

TeamC - Flying Hand

Aerial Manipulator for Non-Destructive Testing

Critical Design Review Report

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Abstract

Non-Destructive Testing (NDT) is a critical part of preventive asset maintenance for industrial infrastructure such as pipelines, transmission towers, and storage tanks, but conventional NDT remains expensive, slow, and hazardous due to scaffolding, rope access, and operational shutdowns. Flying Hand is an aerial robotic system that performs contact-based NDT by combining a fully-actuated hexarotor, a multi-DOF manipulator carrying a contact probe, GPS-denied visual-inertial localization, image-based visual servoing, and a wrench controller. A trained operator pilots the platform to an Area of Interest and selects a Point of Interest from a real-time video feed; the system then autonomously approaches the surface, establishes stable contact, regulates a target normal force, and relays inspection data to the ground station before retreating to the next inspection point. This Critical Design Review Report documents the team's spring-semester progress: design and build of a fully-actuated hexarotor with a tilted-rotor PX4 stack capable of stable position-hold flight; integration of an Isaac-ROS cuVSLAM-based VIO pipeline with EKF2 fusion enabling GPS-denied near-wall hover; deployment of a wrench controller that produces a steady $5\,\mathrm{N} \pm 1\,\mathrm{N}$ contact force in simulation; and a full Gazebo pipeline that takes off, visually servos to a circular Point of Interest, makes contact, and applies sustained force. We summarize the spring validation results, identify weaknesses in autonomous waypoint tracking under EKF2 fallback, present the fall test plan, refined work-breakdown structure, schedule, budget, and risk register, and outline the integration of the multi-DOF arm and on-aircraft visual servoing required to complete the system at the Fall Validation Demonstration.

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1 Project Description

Non-Destructive Testing (NDT) is the backbone of preventive asset maintenance for large-scale industrial infrastructure such as transmission towers, pipelines, storage tanks, chimneys, and processing plants. Despite its central role in safety and reliability, 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, making frequent inspection costly and disruptive.

To address these challenges, our team is developing Flying Hand, an aerial robotic manipulation system that performs contact-based non-destructive testing on hard-to-reach industrial assets. By combining a fully-actuated 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 a specific Point of Interest (POI) directly from the real-time video feed. 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 the 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. Flying Hand targets up to five contact-based NDT measurements per flight, reducing inspection time, cost, and risk.

2 Use Case



Figure 1: Flying Hand autonomously performs contact-based NDT at the operator-selected Point of Interest (POI).

A maintenance team prepares to inspect an industrial structure — such as a chimney, pressure

vessel, or elevated pipe rack — while the surrounding facility continues to operate. Conventional inspection would require scaffolding, rope access, or partial shutdown of the asset, all of which are expensive and disruptive. Instead, the team deploys the Flying Hand system from a staging area near the asset.

A trained operator initializes the system — ground control station, RC transmitter, and the Flying Hand aerial robot — and performs standard preflight checks. The operator manually flies the drone toward the structure while monitoring video streamed from the onboard cameras. As the drone approaches the AOI, the operator surveys the structure with the onboard camera, identifies candidate inspection points, and plans an efficient sequence.

Using the ground-control-station interface, the operator selects a Point of Interest (POI) directly on the video feed. At this point, control transitions from manual navigation to autonomous manipulation. Flying Hand plans a collision-aware end-effector trajectory and uses image-based visual servoing fused with a wrench controller to drive the probe onto the selected point on the structure's surface. The aerial platform and manipulator coordinate to maintain stable end-effector contact while compensating for wind disturbances, 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 station in real time (Figure 1). This immediate feedback allows the maintenance team to assess inspection results as they are collected.



Figure 2: Operational workflow for industrial pipeline contact NDT: takeoff, navigation to AOI, approach to POI, NDT contact, and progression to the next inspection point.

If additional inspection points are required, the operator manually repositions the drone to another AOI and selects a new POI, and the autonomous manipulation and inspection sequence is 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, allowing potential issues to be identified early and maintenance activities to be planned proactively. The end-to-end operational workflow — takeoff,

navigation to AOI, approach, NDT contact, retreat, and progression to the next POI — is summarized in Figure 2.

3 System-Level Requirements

The system-level requirements for Flying Hand were derived from a structured needs analysis: discussions with the CMU AirLab aerial-manipulation team and external NDT domain experts produced an objective tree (Figure 3 in the appendix) that organizes the high-level goals into navigation, manipulation, and NDT execution objectives. These objectives were filtered against feasibility, available resources, and team expertise to produce the following set of mandatory and desirable requirements.

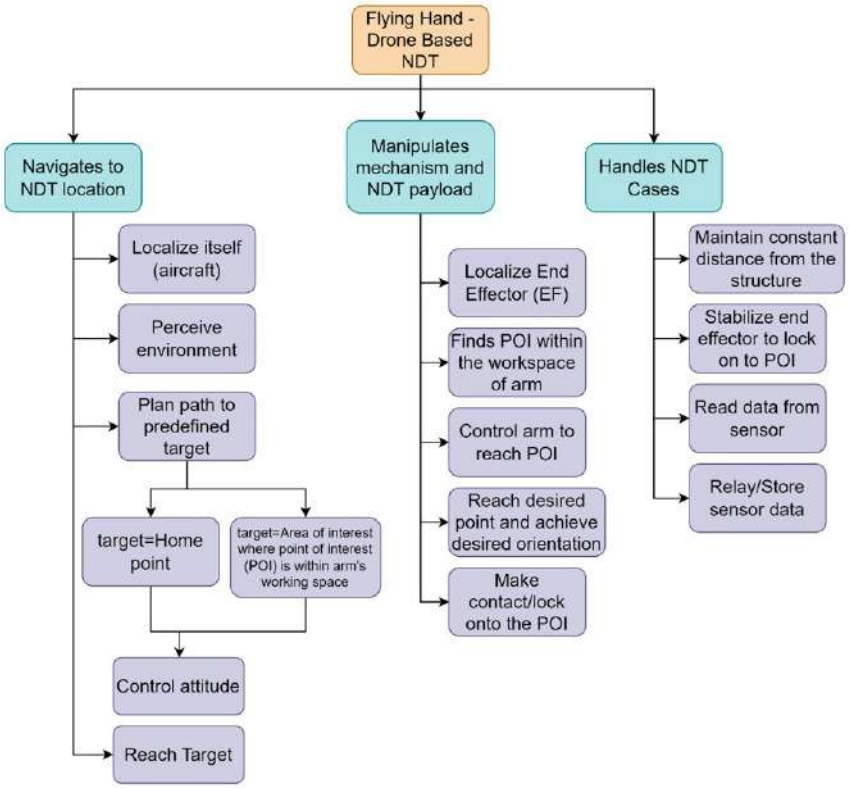


Figure 3: Three-level objective tree from which the system requirements were derived.

The requirements have been refined since the Preliminary Design Review (PDR). The following changes were made and are reflected in the tables below:

- **M.P.2 (Self-localization accuracy):** Relaxed from ± 5 cm to ± 10 cm. Spring testing of the Isaac-ROS cuVSLAM pipeline showed that under realistic flight conditions and EKF2

fusion, ± 5 cm accuracy could not be reliably maintained, while ± 10 cm is achievable and remains sufficient for the manipulator to close in via visual servoing.

- **M.P.4 (POI detection range):** Increased from 0.6 m to 2.5 m to match the verified effective range of the visual servoing controller in simulation, which improves the standoff distance available for safe approach.
- **M.P.5 (End-effector positioning accuracy):** Updated to ± 0.15 m during contact, which is the value validated in simulation for the wrench controller and is consistent with the size of the chosen POI target (150 mm diameter).
- **Subsystem-level allocation:** The mandatory requirements have been allocated across the four primary subsystems — UAV Platform (UAV), Localization & Perception (LOC), Manipulation (MAN), and Communication & Ground Station (COM) — to clarify ownership for the fall semester.

The mandatory functional and performance requirements are summarized in Table 1, with the responsible subsystem indicated. Mandatory non-functional requirements are listed in Table 2. Desirable functional and performance requirements are listed in Tables 3 and 4.

Table 1: Mandatory Functional and Performance Requirements

ID	Functional	Performance	Description	Sub.
M.F.1 / M.P.1	Sense the surrounding environment	Sense within 0.5–4 m of the platform	Onboard depth and inertial sensing for state estimation and obstacle awareness	LOC
M.F.2 / M.P.2	Localize own pose relative to the environment	Self-localization within ± 10 cm of true position under nominal conditions	GPS-denied localization based on visual-inertial odometry fused with the flight controller	LOC
M.F.3 / M.P.3	Allow operator to manually pilot the platform to an AOI	Maximum flight speed up to 1 m/s	Operator commands the drone via the RC link while monitoring telemetry and video	UAV
M.F.4	Provide real-time visual feedback to the operator	—	Live video feed and telemetry shown at the ground control station	COM
M.F.5 / M.P.4	Allow the operator to define a POI on the video feed	Detect POI from at least 2.5 m away	POI selection in image space; visual servoing acquires the target	LOC
M.F.6 / M.F.7 / M.P.5	Plan arm motion and manipulate the end-effector to the POI	End-effector positioning accuracy ± 0.15 m during contact	Combined drone position control and arm trajectory planning to reach the surface	MAN
M.F.8 / M.P.6	Maintain stable contact during NDT execution	Hold position under wind speeds up to 3 m/s	Hybrid wrench / position controller regulates a steady normal force on the surface	MAN
M.F.9 / M.P.7	Perform contact-based non-destructive testing	Sample NDT data at ≥ 5 waypoints in a single flight	Probe interrogates the surface; data is recorded onboard	MAN
M.F.10 / M.P.8	Store and relay NDT data to the ground station	End-to-end communication latency ≤ 100 ms	Inspection data is logged and streamed in real time to the operator	COM

ID	Functional	Performance	Description	Sub.
M.F.11 / M.P.9	Execute a fail-safe response on loss of communication	Fail-safe triggered within 1 s of communication loss	Return-to-home or land behavior on link or sensor loss	UAV

Table 2: 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	A trained operator shall be able to set up and plan a mission in under 15 minutes.
M.N.4	NDT data shall be stored in standard, reusable formats (e.g., CSV, ROS bag).
M.N.5	The system shall operate in temperatures from $-5\,^{\circ}$C to $40\,^{\circ}$C and humidity up to 95%.
M.N.6	The system shall be transportable in a single vehicle with two operators.

Table 3: Desirable Functional Requirements

ID	Description
D.F.1	The system may employ deep learning to automatically identify candidate POIs in the camera feed.
D.F.2	The system may adapt manipulation strategy based on observed surface curvature and material.
D.F.3	The system may navigate fully autonomously from launch to AOI, removing the need for manual piloting.

Table 4: Desirable Performance Requirements

ID	Description
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 may achieve end-effector positioning accuracy within ± 5 cm during contact-based NDT.

4 Functional Architecture

The functional architecture of Flying Hand expresses what the system does, independent of any particular hardware or software implementation. It is bounded on the left by the system inputs — the user-defined POI / mission plan, the operating environment, and electrical power — and on the right by the system outputs — NDT sensor data, the estimated drone and end-effector locations, and a return-to-home confirmation that closes out the mission. A bidirectional Communicates block links the platform to the ground station and routes information between internal functional blocks. The complete diagram is shown in Figure 4.

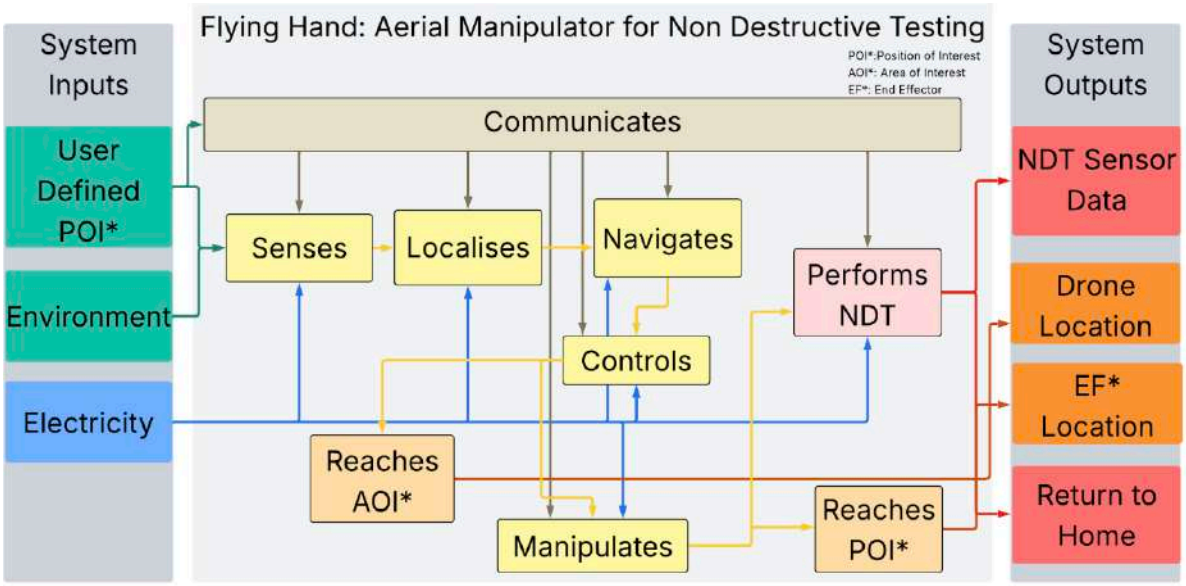


Figure 4: Flying Hand functional architecture. Left: system inputs. Right: system outputs. Yellow blocks are continuous functions; orange blocks are mission-phase state functions; the red block represents the NDT payload function.

- **Senses:** The Senses block acquires data from exteroceptive sensors observing the environment and the inspected structure, as well as proprioceptive sensors measuring drone and arm states. Outputs feed Localizes, Navigates, and Manipulates. Filtering and quality checks are applied at this stage to make downstream estimation robust to noise and intermittent feature loss.

- **Localizes:** The Localizes block estimates the platform's pose relative to the mission frame and tracks the relative location of the user-defined Point of Interest in the camera frame. State estimates and uncertainty bounds are forwarded to Navigates, Reaches AOI, and Reaches POI so that downstream functions can react to current quality of localization.

- **Navigates:** Navigates plans and updates the platform's trajectory from launch to the AOI and between waypoints, using mission goals from Communicates and state estimates from Localizes. The output is a feasible reference trajectory respecting vehicle dynamics, safe

stand-off from the structure, and the operator-set speed limits, which is passed to the low-level Controls function.

- **Hovers Stably / Reaches AOI:** This pair of phase-specific functions handles the transition from gross navigation to inspection. Hovers Stably maintains a quasi-static base near the structure under disturbance, providing a platform on which the manipulator can reliably reach the POI. Reaches AOI refines the platform's pose to bring the AOI into the manipulator's workspace.
- **Manipulates / Reaches POI:** Manipulates plans and executes arm joint motions that move the end-effector from a neutral configuration to the POI while respecting joint limits and avoiding self-collision and platform collision. Reaches POI performs the fine, sensor-driven positioning of the end-effector relative to the surface, achieving the contact force, orientation, and accuracy required by the NDT technique. When the POI is reached, control authority is handed to Performs NDT.
- **Performs NDT:** Performs NDT executes the actual contact-based inspection. It collects, time-stamps, and organizes NDT measurements together with the drone and end-effector location metadata, then streams them to the ground station via Communicates while logging onboard for redundancy.
- **Communicates:** Communicates sits at the top of the architecture and provides the bidirectional information layer between the platform and the ground station, and between internal functional blocks. It carries supervisory commands from the operator, telemetry and video back to the ground, and the low-latency synchronization messages that keep Senses, Navigates, and Manipulates consistent during contact operations.

5 Cyber-Physical Architecture

The cyber-physical architecture maps the functional blocks of Section 4 onto specific hardware and software components and describes the flow of information, energy, and control between them. The current architecture, shown in Figure 5, has been refined relative to the Conceptual Design Review and Preliminary Design Review based on lessons learned during spring development. The two most significant changes from the previous CDR architecture are:

- **Image-Based Visual Servoing (IBVS) is now part of the Controls block**, not the Localizes block. During spring integration we found that fusing visual feedback directly into the low-level controller (alongside cascade control and the wrench controller) produces a much more stable approach and contact behavior than computing a target pose for the navigation stack. The IBVS controller publishes a body-frame velocity command that is blended with the position controller output through a depth-driven switching function, $\lambda(d)$, that transitions smoothly from visual approach to wrench-controlled contact.

- **Image-Based Visual Servoing replaces the deep-learning POI detector in Localizes.** A learned detector is reserved as a desirable functional requirement for fall semester. For SVD, the POI is a circular fiducial detected in image space.

The complete cyber-physical architecture is grouped into five layers — Communicates, Senses, Localizes / Navigates, Controls / Manipulates, and Performs NDT — which are summarized below.

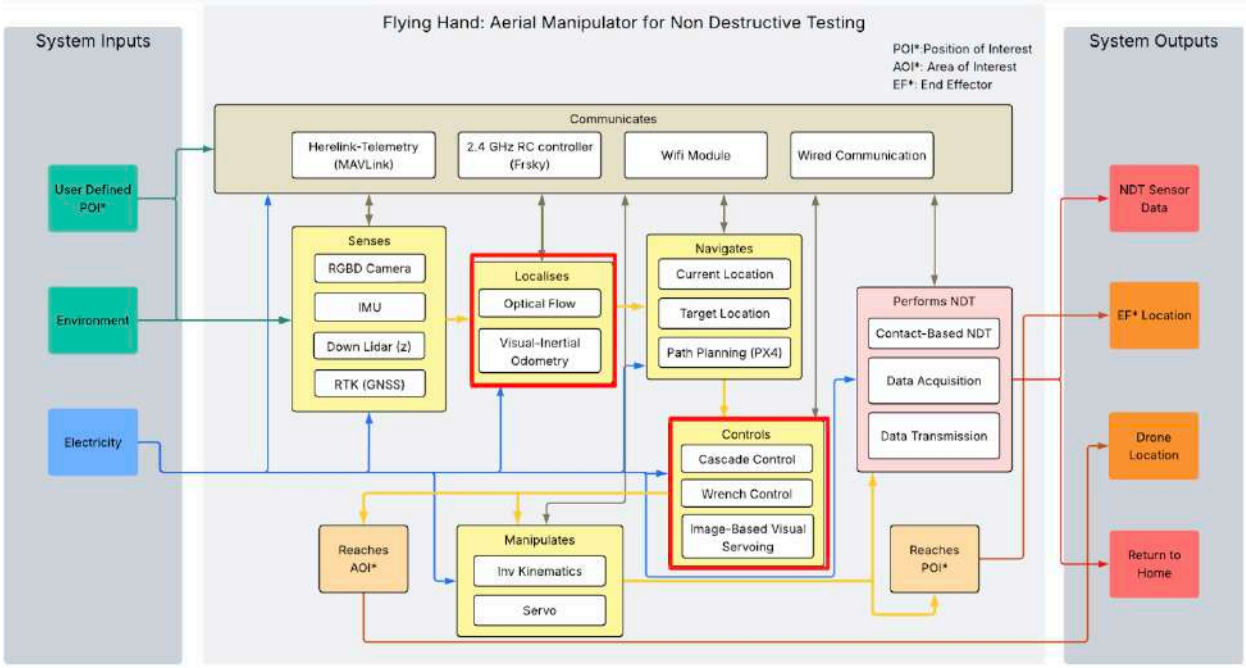


Figure 5: cyber-physical architecture. Highlighted (red) blocks indicate the changes relative to the previous CDR: Image-Based Visual Servoing now sits in the Controls block, blended with the position cascade controller and the wrench controller.

5.1 Communicates

Communicates is realized through four parallel channels. HereLink telemetry over MAVLink provides the primary supervisory link between the ground station, PX4, and the companion computer; it carries flight status, mission commands, and parameter updates. A 2.4 GHz FrSky RC controller provides a dedicated low-latency link for manual piloting, mode changes, and the kill-switch fail-safe. A Wi-Fi module provides high-bandwidth connectivity for ground debugging and live RViz visualization. Wired (serial / USB) connections are used internally between the Jetson Orin Nano, the PX4 flight controller (CubeOrange+), and onboard sensors.

5.2 Senses

Sensing is provided by an Intel RealSense D456 RGB-D camera (depth, IR stereo, and IMU), the CubeOrange+ on-board IMU, an H-Flow downward-facing optical flow + lidar module for

body-frame velocity and altitude, and an RTK GNSS receiver for ground-truth positioning during outdoor tests. The RealSense IR stereo and IMU streams feed the cuVSLAM-based VIO pipeline; the optical-flow module provides a redundant velocity source intended to bridge gaps in VIO when the platform is close to a feature-poor surface.

5.3 Localizes

The Localizes layer fuses two sources. Visual-Inertial Odometry runs inside a Docker container on the Jetson Orin Nano: a ROS 2 message synchronizer and NVIDIA NITROS-based GPU pipeline transports synchronized stereo and IMU data into the proprietary cuVSLAM library, which performs feature extraction, stereo matching, feature tracking, IMU integration, local mapping, and loop closure. A Message Formatter publishes the resulting 6-DoF odometry, which a ROS 2 node then converts from the ROS ENU/FLU convention to the PX4 NED/FRD convention before it is forwarded to MAVROS and ultimately fused by EKF2. Optical Flow provides an independent body-frame velocity estimate published over UAVCAN; both VIO and optical flow can be selectively fused by EKF2 using the EKF2-EV-CTRL bitmask, which we currently set to fuse VIO horizontal position only and reserve optical flow as a backup.

5.4 Navigates and Controls

The Navigates block runs inside PX4 on the CubeOrange+. It compares the EKF2-fused current location against the operator-supplied target waypoints, plans a feasible reference trajectory, and passes setpoints to the Controls block. The Controls block has been substantially modified for fully-actuated flight; modifications are described in detail in Section 6.3.1 and include a new thrust generator that decouples body-frame thrust from body tilt, six omni-mode strategies in ControlMath, and a control-allocation matrix that captures the tilted-rotor geometry of the modified Tarot X6 frame. The same Controls block now also receives velocity commands from the Image-Based Visual Servoing module and force corrections from the Wrench Controller, which run on the Jetson Orin Nano and are merged into the per-rotor thrust output through PX4's offboard mode.

5.5 Manipulates and Performs NDT

For the Spring Validation Demonstration, Manipulates is implemented as a 0-DOF rigid arm carrying the contact probe and the ATI Gamma F/T sensor. The Wrench Controller running on the Jetson Orin Nano reads sensor data over RS-485 / USB, computes a thrust correction, and publishes attitude + thrust commands to PX4. For fall semester, the rigid arm will be replaced by the muti-DOF arm; the inverse-kinematics solver and servo execution module are in place in software. Performs NDT logs sensor data onboard and streams it to the ground station via Communicates.

6 Current System Status

6.1 Spring-Semester Targeted Requirements

For the spring semester our team set a target of meeting the foundational subset of the system-level requirements — specifically, those required to demonstrate fully-actuated flight, GPS-denied localization, and a wrench-controlled contact in simulation, with the rigid 0-DOF arm. The targeted requirements and their current status are summarized in Table 5.

Table 5: Targeted Performance Requirements for Spring Semester

Requirement	Status	Subsystem
M.P.1 Sense the environment within 0.5–4 m of the platform	Passed	Localization
M.P.2 Self-localization within ± 10 cm under nominal conditions (near-wall hover)	Passed (hover); Passed (mission)	Localization
M.P.3 Navigate at speeds up to 1 m/s during manual flight	Passed	UAV Platform
M.P.4 Detect POI from at least 2.5 m	Passed (simulation)	Localization
M.P.5 End-effector positioning accuracy within ± 0.15 m during contact	Passed (simulation)	Manipulation
M.P.6 Maintain stable contact under wind disturbances up to 3 m/s	Passed	Manipulation
M.P.8 Communication latency ≤ 100 ms	Passed	Communication
M.P.9 Execute fail-safe response within 1 s of communication loss	Passed	UAV Platform
M.F.7 / M.F.8 Apply a steady 5 N ± 1 N normal force for ≥ 10 s	Passed (simulation)	Manipulation

6.2 Overall System Depiction

The current Flying Hand platform is shown in Figure 6. It consists of a modified Tarot X6 hexarotor airframe whose rotor mounts have been redesigned with a 30° inward tilt to provide six-DoF (fully-actuated) capability; a CubeOrange+ flight controller running our customized PX4 firmware; an Intel RealSense D456 stereo-IR camera; a Holybro H-Flow optical flow + lidar module; an RTK GNSS receiver; an onboard NVIDIA Jetson Orin Nano running the cuVSLAM VIO pipeline, the Wrench Controller, and the IBVS module; and a rigid 0-DOF manipulator arm carrying an ATI Gamma F/T sensor and a contact probe. A foam-covered false wall fitted with AprilTags is used as the SVD test surface.

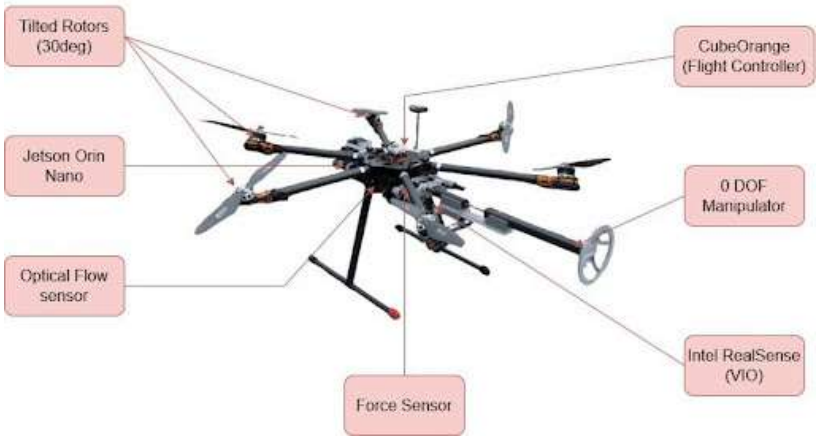


Figure 6: Overall system depiction. The fully-actuated hexarotor is built on a modified Tarot X6 frame with 30° tilted rotors. The 0-DOF arm carries the contact probe and force sensor for SVD.

6.3 Subsystem Descriptions and Depictions

6.3.1 UAV Platform — Software / Controller

The UAV platform is built on the open-source PX4 flight stack [**?**], extended with five categories of modifications to achieve fully-actuated control on a tilted-rotor hexarotor geometry. The architecture follows the integration strategy of Keipour [2], which bridges existing underactuated flight stacks with fully-actuated vehicles by introducing omni-mode attitude strategies rather than replacing the entire controller.

1. **Position Control:** A new Thrust Generator computes the NED thrust vector directly from the desired acceleration without coupling it to body tilt. This decoupling is necessary because a fully-actuated platform can produce lateral thrust at zero attitude—a capability absent in conventional underactuated stacks [2].

2. **ControlMath:** Six omni-mode conversion strategies (modes 0–6) implement different policies for mapping the desired body-frame thrust vector to a feasible attitude/thrust pair. The active mode is selected at runtime depending on the mission phase, following the hybrid switching structure described in [2].

3. **Attitude Controller:** The PX4 attitude failure detector was disabled to permit the controller to accept the reduced attitude vectors $[0,\ 0,\ \psi_{\text{des}}]$ produced by the omni modes, which would otherwise be rejected as ill-formed by the standard sanity checks. This modification is consistent with the full-pose tracking formulation in [2], where roll and pitch setpoints are set independently of the thrust direction.

4. **Control Allocation:** The per-rotor geometry was redefined to encode the 30° outward tilt on each motor, enabling the allocator to generate both vertical and lateral force components

from individual rotor thrusts. The control allocation framework follows the wrench-set formulation of [2], and the full `CA_ROTOR*` parameter set was derived empirically during spring testing on the physical airframe.

5. **Multicopter Position Control:** The position controller was modified to pass the current attitude quaternion into the control loop, closing the body-frame feedback path required by the omni modes. This couples the translational and rotational feedback in the manner described for physical interaction tasks in [2].

6.3.2 UAV Platform — Hardware

The current state of the UAV platform is a fully-actuated hexarotor capable of stable position-hold and waypoint-mission flight, integrated with the GPS-denied localization stack and the rigid 0-DOF manipulator (Figure 7). Five flight-test campaigns at the Robotics Innovation Center (RIC) validated the airframe and the modified PX4 controller. The yaw-rate P gain was reduced to its minimum value to compensate for the much larger yaw authority of the tilted-rotor geometry compared to a standard hexarotor; angle P gains were reduced by approximately 50% to suppress oscillation at hover. Stable Position Hold was achieved on the fifth takeoff, with the EKF2 fallback frequency reduced by adding ground-feature panels in the test cage to improve VIO robustness.



Figure 7: UAV hardware

The fall-semester target configuration (Figure 8) couples the fully-actuated hexarotor with a multi-DOF arm whose workspace is large enough to reach overhead and orthogonal lateral surfaces

from a single hover position; the arm reaches both an overhead inspection point and a left-wall point without the platform repositioning, exploiting the J1 yaw and J2 / J3 pitch joints.

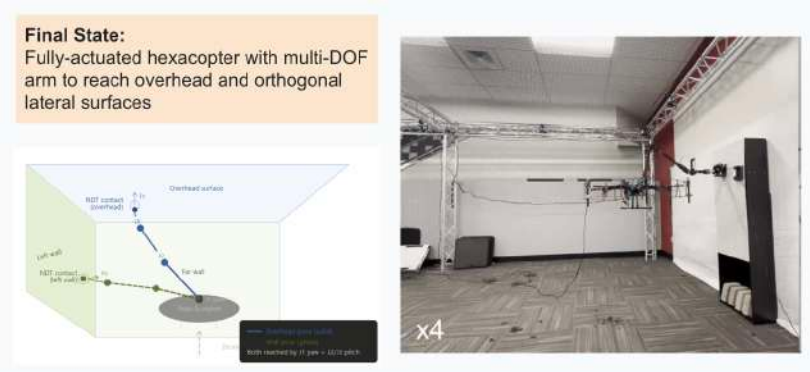


Figure 8: Fall-semester target configuration: fully-actuated hexarotor with multi-DOF arm reaching overhead and orthogonal lateral surfaces from a single hover position.

6.3.3 Manipulation — Software

The simulation environment (Figure 9) follows the Gazebo-based validation approach of He et al. [1], who model a fully-actuated hexarotor aerial manipulator in Gazebo with a 6-axis F/T sensor and an RGB-D camera mounted at the arm tip. We construct an analogous model: the Hexa Scorpion airframe is instantiated in Gazebo with a simulated ATI Gamma F/T sensor at the rigid arm tip and a forward-facing camera.

For visual guidance, He et al. [1] use a line detection and tracking module based on surface-normal filtering and probabilistic Hough transforms to extract bridge edges as image features. Our simulation adopts a complementary approach suited to the inspection scenario: a circular AprilTag-style target is placed on the wall and detected via OpenCV-based circle detection, with the detected pixel centroid serving as the image feature.

The IBVS controller follows the hybrid motion and force control architecture of [1], in which image-space feature error drives a body-frame velocity command τ_{vs}, and an impedance wrench controller τ_f holds the desired contact force normal to the surface. The two commands are blended via a depth-weighted matrix Λ that transitions smoothly from pure motion control to force regulation as the end-effector approaches the contact surface [1]:

$$\tau = (I_{6\times6} - \Lambda)\,\tau_{vs} + \Lambda\,\tau_f. \tag{1}$$

The resulting body-frame wrench command is passed to the PX4 control allocation layer, which maps it to individual rotor thrusts via the tilted-rotor geometry defined in Section 6.3.1. The simulation serves as the primary environment for developing and tuning the IBVS gains and wrench-blending logic before transfer to hardware.



Figure 9: Manipulation software. Left and middle: Gazebo model of the fully-actuated hexarotor with a simulated F/T sensor; the rigid stick acts as the SVD-phase manipulator. Right: detected circle target produced by the IBVS pipeline.

6.3.4 Manipulation — Hardware

The manipulation hardware (Figure 10) uses an ATI Gamma 6-axis F/T sensor connected over RS-485 / Modbus to a USB serial adapter on the Jetson Orin Nano. The Wrench Controller node on the Jetson reads force at ∼1 kHz, low-pass filters it, computes the desired thrust correction, and publishes attitude + thrust commands to PX4 over MAVROS. A small visualizer publishes both the measured force F_x and the commanded thrust for live debugging. As a contingency against ATI's unsupported legacy firmware on this sensor, the SingleTact capacitive sensor was sourced as a backup.

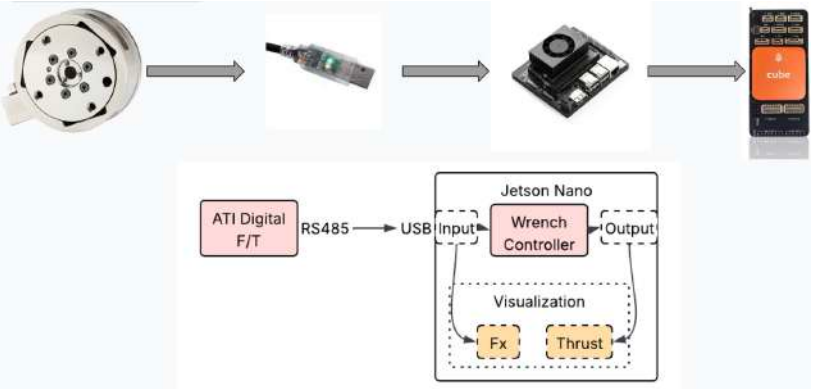


Figure 10: Manipulation hardware. Top: signal chain from the ATI Gamma F/T sensor through an RS-485-to-USB adapter to the Jetson Orin Nano and CubeOrange+ flight controller. Bottom-right: wrench-controller block diagram showing real-time force-to-thrust visualization.

6.3.5 Localization — VIO Pipeline

The GPS-denied localization pipeline is shown in Figure 11 and is hosted entirely on the Jetson Orin Nano. The Intel RealSense D456 publishes 8-bit grayscale IR stereo images and IMU data, which a ROS 2 message synchronizer aligns and a NITROS-based GPU pipeline transports into the cuVSLAM library inside a Docker container. cuVSLAM runs three threads — visual data processing (feature extraction, stereo matching, feature tracking), IMU processing, and a tracking

thread (the VIO solver itself) — with a parallel loop-closure thread for global TF correction. A Message Formatter publishes the GPU pose as a ROS 2 odometry message; a separate ROS 2 node converts from the ROS ENU/FLU convention to PX4 NED/FRD before publishing to MAVROS, which forwards the corrected odometry to PX4's EKF2 for fusion with the IMU.

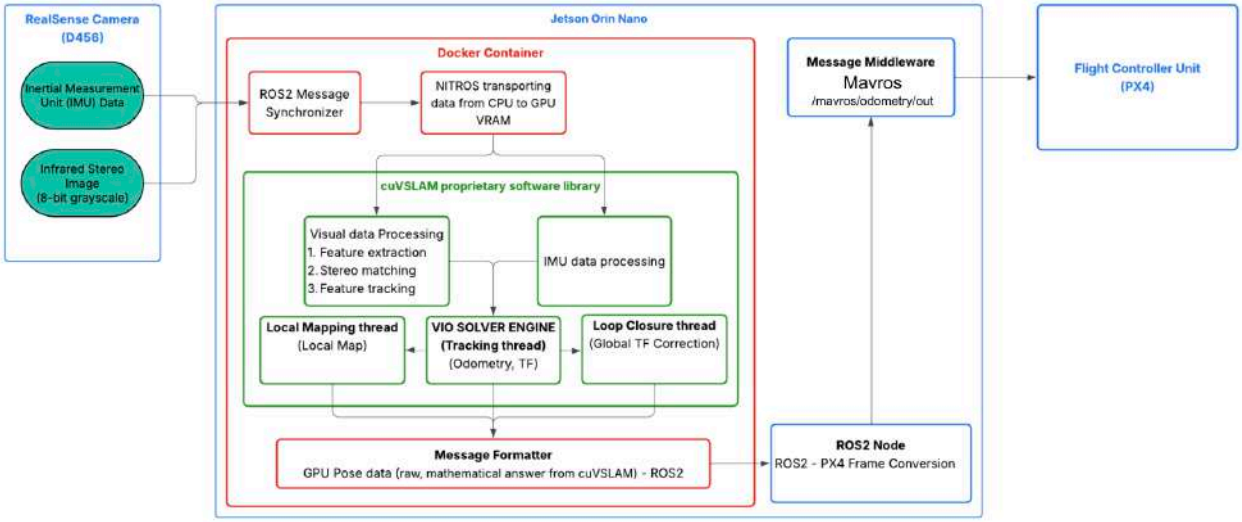


Figure 11: VIO software pipeline. The RealSense D456 feeds IR stereo + IMU into a Dockerized cuVSLAM instance on the Jetson Orin Nano. A ROS 2 frame-conversion node bridges from ROS ENU/FLU to PX4 NED/FRD before publishing to MAVROS.

The hardware setup of the VIO subsystem is shown in Figure 12; key components include the Jetson Orin Nano, the D456, the CubeOrange+ flight controller, a USB-TTL-232 serial adapter for the MAVLink link, an HDMI EDID emulator (required so the Jetson boots into desktop mode without a physical monitor attached), and a regulated power supply tapped from the 22.2 V battery bus.

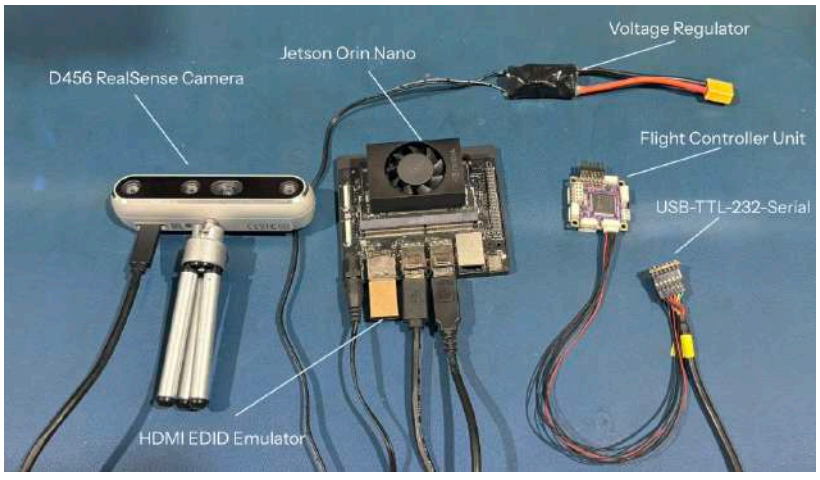


Figure 12: Localization hardware setup

To address VIO drift observed during the early test campaign, the camera is mounted at a $-30°$ downward tilt on a precision-machined fixed bracket. A ROS 2 node `rotated_odometry_relay`

corrects the resulting frame mismatch in real time using the inverse rotation matrix for position and velocity, a left-multiply quaternion composition for orientation, and the standard 6×6 block-diagonal covariance transformation. An EKF2 parameter set was derived experimentally (`EKF2_EV_CTRL`=1, `EKF2_EV_NOISE_MD`=1, `EKF2_EVP_NOISE`=0.1 m, `EKF2_EVP_GATE`=5.0 SD, `EKF2_EV_DELAY`=40 ms, `EKF2_NOAID_TOUT`=10^7, `EKF2_GPS_CTRL`=0); these settings prevent EKF2 from over-trusting cuVSLAM's $\sim 10^{-15}$ covariance values, allow the system to bridge transient VIO gaps without entering dead-reckoning failsafe, and remove conflicts between VIO and GPS as horizontal position sources.

6.4 Modeling, Analysis, and Testing

The major modeling, analysis, and unit-test activities of the spring semester are summarized in Table 6. Modeling effort focused on three areas: (1) a Gazebo simulation of the fully-actuated hexarotor with a simulated F/T sensor, used to validate the wrench controller and the IBVS / wrench blending logic before hardware deployment; (2) the camera-tilt mathematical correction, which was first validated on the bench by walking the platform forward 3 m and confirming that VIO horizontal motion was preserved while spurious vertical motion was eliminated; and (3) the flight-controller modifications, which were first compiled and run in PX4 SITL with QGroundControl before the actual takeoff campaign on hardware.

Table 6: Spring-semester modeling, analysis, and testing summary

Activity	Success Criterion	Result
Wrench Controller — Force Tracking (simulation)	Maintain 5 N $\pm$1 N for $\geq$ 10 s	Achieved 5 N $\pm$1 N for $>$ 15 s; force-convergence time after contact $<$ 3 s
Visual Servoing Effective Range (simulation)	Lock onto POI from $\geq$ 2.5 m	Lock-on at $>$ 2.5 m verified
Camera-Tilt Frame Correction (bench)	Forward motion only along X axis after correction	Walked 3 m: raw X=2.887 m, Z=1.769 m; corrected X=3.384 m, Z=0.088 m
PX4 SITL with Modified Firmware	Drone takes off and accepts MAVLink commands in Gazebo	Achieved on AirLab PX4 v1.16 fork
Maiden Fully-Actuated Flight Campaign	5 takeoffs without crash; achieve Position Hold	Achieved on takeoff 5 with stable Position Hold
EKF2 Tuning	VIO accepted by EKF2 without rejection; no dead-reckoning entries during 30 s hover	Achieved with the parameter set in Section 5.3
Force Sensor (hardware)	Read 5 N within $\pm$1 N at the Jetson Nano	Achieved (with simulated source while ATI sensor remained blocked); SingleTact backup sourced

6.5 SVD Performance Evaluation

The Spring Validation Demonstration consisted of two complementary tests — Test 1 a teleoperated hardware demonstration and Test 2 a fully-autonomous simulation. The verification cri-

teria and results are summarized in Tables 7 and 8.

Table 7: SVD Test 1 — Real hardware demonstration

Procedure step	Success criterion	Result
Initialize take-off / landing points; verify GPS-denied localization; upload and execute 4-waypoint autonomous mission	Successful waypoint navigation under GPS-denied localization	Partially passed
Tele-operate the drone forward / lateral to demonstrate full-actuation; hold for 10–20 s to show drift	Stable Position Hold; bounded drift	Passed
Approach a foam-covered false wall to within ~ 10 cm; hover stably for 20–30 s	Continuous hover near surface for ≥ 30 s	Passed (hover at ~ 0.3 m for 30 s)
Tele-operate to make contact; apply ~ 5 N normal force measured by the F/T sensor	F/T data and wrench-controller output streamed to ground station with no interruption	Passed
Retreat and repeat the contact maneuver, then land	Repeatable contact / retreat cycle	Passed

Table 8: SVD Test 2 — Autonomous simulation pipeline

Procedure step	Success criterion	Result
Launch Gazebo simulation; auto-takeoff to a predefined height	Drone reaches the takeoff pose	Passed
Detect the 300 mm circular POI at 1.5 m height; lock on with IBVS	POI locked on at distance $\geq$ 2.5 m	Passed
Approach and contact the wall under hybrid IBVS / wrench control	End-effector contact error $\leq$ 0.15 m	Passed
Apply a steady 5 N $\pm$1 N force for ≥ 10 s	Force-convergence after contact < 3 s; sustained ≥ 10 s	Passed (sustained > 15 s)
Retreat from the wall and land	Safe disengagement and landing	Passed

The simulation pipeline is shown in Figures 13 and 14. The mission script is a state machine with phases *Pre-flight* $\rightarrow$ *Takeoff* $\rightarrow$ *Hover* $\rightarrow$ *Approach* $\rightarrow$ *Contact* $\rightarrow$ *Force-hold* $\rightarrow$ *Retreat / Land*. During flight, three control loops are active simultaneously, with control authority allocated by axis: the position controller (PID on position error) drives all three axes during free-flight; once contact is detected, the wrench controller (PID on force error) takes over the wall-normal x-axis while the IBVS controller (velocity / twist from pixel error) maintains lateral y/z alignment.

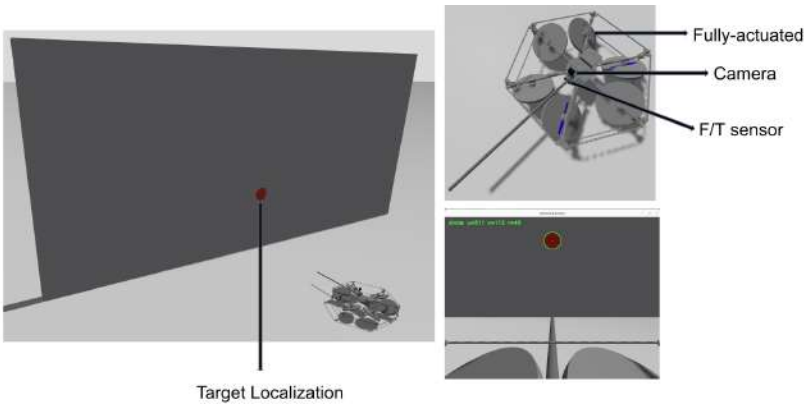


Figure 13: Simulation setup. Left: Gazebo world with a wall and a red POI sphere acting as the target. Right: detail of the fully-actuated hexarotor model including the simulated F/T sensor and forward-facing camera, plus the IBVS detected-circle output.

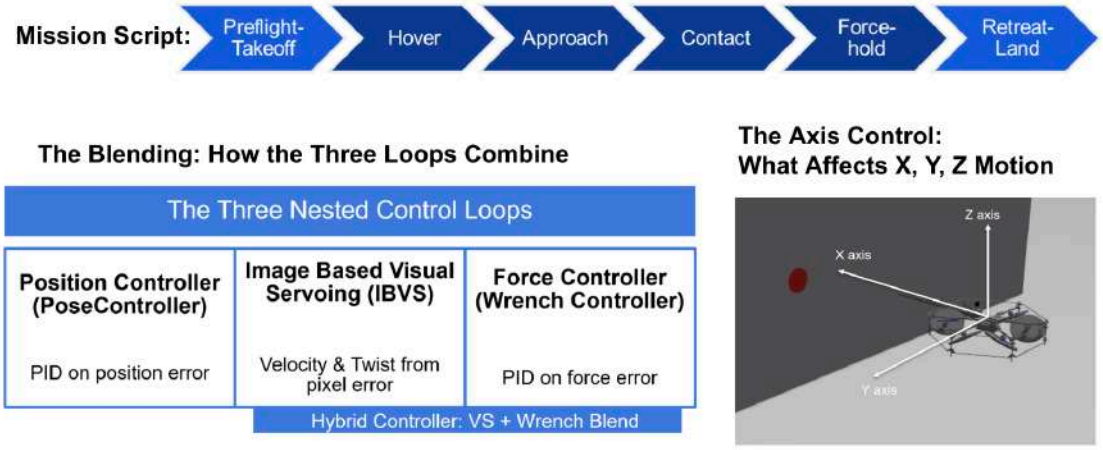


Figure 14: Mission state machine and control-loop blending. Three nested control loops — position, IBVS, and wrench — are blended axis-by-axis and phase-by-phase to balance free-flight precision with compliant contact.

The hardware near-wall hover (Figure 15) and the corresponding open-area waypoint navigation (Figure 16) demonstrate the localization performance achieved during SVD. The drone successfully held position at ~ 0.3 m from the AprilTag wall at ~ 1.5 m flight height for the full 30 s hover; in open-area waypoint mode, the drone navigated to the goal and landed within 0.5 m of the target point.



Figure 15: Near-wall position hold using VIO. Drone hovers ~ 0.3 m from the AprilTag wall at ~ 1.5 m flight height for the full 30 s SVD hover window.



Figure 16: Oen-area autonomous waypoint navigation ran on VIO with EKF2 fusion (no GPS).

The full Spring Validation Demonstration — platform integration, localization, manipulation, simulation pipeline, and force application — met all targeted SVD verification criteria, with the partial exception of waypoint tracking on hardware described in the next subsection.

6.6 Strong and Weak Points

Strong points:

- **Fully-actuated platform integrated end-to-end.** Modified PX4 fork (omni modes, control allocation), redesigned $30°$-tilted-rotor airframe, and stable Position Hold in flight, all achieved on hardware before the SVD deadline.
- **Wrench controller validated in simulation.** The drone autonomously took off, used IBVS to drive the approach, made contact, and applied a continuous 5 N ± 1 N force for over 10 s.

All performance criteria for the manipulation simulation were met.

- **Near-wall GPS-denied hover works.** VIO + EKF2 with the tilted-camera correction held position at ~ 0.3 m from a feature-rich wall for 30 s, demonstrating that the localization stack is precise enough to support contact operations from a stationary base.
- **Force / wrench-controller pipeline running on the Jetson Orin Nano.** The companion-computer side of the contact pipeline is hardware-deployed and visualized; only the F/T sensor end remains to be unblocked.

Weak points:

- **Waypoint navigation under EKF2.** In autonomous mission mode, EKF2 occasionally fell back to dead-reckoning on the accelerometer rather than continuing to fuse VIO, leading to localization drift and degraded waypoint tracking; manual teleoperation was required mid-flight to recover. EKF2 fine-tuning is the highest-priority fall task.
- **Optical-flow integration on CubeOrange+.** The same H-Flow configuration that works on the spare CubeOrange does not publish estimates on the primary CubeOrange+. Root cause is suspected to be a CAN / parameter discrepancy and is carried forward.
- **VIO degradation near feature-poor surfaces.** VIO loses tracking when the camera is closer than ~ 1 m to a plain wall. Camera-tilt and optical-flow fusion are the two mitigations under investigation; the camera-tilt approach has been deployed but will be hardened in fall.

7 Project Management

7.1 Work Breakdown Structure

The Work Breakdown Structure (WBS) for Flying Hand is product-oriented and decomposes the project into five top-level work packages: Robot Platform (Mechanical), Electrical System, Software System, Integration & Testing, and Management (Figure 17). Each top-level package is decomposed further into subsystems, and most leaf-level tasks follow a uniform *design* → *build* → *test* → *integrate* workflow.

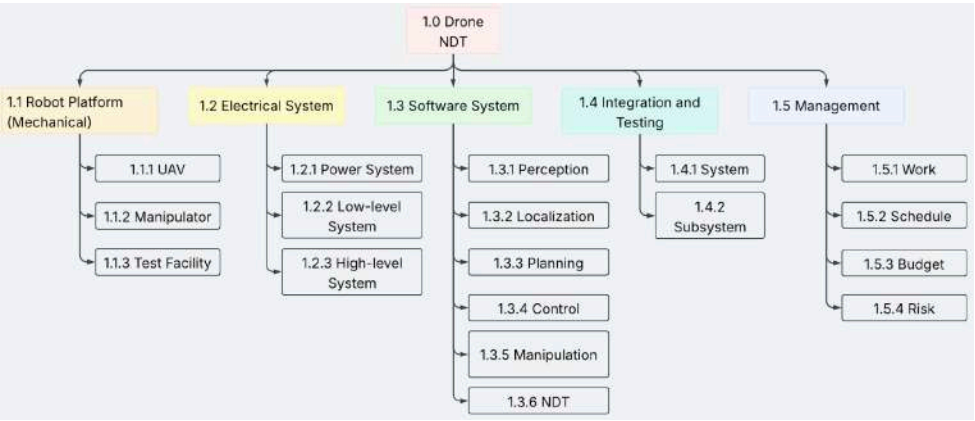
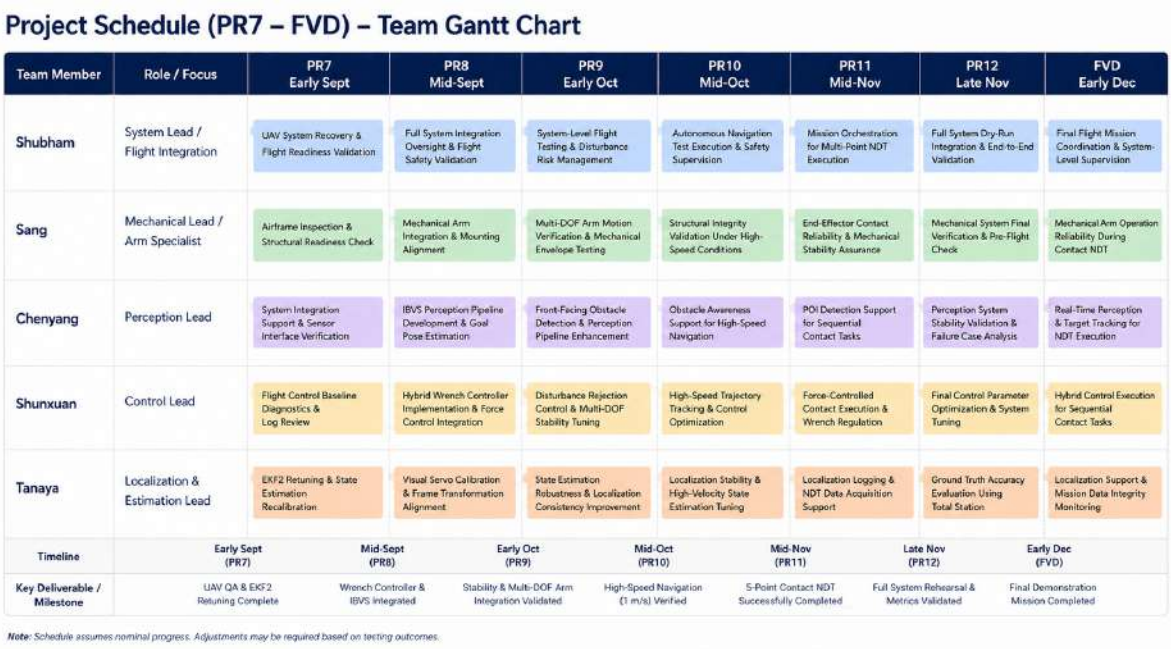


Figure 17: Three-level Work Breakdown Structure for Flying Hand.

The Robot Platform package covers (1.1.1) the UAV airframe, power-train, and avionics; (1.1.2) the manipulator and NDT probe; and (1.1.3) the test facility. The Electrical System package covers the (1.2.1) power, (1.2.2) low-level control / RC / telemetry, and (1.2.3) high-level companion-computer / sensor systems. The Software System package is split into (1.3.1) Perception, (1.3.2) Localization, (1.3.3) Planning, (1.3.4) Control, (1.3.5) Manipulation, and (1.3.6) NDT. Cross-subsystem activity is captured under (1.4) Integration & Testing, separated into system-level (1.4.1) and subsystem-level (1.4.2) testing. Management (1.5) covers work tracking, scheduling, budget, and risk. The WBS has not changed structurally since the PDR; only the manipulator package has been updated to reflect the phased approach (rigid 0-DOF arm in spring, 3-DOF arm in fall).

7.2 Schedule Status

The fall schedule (Figure 18) outlines a comprehensive development timeline spanning from PR7 to the FVD. The roadmap is divided into seven key milestones, detailing the specialized tasks assigned to each team member.



Project Schedule (PR7 – FVD) – Team Gantt Chart

Team Member	Role / Focus	PR7 Early Sept	PR8 Mid-Sept	PR9 Early Oct	PR10 Mid-Oct	PR11 Mid-Nov	PR12 Late Nov	FVD Early Dec
Shubham	System Lead / Flight Integration	UAV System Recovery & Flight Readiness Validation	Full System Integration Oversight & Flight Safety Validation	System-Level Flight Testing & Disturbance Risk Management	Autonomous Navigation Test Execution & Safety Supervision	Mission Orchestration for Multi-Point NDT Execution	Full System Dry-Run Integration & End-to-End Validation	Final Flight Mission Coordination & System-Level Supervision
Sang	Mechanical Lead / Arm Specialist	Airframe Inspection & Structural Readiness Check	Mechanical Arm Integration & Mounting Alignment	Multi-DOF Arm Motion Verification & Mechanical Envelope Testing	Structural Integrity Validation Under High-Speed Conditions	End-Effector Contact Reliability & Mechanical Stability Assurance	Mechanical System Final Verification & Pre-Flight Check	Mechanical Arm Operation Reliability During Contact NDT
Chenyang	Perception Lead	System Integration Support & Sensor Interface Verification	IBVS Perception Pipeline Development & Goal Pose Estimation	Front-Facing Obstacle Detection & Perception Pipeline Enhancement	Obstacle Awareness Support for High-Speed Navigation	POI Detection Support for Sequential Contact Tasks	Perception System Stability Validation & Failure Case Analysis	Real-Time Perception & Target Tracking for NDT Execution
Shunxuan	Control Lead	Flight Control Baseline Diagnostics & Log Review	Hybrid Wrench Controller Implementation & Force Control Integration	Disturbance Rejection Control & Multi-DOF Stability Tuning	High-Speed Trajectory Tracking & Control Optimization	Force-Controlled Contact Execution & Wrench Regulation	Final Control Parameter Optimization & System Tuning	Hybrid Control Execution for Sequential Contact Tasks
Tanaya	Localization & Estimation Lead	EKF2 Retuning & State Estimation Recalibration	Visual Servo Calibration & Frame Transformation Alignment	State Estimation Robustness & Localization Consistency Improvement	Localization Stability & High-Velocity State Estimation Tuning	Localization Logging & NDT Data Acquisition Support	Ground Truth Accuracy Evaluation Using Total Station	Localization Support & Mission Data Integrity Monitoring
Timeline		Early Sept (PR7)	Mid-Sept (PR8)	Early Oct (PR9)	Mid-Oct (PR10)	Mid-Nov (PR11)	Late Nov (PR12)	Early Dec (FVD)
Key Deliverable / Milestone		UAV QA & EKF2 Retuning Complete	Wrench Controller & IBVS Integrated	Stability & Multi-DOF Arm Integration Validated	High-Speed Navigation (1 m/s) Verified	5-Point Contact NDT Successfully Completed	Full System Rehearsal & Metrics Validated	Final Demonstration Mission Completed

Note: Schedule assumes nominal progress. Adjustments may be required based on testing outcomes.

Figure 18: Fall 2026 schedule.

The team is on schedule. All targeted SVD verification criteria were met — fully-actuated flight, GPS-denied hover, and the simulation contact pipeline — with the exception of autonomous waypoint tracking, which functions but is sensitive to EKF2 fallback. The work required to harden waypoint tracking is captured under the August / September fall milestones below. The only area where we are slightly behind plan is optical-flow fusion on the CubeOrange+; however, we can still rely on VIO for localization.

7.3 Test Plan

7.3.1 Major remaining milestones

The major fall-semester milestones are listed in Table 9. Each milestone aligns with a Progress Review and produces a concrete deliverable that feeds the FVD.

Table 9: Fall-semester capability milestones aligned with the MRSD Progress Reviews

PR	Capability	Validation Test
PR 7 (Early Sept)	UAV summer-break quality assurance; EKF2 retuning	The UAV completes all spring-semester tasks (Position Hold, near-wall hover, manual mission flight, fail-safe). Pass criterion: same SVD verification applied after summer downtime.

PR	Capability	Validation Test
PR 8 (Mid-Sept)	Wrench controller and visual servoing integrated on hardware	(1) IBVS publishes a correct goal pose under varied lighting and target distance from a stationary platform. (2) The hybrid wrench / IBVS controller holds a stable position with consistent contact on the SVD wall when the platform is hand-stabilized.
PR 9 (Early Oct)	Front-facing obstacle awareness; multi-DOF arm integrated; dynamic stability	Disturbance-rejection test: the drone holds a stable hover ($\pm 2^\circ$ attitude) while the multi-DOF arm executes maneuvers across its full operational workspace.
PR 10 (Mid-Oct)	Parallel-surface approach; high-speed nav	Drone autonomously approaches an overhead / floor target; telemetry log verifies 1 m/s peak velocity (M.P.3).
PR 11 (Mid-Nov)	Semi-autonomous five-point contact NDT	The drone sequentially traverses five predefined POI coordinates and successfully makes contact at each, with end-effector error $\leq$ 0.2 m and a hold time sufficient to record NDT data.
PR 12 (Late Nov)	Full system rehearsal; metric validation	Dry-run video of the full FVD; ground-truth measurement of ± 0.2 m end-effector accuracy via the Total Station.
FVD (Early Dec)	Fully-actuated drone with multi-DOF arm conducts contact-based NDT at five sequential POIs	See Section 7.3.3.

7.3.2 Test Details

The fall test plan extends the spring tests to dynamic manipulation, multi-POI missions, and ground-truth validation. The major fall tests are listed in Table 10; subsystem-level unit tests that have already passed in spring (e.g. cuVSLAM bring-up) are not repeated here.

Table 10: Major fall-semester test activities

Test	Description	Pass Criterion
Post-summer airworthiness	Re-validate all SVD capabilities after summer down-time	All SVD verification criteria still pass
EKF2 mission-mode tuning	Re-tune EKF2 to remove dead-reckoning fall-back during mission-mode flight	Two-minute autonomous mission with no manual recovery; horizontal drift $\leq$ 10 cm
Optical-flow integration on CubeOrange+	Resolve the parameter / firmware discrepancy that prevents OF fusion	OF velocity fused alongside VIO without rejection
F/T sensor integration	Integrate the ATI Gamma (or SingleTact backup) on hardware	5 N reading at the wrench controller within ± 1 N error
Visual servoing on hardware	Lock-on test using only the onboard camera (platform stationary)	Pixel error converges to zero from $\geq$ 2.5 m
Muti-DOF arm dynamic-stability test	Hover with arm executing full workspace maneuvers	Attitude held within $\pm 2^\circ$; thrust effort logged with and without CoM compensation
Five-point contact NDT rehearsal	Sequential contact at five predefined POIs	End-effector accuracy $\leq$ 0.2 m; force 5 N ± 1 N held for $\geq$ 10 s at each

7.3.3 FVD

Objective. Demonstrate the full Flying Hand pipeline: a fully-actuated drone with a multi-DOF arm performs sequential contact-based NDT measurements at five operator-selected POIs without crashing or losing tracking.

Element. Flying Hand (fully-actuated hexarotor + 3-DOF arm + contact probe + ATI / Single-Tact F/T sensor).

Location. RIC Drone Cage and / or Mill 19 cage, depending on weather and required ground-truth equipment availability.

Equipment. (1) Fully-actuated Flying Hand drone with the 3-DOF arm and force sensor; (2) Ground Control Station laptop with QGroundControl and the team's mission script; (3) Futaba 2.4 GHz transmitter (manual override); (4) Charged 22.2 V 6S LiPo battery pack (≥ 3 batteries); (5) Test wall fitted with five circular AprilTag-style POIs at heights between 0.5 m and 2.0 m; (6) Total Station for ground-truth measurement of POI position and end-effector contact location; (7) Safety equipment (pulley tether at takeoff height, safety glasses, fire extinguisher).

Personnel. Sang (pilot), Shubham (co-pilot / safety), Tanaya (perception monitor), Chenyang (controls / data), Shunxuan (manipulation / data).

Procedure. (1) Pilot performs the standard pre-flight check (battery, telemetry, kill-switch). (2) Drone is armed and manually flown to a station-keeping position ~ 2 m from the test wall. (3) Operator selects the first POI on the GCS video feed. (4) The drone transitions to semi-autonomous mode: IBVS guides the platform onto the POI, the multi-DOF arm extends, and the wrench controller establishes a 5 N contact for 5–10 s. (5) Real-time force and end-effector telemetry are logged on the Jetson and streamed to the GCS. (6) Drone retreats; pilot manually repositions to the next POI; steps 3–5 repeat for all five points. (7) After the fifth POI the drone is switched to Return-to-Home and lands. (8) Total Station measurements are taken offline against in-flight telemetry to verify accuracy.

Verification criteria. (1) End-effector probe contacts within a 0.2 m radius of the operator-selected target (measured against Total Station ground truth). (2) Wrench controller maintains 5 N ± 1 N normal force for ≥ 10 s at each of the five points. (3) All five POIs are completed within a single battery's flight time. (4) No loss of communication, fail-safe trigger, or unintended landing during the run. (5) Real-time NDT data, force traces, and end-effector positions are visualized on the GCS without interruption (M.P.8).

7.4 Budget

No.	Date	Part Name	Quantity	Price
#3	02/23/26	Eolo Carbon Fiber Reinforced Nylon UAV Propellers	6	$107.94
#4	02/23/26	Holybro H-Flow Optical Flow and Distance Sensor Module	1	$145
#5	03/21/26	Calibrated Capacitive Force Sensor	1	$135.95
#29	03/24/26	12000mAh 22.2V 6S 20C Lipo Battery	4	$399.96
#33	04/01/26	RM3100 Compass	1	$79.9
#35	04/08/26	RC Series 10000mAh 22.2V 6S 100C Lipo Battery	2	$305.98

Total Expenses: $1321.18 / $5000



Figure 19: Spring-semester budget. Total spent: $1,321.18 / $5,000.

Our budget cap is $5,000. Total expenditure to date is $1,321.18, or approximately 26.4% of the budget. The largest spring expenses (Figure 19) are the LiPo battery packs ($705.94 for two sets of high-discharge 22.2 V 6S packs that support sustained fully-actuated flight) and the calibrated capacitive force sensor ($135.95, the SingleTact backup); these together account for 64% of the spring spend. The remaining ∼$3,680 budget is reserved for the multi-DOF arm components (servo motors, joint hardware), the SingleTact / ATI integration hardware, and a contingency for crash repairs (propellers and motor replacements) during the fall flight campaign.

Big-ticket items. (1) LiPo battery packs — $705.94 for two sets, sized for sustained fully-actuated hover; (2) carbon-fiber reinforced propellers — $107.94 (six props sized for the new tilted geometry); (3) calibrated capacitive force sensor (SingleTact) — $135.95; (4) RM3100 compass — $79.90; (5) Holybro H-Flow optical flow + lidar module — $145. Anticipated fall big-ticket items are the multi-DOF arm servos and the manipulator linkage, which we have estimated at ∼$500 based on the trade-study selection.

7.5 Risk Management

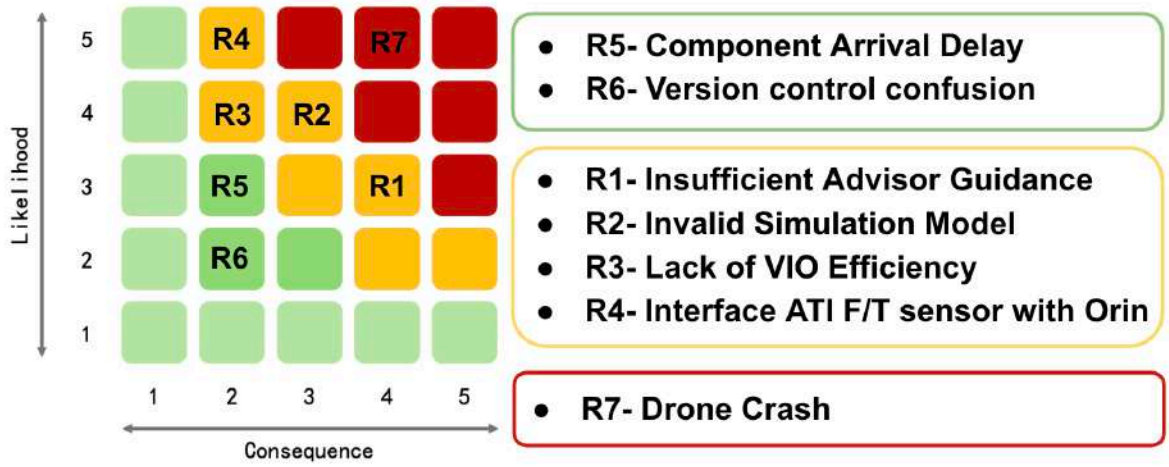


Figure 20: Updated risk likelihood-consequence matrix.

The team tracks risks weekly and updates the likelihood-consequence matrix at every PR. Compared to the PDR risk register, three changes have been made: (1) the original ”Insufficient Manipulation Precision” risk has been replaced by the more concrete ”Inability to interface ATI F/T sensor with Orin”; (2) ”Code Integration Error” has been promoted to a higher-likelihood ”Version control confusion” risk based on actual spring experience; and (3) a new ”Drone Crash” risk has been added in the high-likelihood, high-consequence quadrant after the maiden fully-actuated flight campaign confirmed how aggressive the tilted-rotor yaw response is. Risk 1 (Insufficient Advisor Guidance) and Risk 2 (Invalid Simulation Model) have been carried forward and partially mitigated by establishing direct contacts with the AirLab and LeCAR labs.

The current likelihood-consequence matrix is shown in Figure 20 and the corresponding mitigation plans are listed in Figure 21.

Risk ID	Risk Description	Likelihood	Impact	Mitigation Plan
R1	Insufficient Advisor Guidance	4	3	Establish connections with partner labs
R2	Invalid Simulation Model	3	4	Modify the model based on the reference materials and obtain feedback
R3	Lack of VIO Efficiency for GPS-Denied Navigation	2	4	Fusion of multi-sensor data, including optical flow and IMU, to achieve robust performance
R4	Inability to interface ATI F/T sensor with Orin (on-board computer)	2	5	Try to use single axis piezoelectric
R5	Component Arrival Delay	2	3	Construct the whole picture of the technical implementation as early as possible
R6	Version Control Confusion	2	2	Timely update and delete unused branches
R7	Drone Crash	4	5	Pre-Check and Simulation

Figure 21: Risk details

Top mitigations carried into fall.

- **R7 Drone Crash** (high likelihood, high consequence): All new flight envelopes (multi-DOF arm hover, near-overhead approach, 1 m/s waypoint chase) will first be exercised in Gazebo. The pulley tether system designed in spring will be re-deployed for early fall takeoffs of the new multi-DOF configuration. Pre-flight checklists are signed off by two team members.
- **R4 ATI F/T sensor** (low likelihood, high consequence): SingleTact backup procured and ready to deploy if the ATI legacy-software issue is not resolved by PR 8. Wrench controller already runs on simulated data so software development is not blocked.
- **R5 / R6 Component delay and version-control confusion**: All long-lead-time fall components (servos for the 3-DOF arm, additional batteries) are ordered in the first week of August. Version control is enforced via feature branches with mandatory two-person review for the PX4, controls, and visual-servoing repositories.

8 Conclusions

8.1 Lessons Learned

- **RIC Test Location:** Magnetometer readings were unreliable due to heavy magnetic interference at the site, leading to poor heading estimation. Additionally, low satellite count (likely due to RF interference) prevented GPS and RTK from functioning properly, limiting ground truth trajectory validation to only a partial segment.
- **Hardware is Never Plug-and-Play:** Integrating modules we assumed would ”just work” (optical flow, Emlid RTK, F/T sensor alternatives) consumed significant time; each required ad hoc troubleshooting and in some cases full replacement — hardware integration overhead must be budgeted upfront.
- **Key-Man Risk per Subsystem:** Each subsystem being majorly owned by a single person created blind spots and no fallback — having at least two people per subsystem would improve fault anticipation, provide redundancy, and avoid development happening in isolation.

8.2 Key Fall Activities

The fall semester is organized around the four activities below, each tied directly to one or more fall test-plan items in Section 7.3.

- **Integration and validation of the wrench controller and visual servoing on hardware:** Bring the wrench controller and IBVS, both of which work in simulation today, onto the real platform with the real F/T sensor (ATI or SingleTact backup) and the real RealSense camera. Demonstrate IBVS lock-on, contact, and a 5 N ± 1 N hold on the test wall by PR 8.

- **Manipulator design, build, and CoG-balanced integration:** Finalize the design of the 3-DOF arm chosen in the trade study (3-DOF arm at $4.3/5$, optimal balance of dexterity, weight, and cost), 3D-print and assemble it, and integrate it on the platform with explicit CoM compensation. The dynamic-stability test at PR 9 (hover within $\pm 2^{\circ}$ while the arm moves through its full workspace) is the first capability gate.
- **Multi-POI semi-autonomous mission:** Extend the single-contact pipeline validated in spring into a sequential five-POI mission. The drone must reach all five waypoints within ± 0.2 m of the target coordinates, hover for the time required to perform NDT data collection at each, and complete the run on a single battery.
- **Tuning, rehearsal, and FVD:** Front-load EKF2 tuning, IBVS gain tuning, and wrench-controller re-tuning to PR 7 / PR 8 so the remaining fall sprints can focus on integration and rehearsal. Run a full-mission dry-run at PR 12 with Total Station ground-truth measurements before the FVD in early December.

References

[1] Guanqi He, Yash Jangir, Junyi Geng, Mohammadreza Mousaei, Dongwei Bai, and Sebastian Scherer. Image-based visual servo control for aerial manipulation using a fully-actuated UAV. In *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2023.

[2] Azarakhsh Keipour. *Physical Interaction and Manipulation of the Environment using Aerial Robots*. PhD thesis, Carnegie Mellon University, 2022.