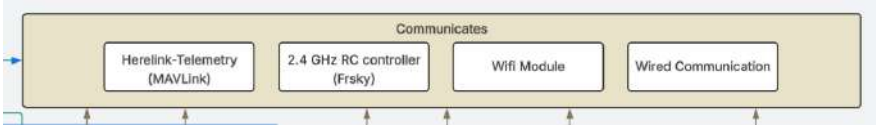


Figure 6: Communication Block

- The system utilizes **HereLink telemetry** operating via the **MAVLink protocol** to establish a robust data link that handles real-time transmission of flight status and sensor data to the ground station.
- A **2.4 GHz RC controller (FrSky)** provides a dedicated, low-latency link for manual teleoperation by the pilot and safety overrides.
- A **Wi-Fi module** is integrated for high-bandwidth connectivity during ground debugging.
- Internally, **physical wiring** connects the onboard sensors and computing units to ensure reliable data transfer.

7.2 Sensing

The sensing subsystem provides the raw inputs required for environmental awareness and state estimation. It synthesizes heterogeneous data streams from a multi-modal sensor array:

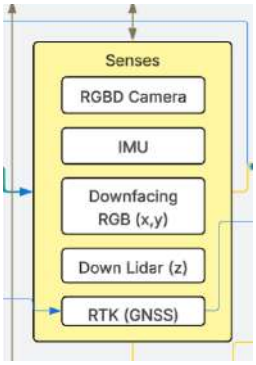


Figure 7: Sensing Block

- An **RGB-D camera** captures color and depth information, while **down-facing RGB sensors** provides data necessary for **optical flow** function which is used for velocity estimation and position holding.
- An **IMU** tracks acceleration and rotational rates.
- Altitude is precisely measured using a **down-facing LiDAR** (z-axis).
- Global positioning is secured via **RTK (GNSS) modules**.

These sensors collectively allow the drone to perceive depth, motion, and absolute altitude with high precision.

7.3 Localization

The localization subsystem processes sensor data to estimate the drone's position relative to both the global frame and the inspection target.

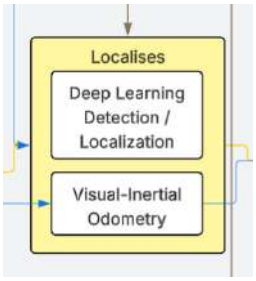


Figure 8: Localization Block

Self-Localization:

- The system fuses data from the **RTK (GNSS)** and the **Visual-Inertial Odometry (VIO)** pipeline to estimate the drone's position and orientation (pose).
- VIO uses camera and IMU data to track relative motion and orientation.
- The RTK module provides absolute global reference, ensuring centimeter-level positioning accuracy during outdoor flight.

Target Localization:

- The system plans to employ **deep-learning-based detection algorithms** to identify the Point of Interest (POI) and Area of Interest (AOI).
- These algorithms estimate the target's relative location for inspection.

7.4 Navigation

The navigation subsystem acts as the central controller for flight execution.

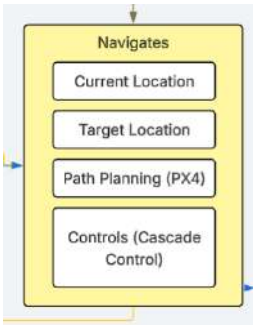


Figure 9: Navigation Block

- **Path Planning:** Identifies the current state and the target location, generating optimal flight trajectories using the **PX4 flight stack**.
- **Flight Control:** Maintains flight stability through **cascade control** loops that sequentially regulate position, velocity, and attitude.

7.5 Hover Stably

This subsystem is a specialized control block dedicated to stable-keeping, which is critical for effective NDT operation.

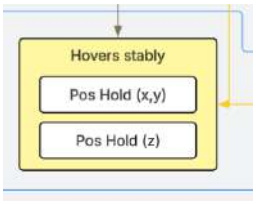


Figure 10: Hover Stably Block

- By integrating **optical flow** and **LiDAR** data, the system performs active Position Hold in x, y, and z axes.
- This minimizes drift, providing a stable floating base for the manipulator.

7.6 Manipulation

Once the drone establishes a stable hover at the AOI, the manipulation subsystem controls the motion of the robotic arm.

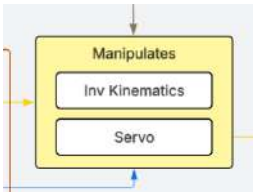


Figure 11: Manipulation Block

- The onboard computer calculates the required joint angles via **Inverse Kinematics (IK)** to align the end-effector with the inspection surface.
- **Servo motors** actuate these joint angles for precise probe placement.

7.7 Perform NDT

The final subsystem executes the mission payload operations.

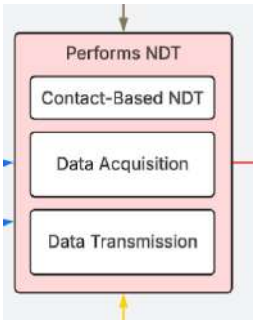


Figure 12: Perform NDT Block

- The system performs **contact-based NDT** using the probe to acquire inspection data.
- The acquired data and defect location are transmitted back to the ground station for analysis.

8 Project Management

8.1 Work plan and tasks

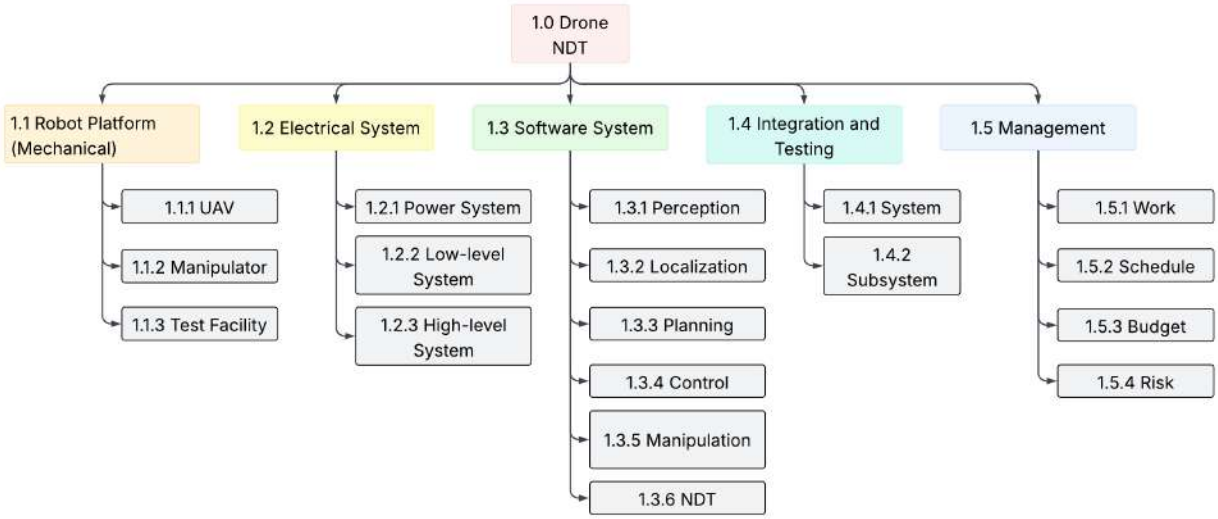


Figure 13: Work Breakdown Structure (WBS)

According to Figure 13, the Work Breakdown Structure (WBS) for the Drone NDT project is summarized as follows. Our WBS is product-oriented. At the top level, the project is divided into five major components: Robot Platform (Mechanical), Electrical System, Software System, Integration and Testing, and Management.

At Level 2, each component is further decomposed into its primary functional elements. The Robot Platform consists of the UAV, the manipulator, and the test facility. The Electrical System includes the power system, the low-level system, and the high-level system. The Software System is structured into six modules: perception, localization, planning, control, manipulation, and NDT. While each module undergoes unit testing, the project also requires

comprehensive system-level and subsystem-level integration and testing, which are captured under the Integration and Testing component. The Management component is organized into four categories: work, schedule, budget, and risk.

At Level 4, the Level 3 components are further decomposed into specific processes. Most of these processes follow a design–build–test–integrate workflow.

8.1.1 Hardware

For the Robot Platform, the first subsystem is the UAV. We redesign the existing UAV airframe into a fully actuated drone and subsequently build the required UAV modules. After construction, we conduct flight performance and reliability testing before integrating the complete UAV system.The second subsystem is the manipulator. Since no off-the-shelf arm meets our requirements, we design the manipulator in-house and select an appropriate NDT probe for the inspection tasks. We then build the actuation components and joint assemblies. Following assembly, we test the manipulator and integrate its firmware with the system.To support the final project demonstration, we also design and construct a dedicated test facility as the third part of the Robot Platform.

For the Electrical System, the first subsystem is the power system, which includes the battery, PDB, ESCs, and motors. We design and build the power distribution and electrical harness assemblies. After assembly, we test power delivery stability and thermal performance, followed by subsystem integration.Next is the low-level system, which consists of the flight controller (FC), remote controller (RC), and telemetry. We design the control and communication modules, evaluate control response, link reliability, and signal latency, and then integrate all control and communication components.Finally, the high-level system includes the companion computer and onboard sensors. We design and build the sensor modules and mechanical mounts, then test sensor accuracy, latency, and robustness. The last step is integrating the sensors with the middleware and mission-level software stack.

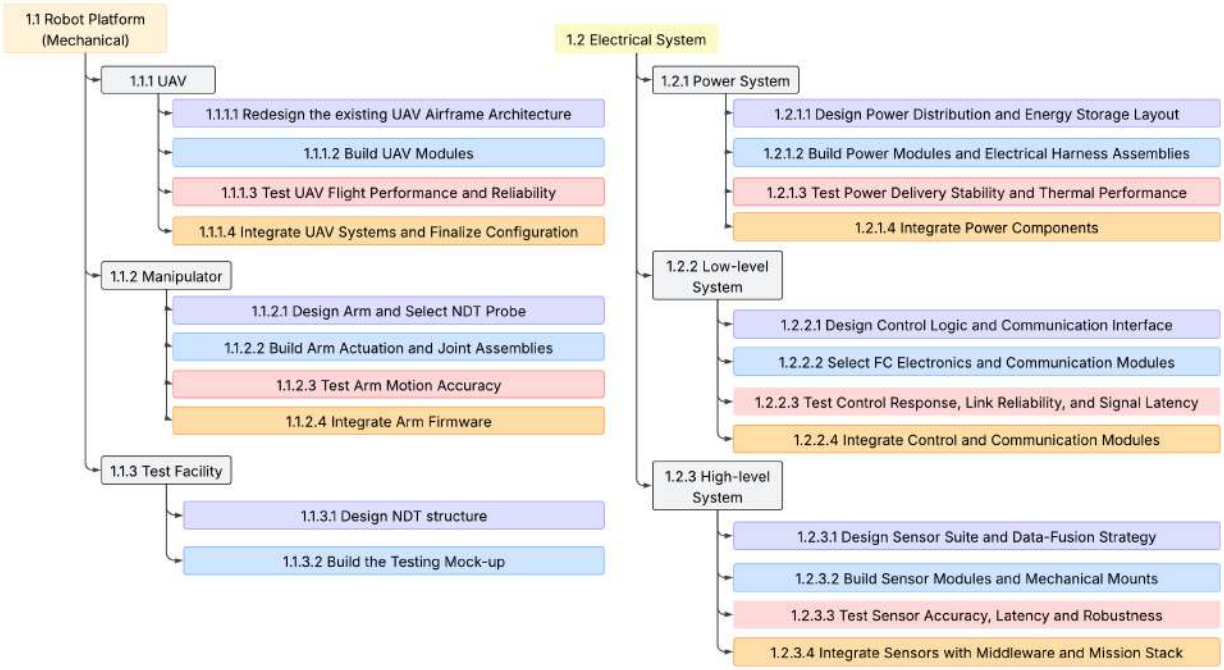


Figure 14: WBS - Hardware

8.1.2 Software

For the Software System, the perception module requires the design and implementation of data-processing pipelines and perception algorithms. Because the drone must localize both itself and the inspection target, we develop separate localization frameworks and corresponding processing pipelines.The planning and control module involves designing and implementing PX4-compatible planning and control algorithms to ensure reliable autonomous flight. For the manipulation module, we design the manipulation algorithms, develop the corresponding kinematics solvers, and build the servo execution modules needed for precise end-effector motion.Each software module undergoes testing for accuracy, robustness, and latency, followed by integration with the overall system.

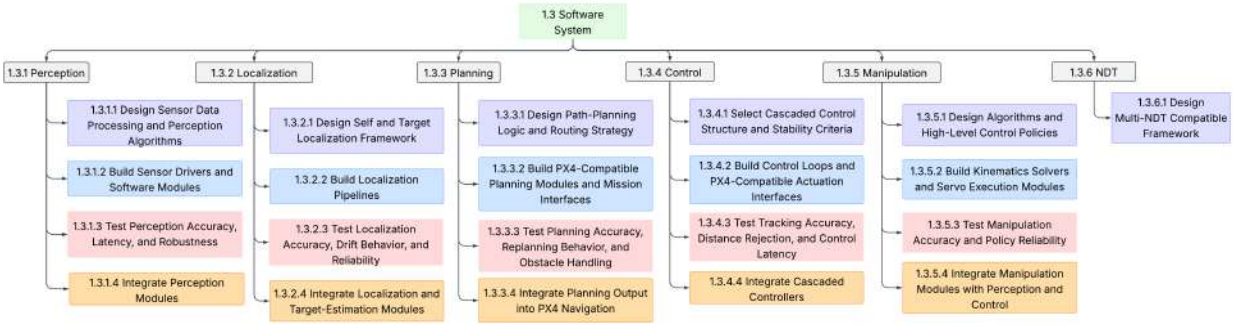


Figure 15: WBS - Software

8.2 Schedule

We are managing the project using industry tools like Asana to breakdown tasks, assign them and track them. We plan to follow bi-weekly sprints to track deliverables. A detailed Gantt Chart for our schedule is attached below.

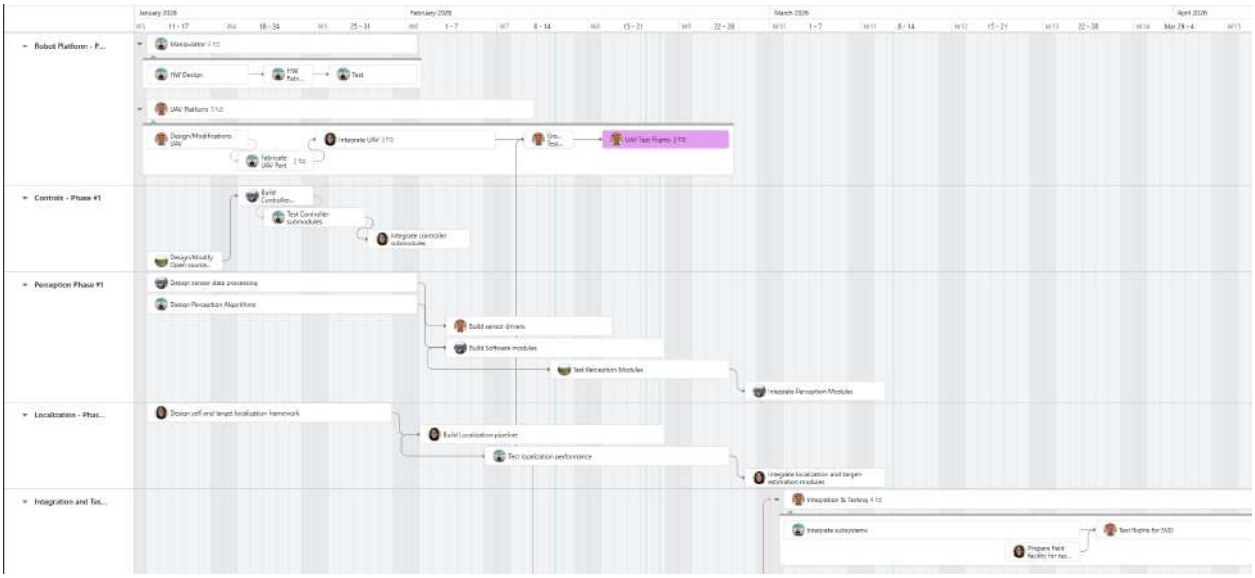


Figure 16: Spring 2026 Schedule

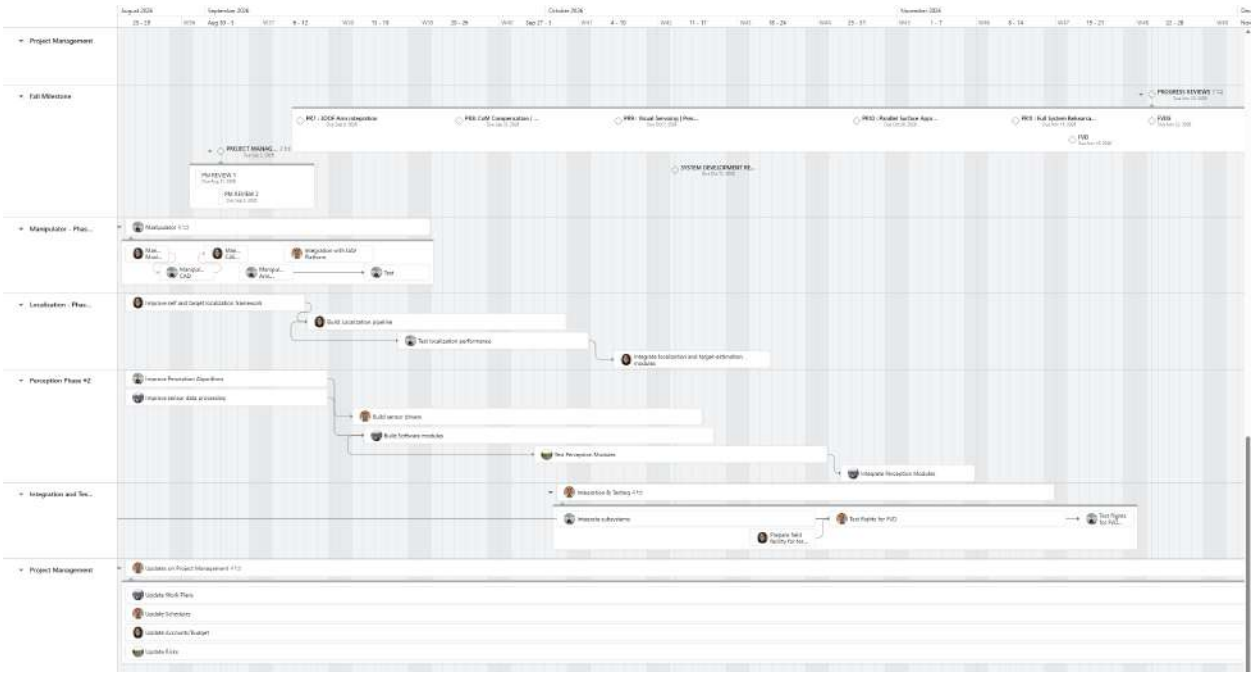


Figure 17: Fall 2026 Schedule

8.2.1 Key Milestones

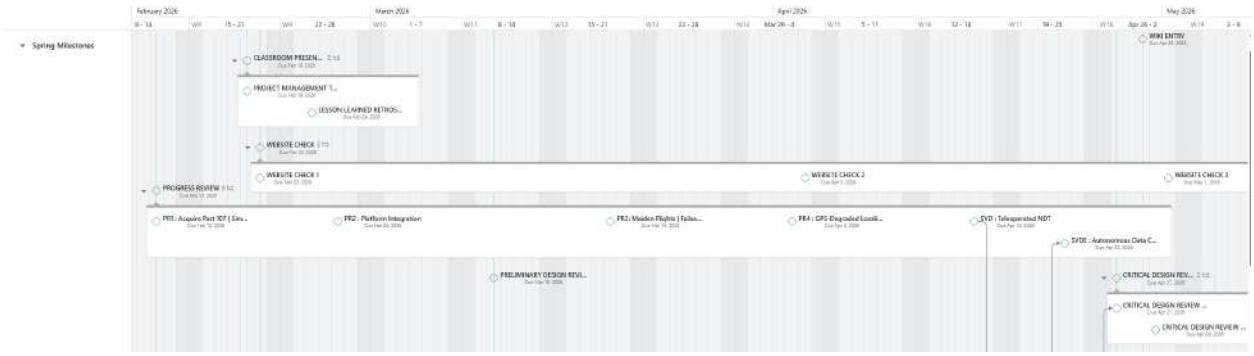


Figure 18: Spring 2026 Milestones

Spring 2026: Foundation & Safety

Focus: The primary objective is to establish “Airworthiness” and “Basic Functionality,” along with safety stack validation, and GPS-degraded operation.

Table 6: Spring 2026 Project Milestones: Foundation & Safety

Date	Milestone	Deliverables (Evidence)
Feb 12 (PR 1)	1. Acquire Drone License 2. Simulation Operational	**A.** Copy of FAA Part 107 Cert[3]. **B.** Video of drone in Gazebo responding to velocity commands.
Feb 26 (PR 2)	3. Platform Integration *(Bench Tests)*	**A.** Bench Test Video: Motors spinning, arm actuating, sensors streaming. **B.** Electrical Integration Report.
Mar 19 (PR 3)	4. Maiden Flight (Manual) 5. Failsafe Validated	**A.** Flight Video: Manual takeoff/landing in cage. **B.** Safety Log: Video of "Kill Switch" cutting power (PR.10).
Apr 2 (PR 4)	6. GPS-Denied Localization	**A.** Rviz Capture: Camera feed vs. position map in steel structure. **B.** Drift Analysis Plot: 60s hover without GPS.
Apr 16 (Spring Val 1)	7. Teleoperated NDT	**A.** Live Demo: Pilot flies to wall, makes contact (compliant arm), holds. **B.** Data Viz: Graph showing NDT sensor data.
Apr 23 (Spring Val 2)	8. Autonomous Data Collection	**A.** Autonomous Demo: (Takeoff $\rightarrow$ Contact $\rightarrow$ Return). **B.** Validation Checklist: FR.1–FR.12 met. **C.** Processed NDT Report (NFR.4).
Apr 27 (CDR)	Critical Design Review	**A.** CDR Slide Deck: Spring summary & Fall design plan.

Fall 2026: Advanced Capabilities

Focus: The fall semester focuses on "Complexity" and "Precision," integrating the 3-DOF manipulator and Visual Servoing.

Table 7: Fall 2026 Project Milestones: Advanced Capabilities

Date	Milestone	Deliverables (Evidence)
Sep 9 (PR 7)	1. Mechanical Integration *(3-DOF Arm)*	**A.** Hardware Demo: Arm moving via onboard computer. **B.** Mass Properties Report: Final CoM calculation.
Sep 23 (PR 8)	2. CoM Compensation 3. Dynamic Stability	**A.** Disturbance Rejection Video: Hover ($\pm 2^\circ$) during arm movement. **B.** Flight Log: Control effort (Compensator On vs. Off).
Oct 7 (PR 9)	4. Visual Servoing 5. Precise POI Lock	**A.** "Lock-On" Demo: Hold position using only camera. **B.** Error Plot: Pixel error converging to zero.
Oct 28 (PR 10)	6. Parallel Surface Approach 7. High-Speed Nav	**A.** Ceiling/Floor Test: Autonomous approach. **B.** Telemetry Log: Verifying 1 m/s velocity (PR.3).
Nov 11 (PR 11)	8. Full System Rehearsal 9. Metric Validation	**A.** Dry Run Video: Full mission with visual servoing. **B.** Accuracy Report: Ground truth of 5cm accuracy (PR.2).
Nov 16 (FVD)	10. Fall Validation Demo	**A.** Live Demo: Autonomous NDT on complex geometry. **B.** FVD Scorecard: Verified Fall requirements.

8.3 System validation demonstrations

8.3.1 Spring Validation Demo (SVD)

Concept of Operations: The SVD verifies the system's ability to operate in a GPS-degraded industrial setting (Mill 19). The primary goal is to demonstrate autonomous localization and physical contact with a vertical surface using a static (0-DOF) compliant arm.

Table 8: Spring Validation Demo (SVD) Plan

Steps to Evaluate	Evaluated Requirements
1. Setup & Transport: Verify system portability and setup speed at the Mill 19 facility.	**NFR.2** Lightweight (15 kg) **NFR.5** Compact **NFR.6** Adaptable
2. Teleoperation & Approach: Pilot navigates to the AOI. Responsiveness and video latency are verified.	**FR.5** Fly to AOI **FR.12** Comm. with GS **PR.5** Latency (< 100ms)
3. Autonomous Lock & Contact: Drone localizes relative to the structure, approaches, and maintains contact using the compliant probe.	**FR.1** Sense Env **FR.2** Localize (Functionality) **FR.6** Hover Stably **FR.10** Perform NDT **PR.7** Accuracy ($\pm$10cm)
4. Mission Cycle: Drone retreats safely, stores data, and repeats the cycle for multiple waypoints.	**FR.4** Plan Path **FR.11** Store/Relay Data **PR.6** Sample 5 Waypoints
5. Safety Test: Communication link is manually severed to verify immediate failsafe response.	**PR.10** Execute fail-safe (1s)

8.3.2 Fall Validation Demo (FVD)

Concept of Operations: The FVD extends the operational envelope to complex geometries (parallel surfaces) and dynamic payloads. It validates the high-precision requirements that necessitate the 3-DOF arm and Visual Servoing.

Table 9: Fall Validation Demo (FVD) Plan

Steps to Evaluate	Evaluated Requirements
1. Complex Geometry Approach: Drone detects and approaches parallel surfaces (ceiling/floor).	**FR.7** Detect POI Precisely **PR.1** Range Ver. (0.5–4m)
2. Precision Localization: Validation of position estimation against external ground truth.	**PR.2** Localize within 5cm
3. High-Speed Navigation: Drone traverses distant waypoints at max operational velocity.	**PR.3** Max Speed (1 m/s)
4. Dynamic Manipulation: Drone utilizes the 3-DOF arm to orient the probe while the flight controller compensates for the shifting CoM.	**FR.8** Plan Arm Motion **FR.9** Dynamic Manip. **PR.7** Accuracy (Moving Arm)

8.4 Responsibilities

Subsystem	Primary Owner	Secondary Owner
Hardware	Shubham	Tanaya
Odometry & Localization	Chenyang	Weerachai
UAV Controls	Shunxuan	Chenyang
POI Detection & Tracking	Tanaya	Shubham
Manipulation	Weerachai	Shunxuan
Autonomy	Shubham	Weerachai

8.5 Provisional parts list and budget

As some hardware selections have not been finalized, only estimated components and a preliminary purchase budget are provided here.

Component	Source	Cost	Quantity	Total Cost
Tarot X6 hex-rotor platform (frame, motors, propellers)	AirLab	0	1	0
Flight controller & avionics	AirLab	0	1	0
Ground GPS/RTK receiver and antenna	AirLab	0	2	0
Onboard GPS-RTK-SMA breakout	Self-purchase	259	2	518
Intel RealSense RGB-D depth camera	Self-purchase	424	1	424
Jetson AGX Orin 32GB	AirLab	0	1	0
HereLink HD video & telemetry link	AirLab	0	1	0
3DoF robotic arm	3D print	100	1	100
Robotic arm servo motor	Self-purchase	126	3	378
Carbon Fiber Tube	Self-purchase	78	2	156
RFD900 communication modules set	Self-purchase	310	1	310
NDT Sensor	TBD	TBD	1	TBD
TOTAL				1886

8.6 Risk management

This section identifies the major risks for the Flying Hand project and outlines our strategy to manage them. We selected five risks based on three risk levels, and for each provide an estimate of likelihood, impact, and key mitigation actions. An overview of the risks and their distribution is shown in Figure 19.

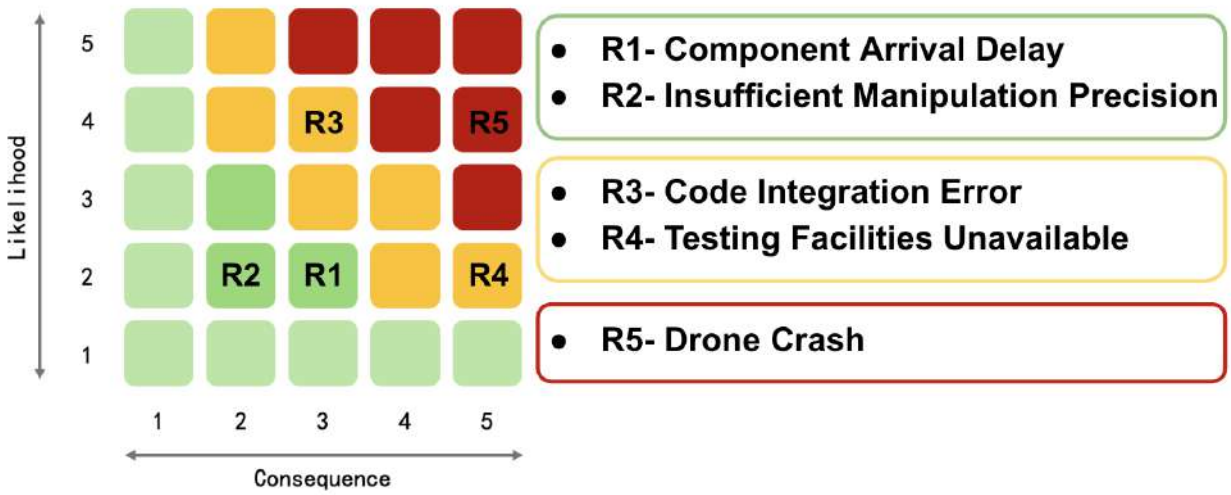


Figure 19: Risk Overview

The specific details and mitigation plans for each risk are as follows.

Risk 1: Component Arrival Delay (Likelihood: 2 Consequence: 3)

- **Description:** Ordered or printed parts cannot be obtained on time due to shipping or raw material issues
- **Type:** Schedule
- **Consequence:** Hardware setup cannot be completed, algorithm testing cannot be conducted
- **Mitigation Plan:** Order or build components in advance with buffer time. Prepare multiple sets of backup components in advance

Risk 2: Insufficient Manipulation Precision (Likelihood: 2 Consequence: 2)

- **Description:** The precision of robotic arm manipulation does not meet NDT requirements due to algorithm selection or experimental environment
- **Type:** Technology, Schedule
- **Consequence:** NDT cannot be performed normally, making function verification and demonstration impossible
- **Mitigation Plan:** Try using a tracking algorithm for the end effector to ensure precision. Select an experiment site with less external disturbance (such as wind)

Risk 3: Code Integration Error (Likelihood: 4 Consequence: 3)

- **Description:** The algorithms used are referred to open-source content, leading to difficulties in constructing and integrating the algorithm pipeline
- **Type:** Technology, Schedule
- **Consequence:** The software algorithm cannot be implemented, resulting in delays in subsequent integration and testing

- **Mitigation Plan:** Thoroughly investigate the input and output requirements of algorithms to identify integration challenges. Use clear API documentation, do weekly integration tests and version control with feature branches

Risk 4: Testing Facilities Unavailable (Likelihood: 2 Consequence: 5)

- **Description:** Unable to find a suitable real-world site for aerial NDT testing
- **Type:** Schedule
- **Consequence:** Unable to verify and demonstrate the aerial NDT, resulting in poor presentation outcomes or project delay
- **Mitigation Plan:** Conduct thorough research on internet, staff, and student information in advance of system-level testing. Identify potential sites and conduct on-site inspections

Risk 5: Drone Crash (Likelihood: 4 Consequence: 5)

- **Description:** The drone crashed during flight testing
- **Type:** Budget, Schedule
- **Consequence:** Damage to drones, robotic arms, or NDT sensors. Requires repurchase, reassembly, and recalibration
- **Mitigation Plan:** Conduct thorough simulation testing prior to flight experiments. Use safety facilities during testing (suspended safety ropes). Perform thorough pre-flight checks during each takeoff

References

[1] Intel Corporation. *Intel® RealSense™ D400 Series Product Family Datasheet*, January 2024. Revision 019.

[2] Mina Kamel, Sebastian Verling, Omar Elkhatib, Christian Sprecher, Paula Wulkop, Zachary Taylor, Roland Siegwart, and Igor Gilitschenski. The voliro omniorientational hexacopter: An agile and maneuverable tiltable-rotor aerial vehicle. *IEEE Robotics amp; Automation Magazine*, 25(4):34–44, December 2018.

[3] Federal Aviation Administration. Part 107 – small unmanned aircraft systems, 2016. Accessed: 2026-02-12.