Flying Hand

Aerial Manipulator for Non Destructive Testing

TEAM C



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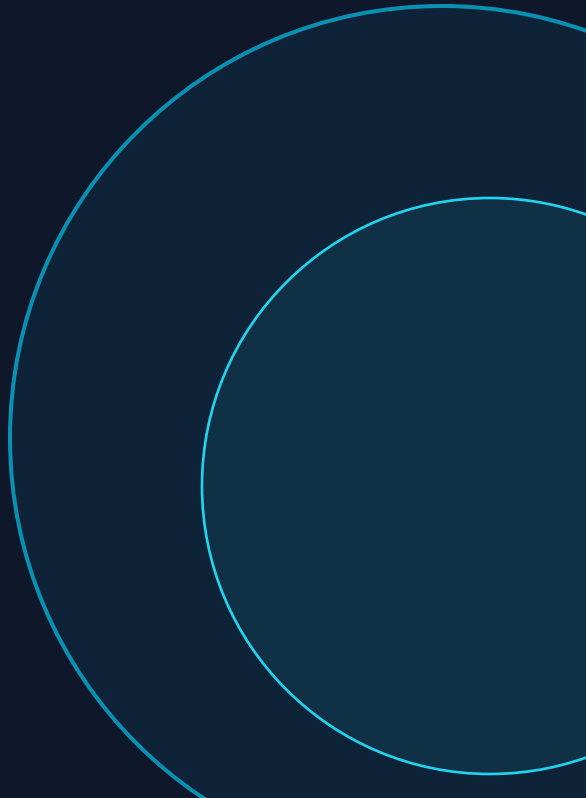
Chenyang Mao



Shunxuan Wang

01

Project Description



Background







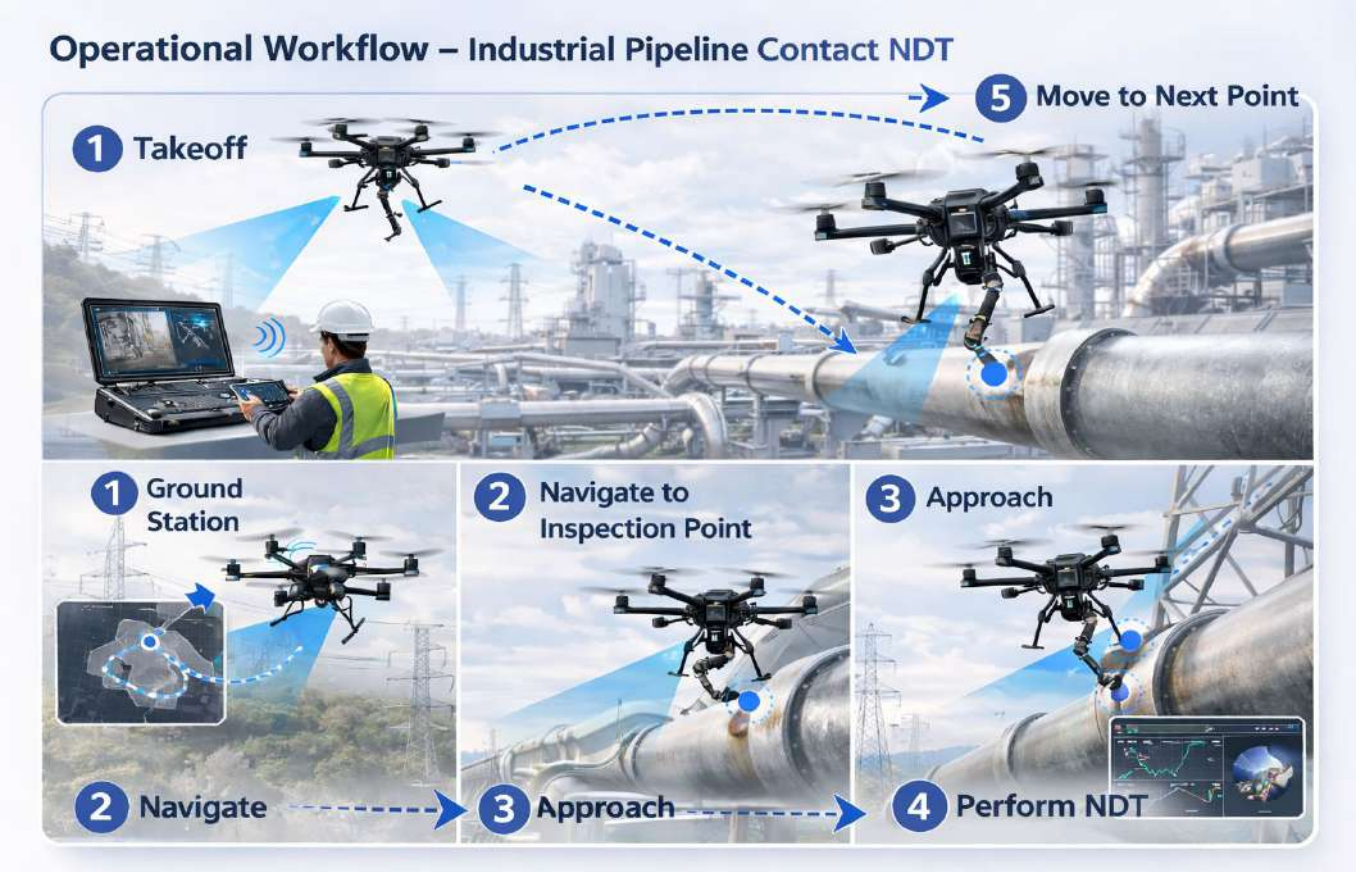
Non Destructive Testing is the backbone of preventive asset maintenance —
but still limited by costly inspection downtime, accessibility constraints and safety risks.

Use Case

An industrial maintenance team conducts routine pipeline inspection **without interrupting normal operations**. An operator deploys the Flying Hand to **hard-to-reach areas**, where it autonomously navigates to inspection points, approaches the pipe surface, and uses its onboard robotic arm to perform **contact NDT**. The system sends real-time observations and inspection data to the operator, helping the team detect early signs of damage and plan timely maintenance **before serious issues develop**.

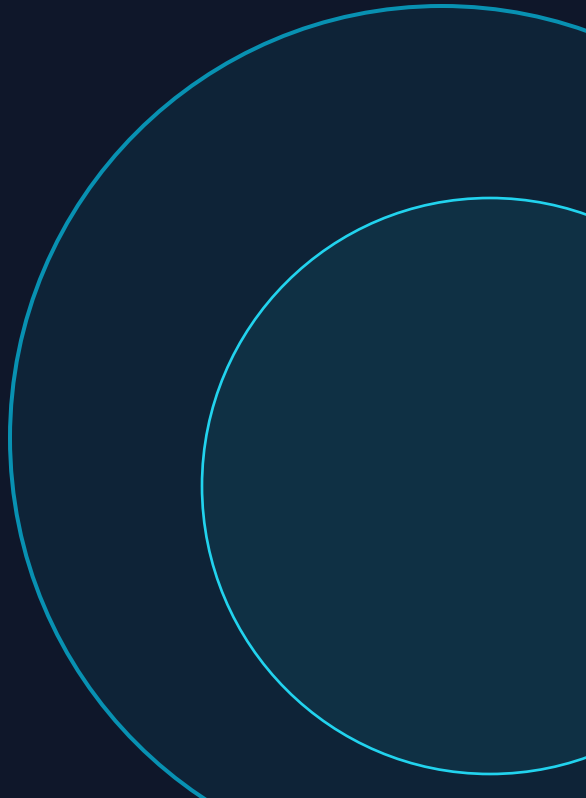


Our Solution



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System-Level Requirements



Functional Requirements

The Flying Hand SHALL

- Sense the environment
- Localize itself
- Localize POI (Point of Interest)
- Plan the drone's path
- Fly to the AOI (Area of Interest)
- Hover stably
- Detect POI precisely
- Plan the arm's motion
- Manipulate the end-effector
- Perform NDT
- Store/Relay sensor information
- Provide real-time visual feedback to the operator
- Execute a fail-safe response upon loss of communication

Performance Requirements

The Flying Hand WILL

- **Sense** the environment in the range of **0.5-4 m** away from itself
- **Localize** itself within **10 cm** of true position
- **Navigate** the environment at the maximum speed of **1 m/s**
- **Detect** POI from the distance of at least **2.5m**
- **Communicate** with maximum latency in **100ms**
- **Sample** NDT data at **5** waypoints in a single flight
- **Maintain** end-effector positioning accuracy of **±0.15 m** during optimal operation
- **Maintain** position hold under **wind speeds up to 3 m/s**
- **Execute** fail safe response within **1 s** of communication loss

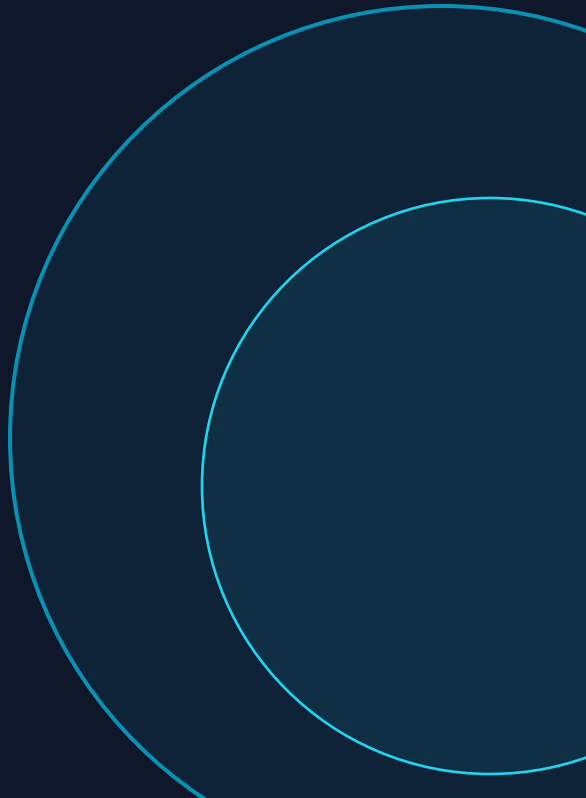
Non-functional Requirements

The Flying Hand WILL

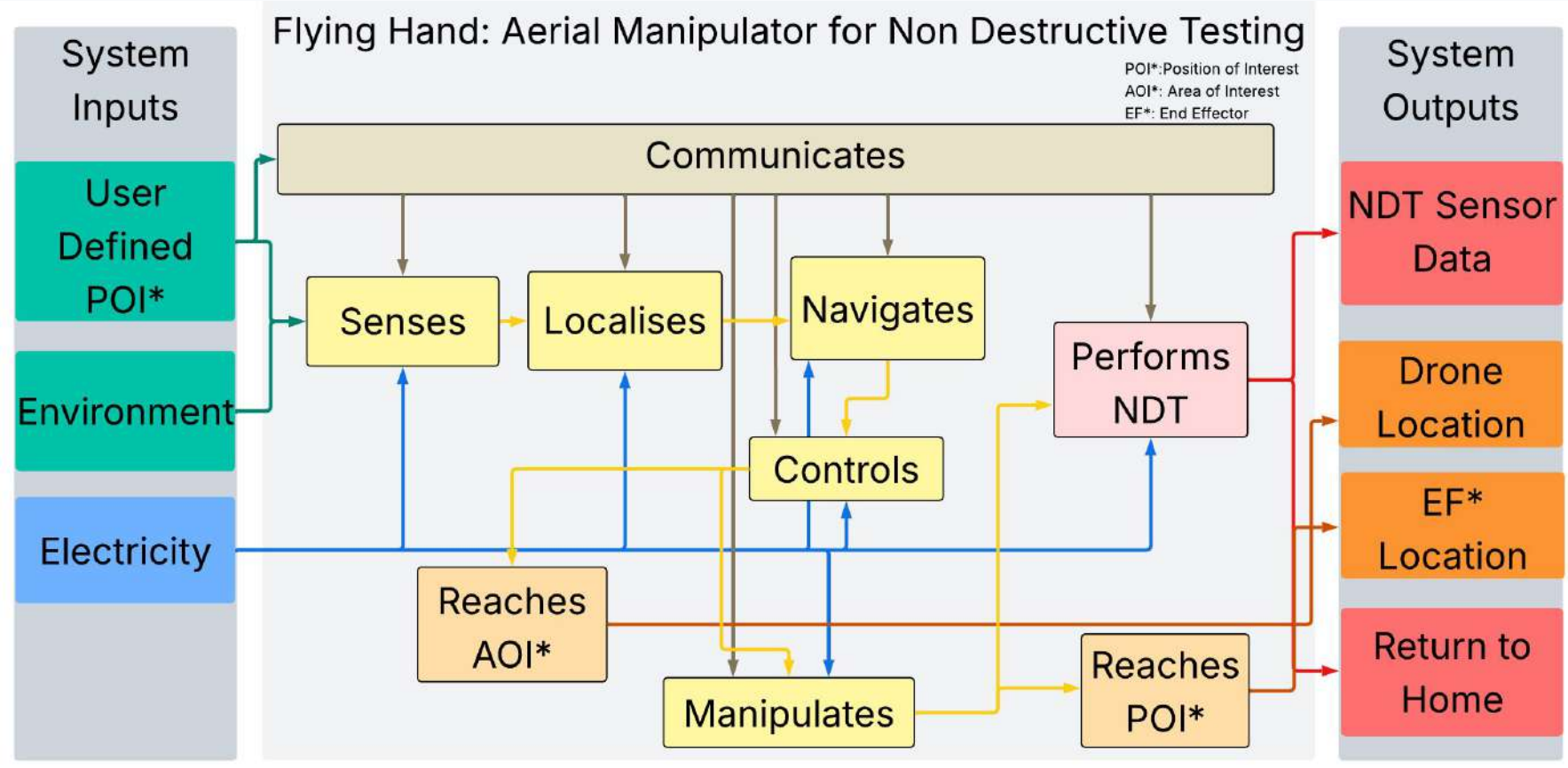
- **Be modular** (Quick probe replacement or end-effector module exchange)
- **Be lightweight** (Total take-off mass will no more than 15 kg)
- **Be easy to use** (Trained operator can plan the mission quickly)
- **Convey actionable information** (Store NDT data in standard formats)
- **Be compact** (The system's size will be small for transportation)
- **Be adaptable to environment** (Operate in temperature from −5°C to +40°C & humidity upto 95%)

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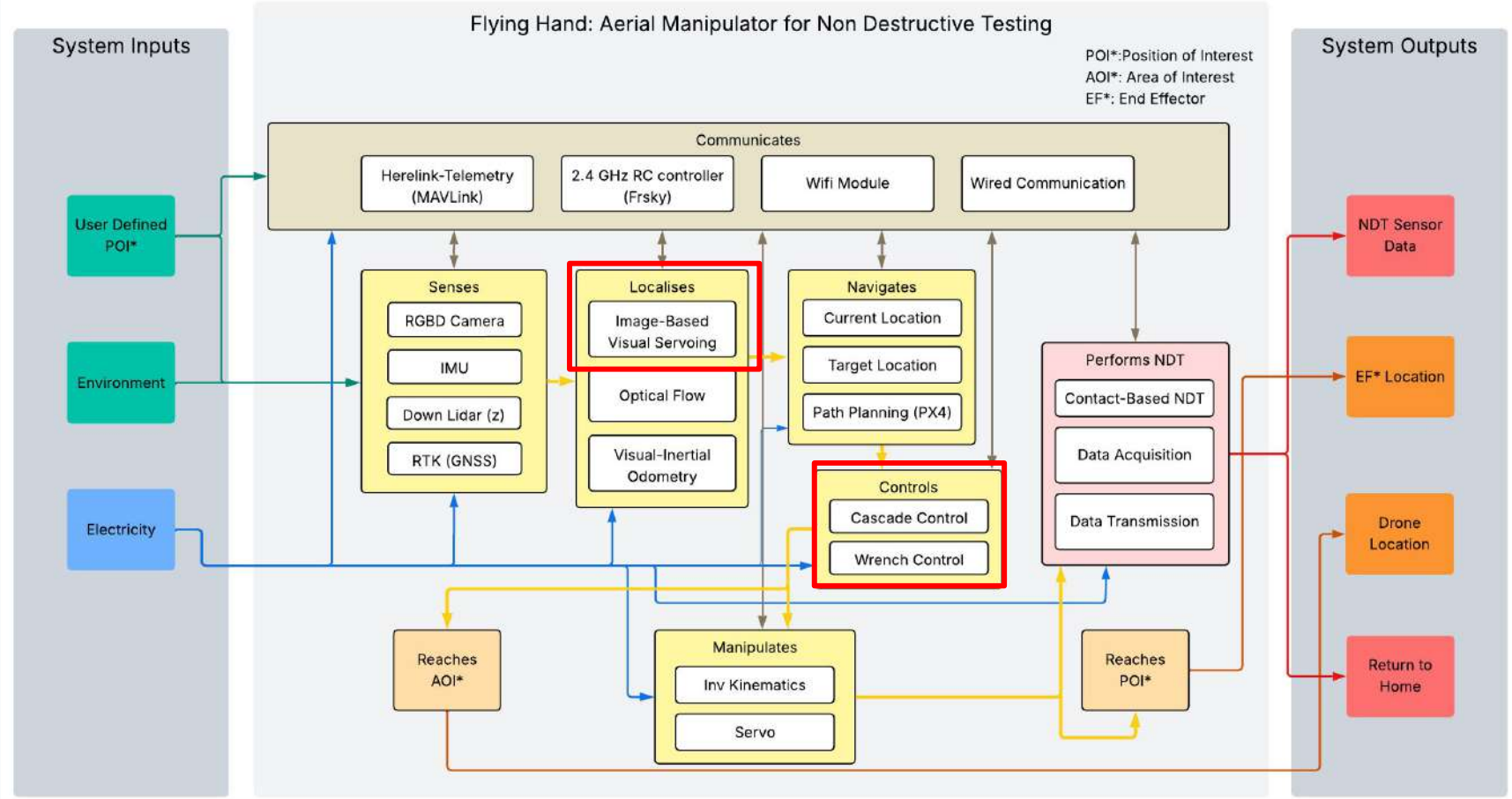
Architecture



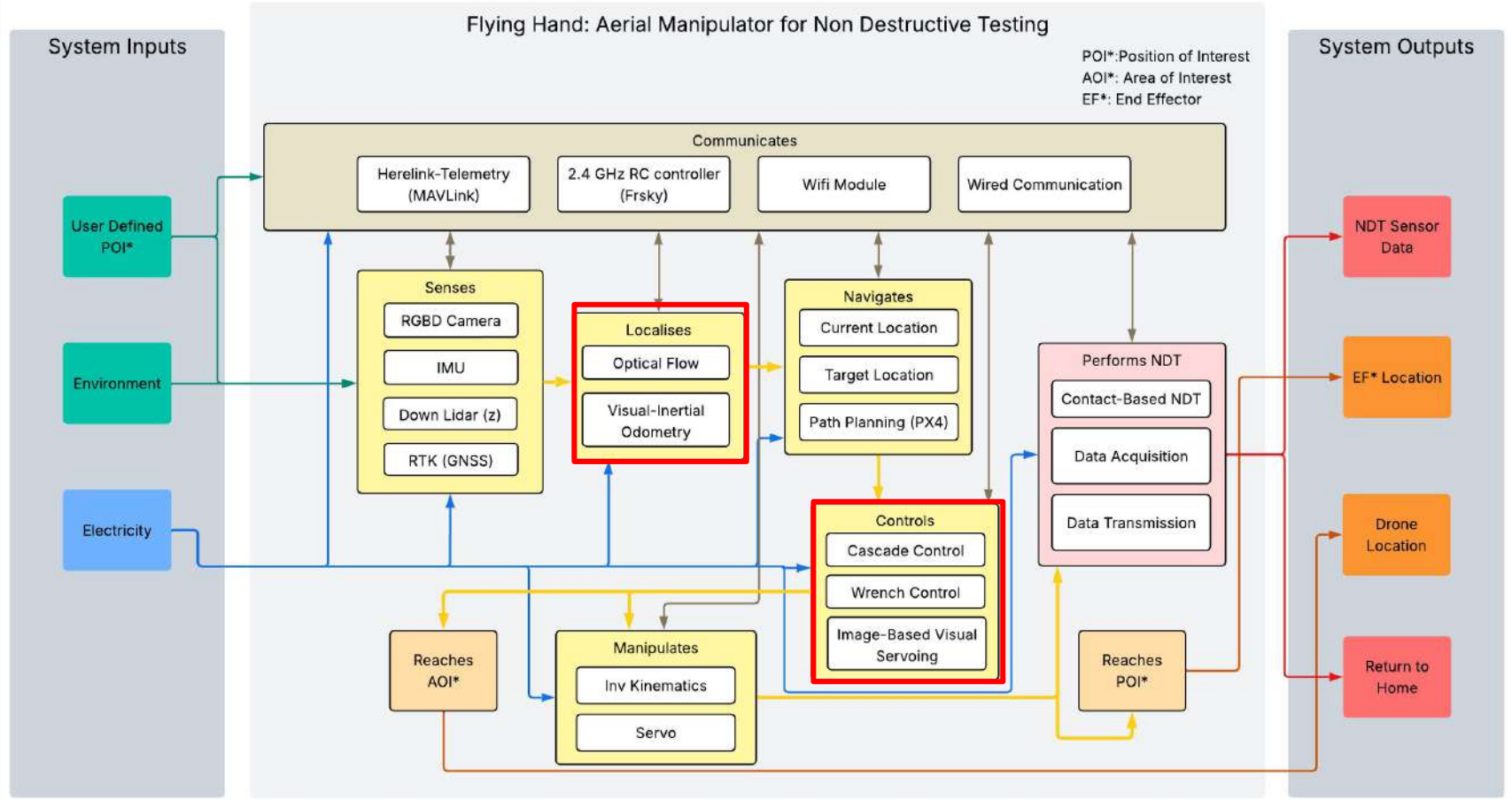
Functional Architecture



Old - Cyber-Physical Architecture



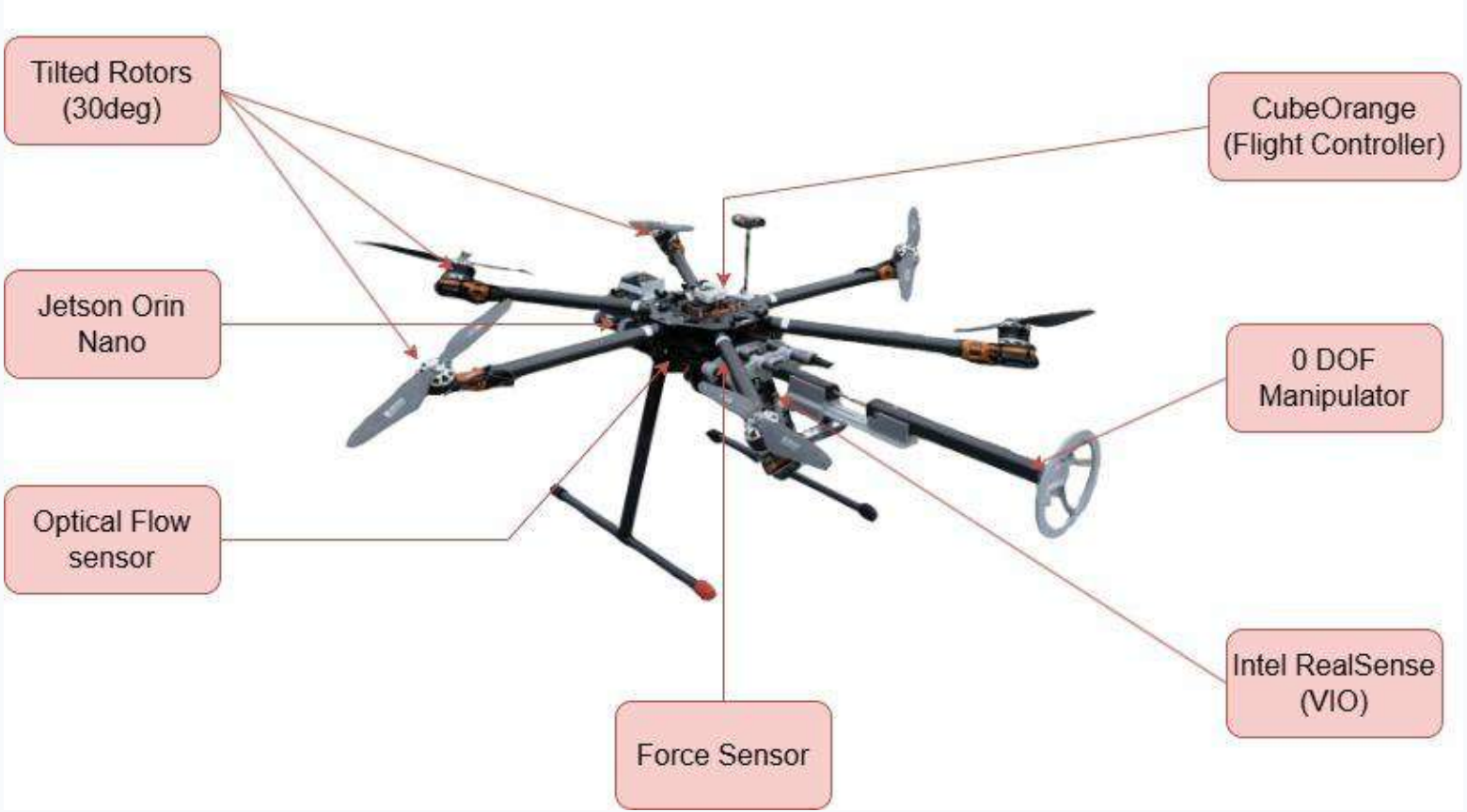
New - Cyber-Physical Architecture



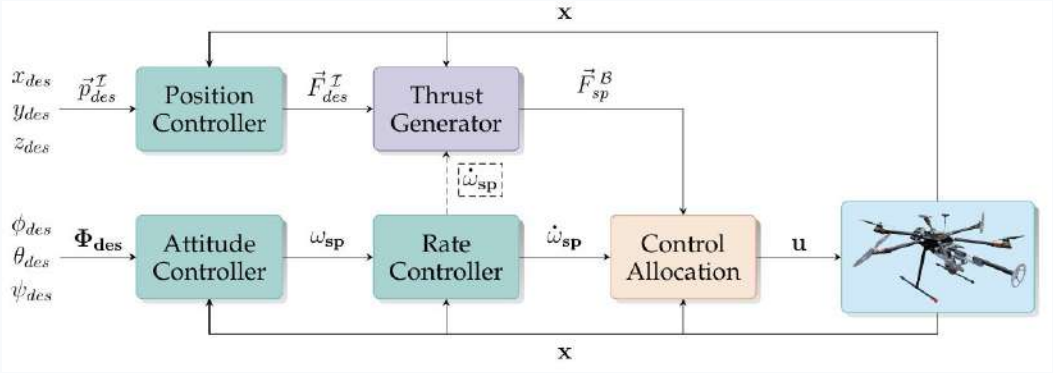
04

Current System Status

Overall System



UAV Platform - Software/Controller



Modifications Done to the PX4

1. **Position Control:** Created new function that computes the NED thrust vector directly from acceleration without coupling it to body tilt. (Thrust Generator)
2. **ControlMath:** Backs this up with 6 new conversion strategies (the omni modes 0–6), each a different policy for how to set attitude while still delivering the required body-frame thrust.
3. **Attitude Controller:** Disabled attitude failure detection to allow functioning with only desired yaw, [0, 0, ψ_des]
4. **Control Allocation:** The per-rotor geometry with tilted axis is defined such that allocator has both vertical and lateral force components.
5. **Multicopter Position Control:** Modified to pass the current quaternion to close the feedback loop (x).

Image courtesy of Azarakhsh Keipour, CMU-RI, 2022. Used for academic purposes.

UAV Platform - Hardware



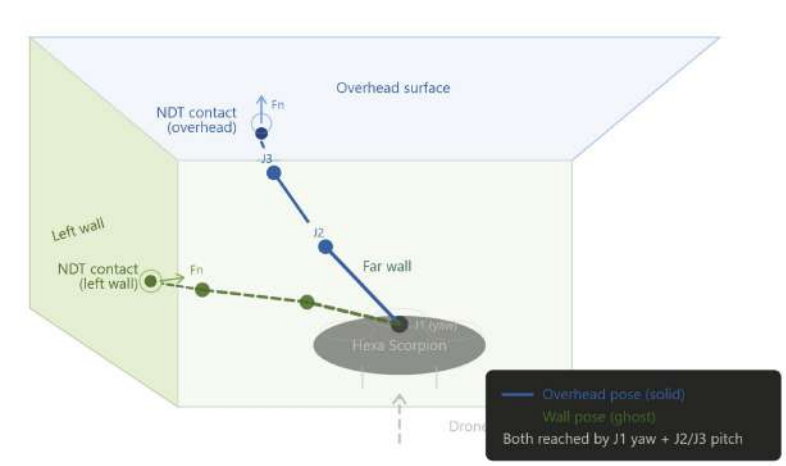
Current Status:

- Fully-actuated hexa-rotor capable of stable position-hold and mission flights
- Integrated with the GPS-denied localization system and 0 DOF manipulator system.



UAV Platform - Hardware

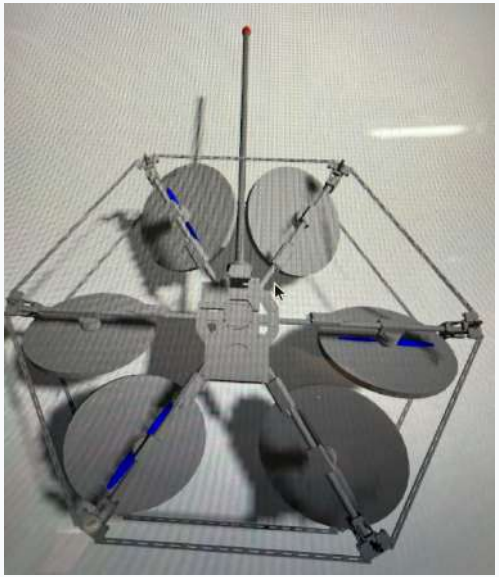
Final State:
Fully-actuated hexacopter with multi-DOF arm to reach overhead and orthogonal lateral surfaces

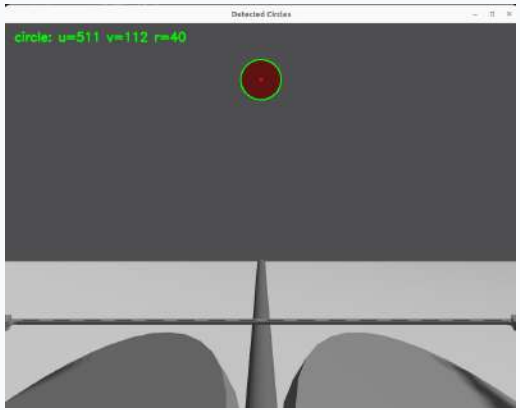




Manipulation - Software







Fully actuated hexacopter with F/T sensor in the gazebo simulation

Manipulation - Hardware

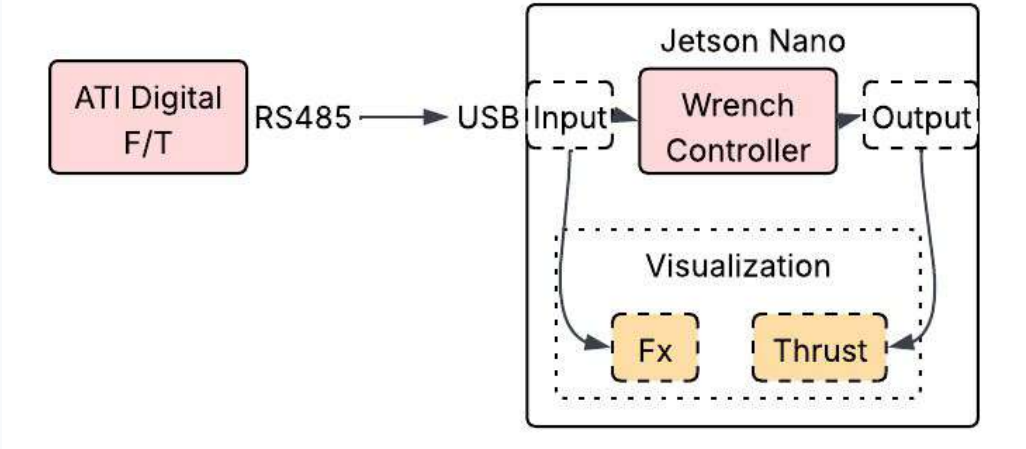












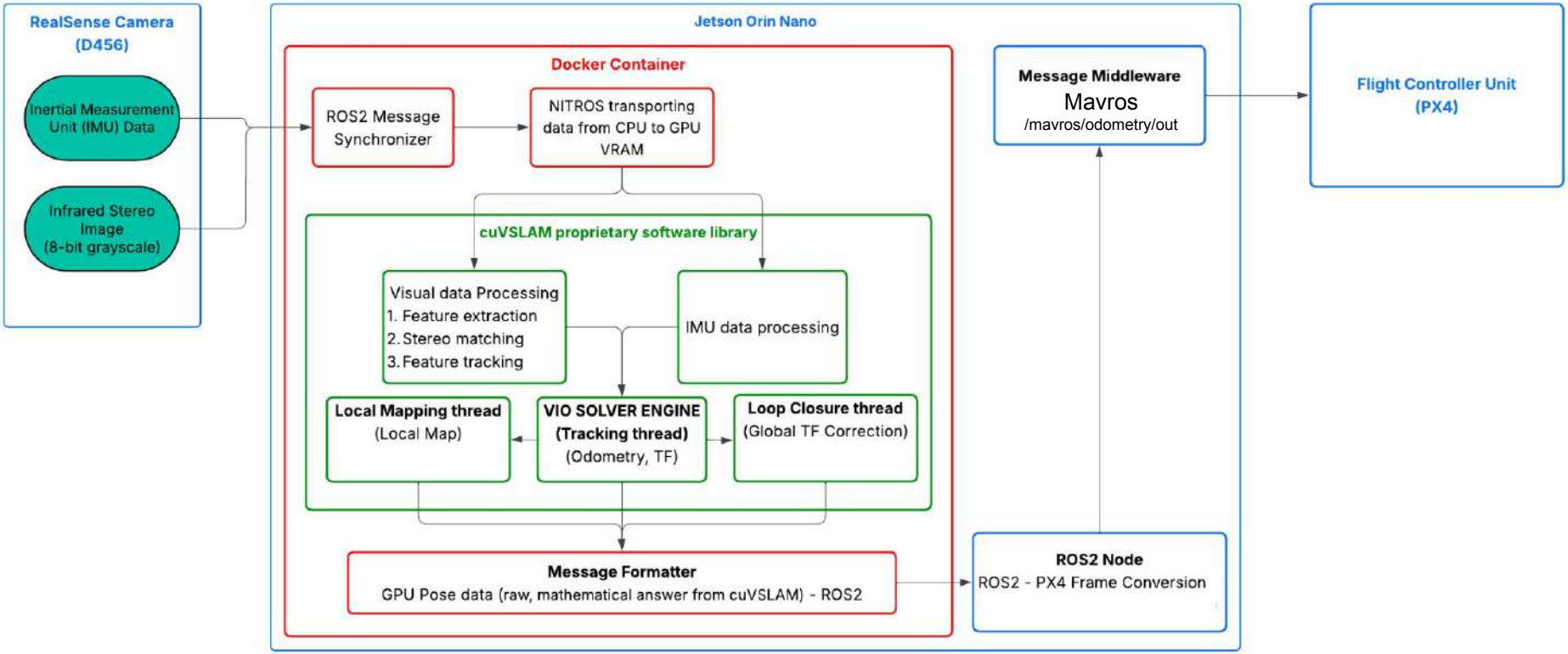
Manipulation - SVD Performance Evaluation

- The drone can perform **fully-actuated (6DOF)** flight, and **make contact** with flat surfaces with wind speeds upto 2 m/s and gusts of 5m/s.
- The force sensor can **measure contact force(5N)** and calculate **desired thrust** output from the **Wrench Controller**

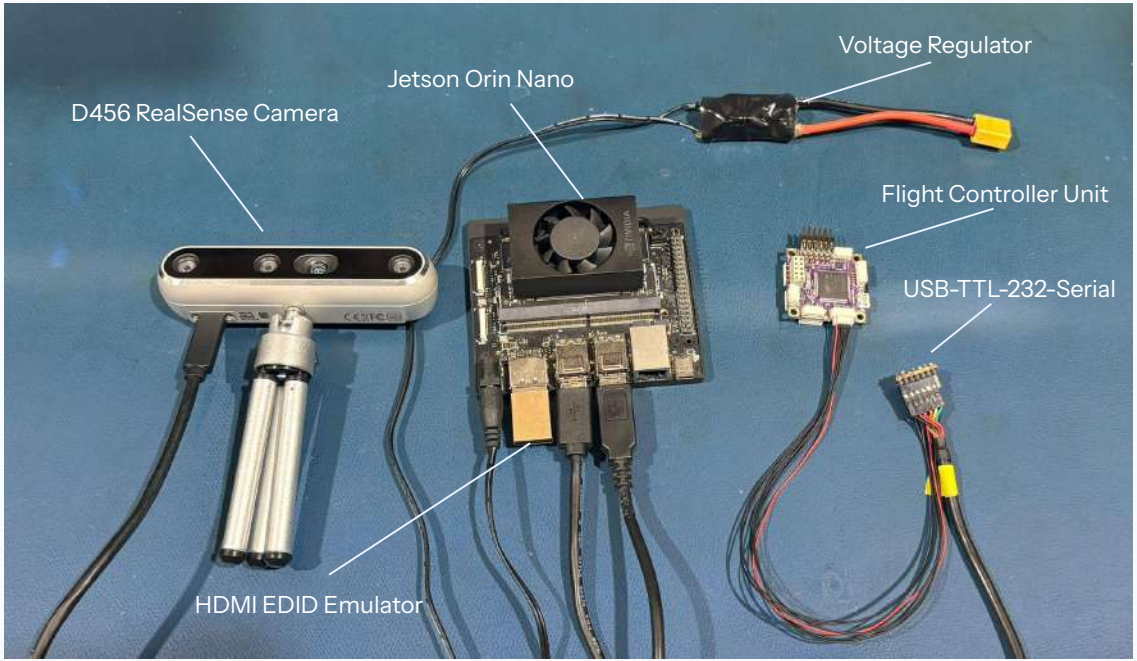




Localization - VIO (Software Pipeline)



Localization - VIO (Hardware Setup)

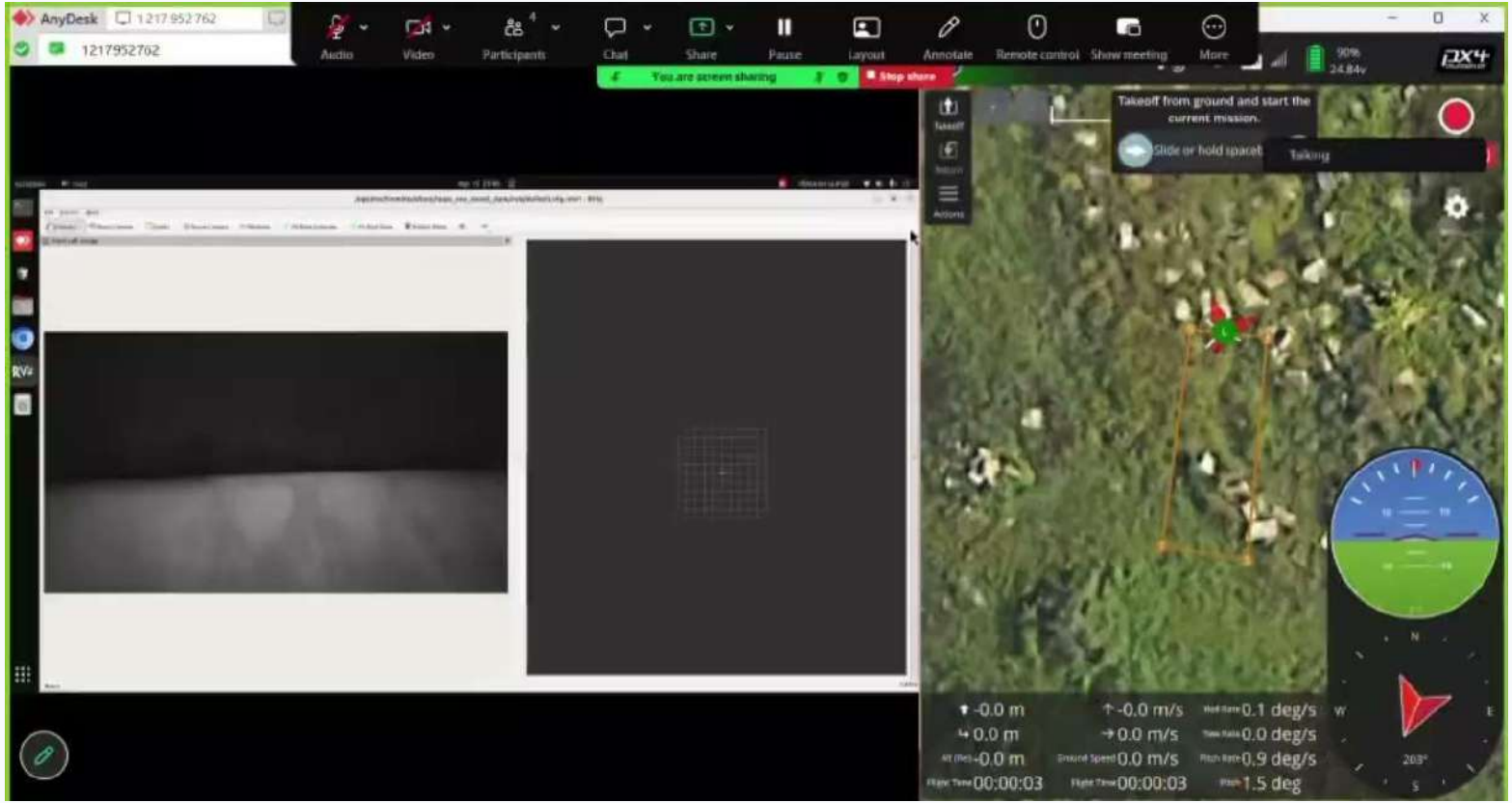


- Voltage Regulator
- Jetson Orin Nano
- D456 RealSense Camera
- Flight Controller Unit
- USB-TTL-232-Serial
- HDMI EDID Emulator

Localization - VIO (Position Hold + Applying Force)



Localization - VIO (Waypoints Navigation)



Localization - SVD Performance Evaluation

Open-Area autonomous navigation

Do waypoints navigation and
land automatically within 0.5 m of target point

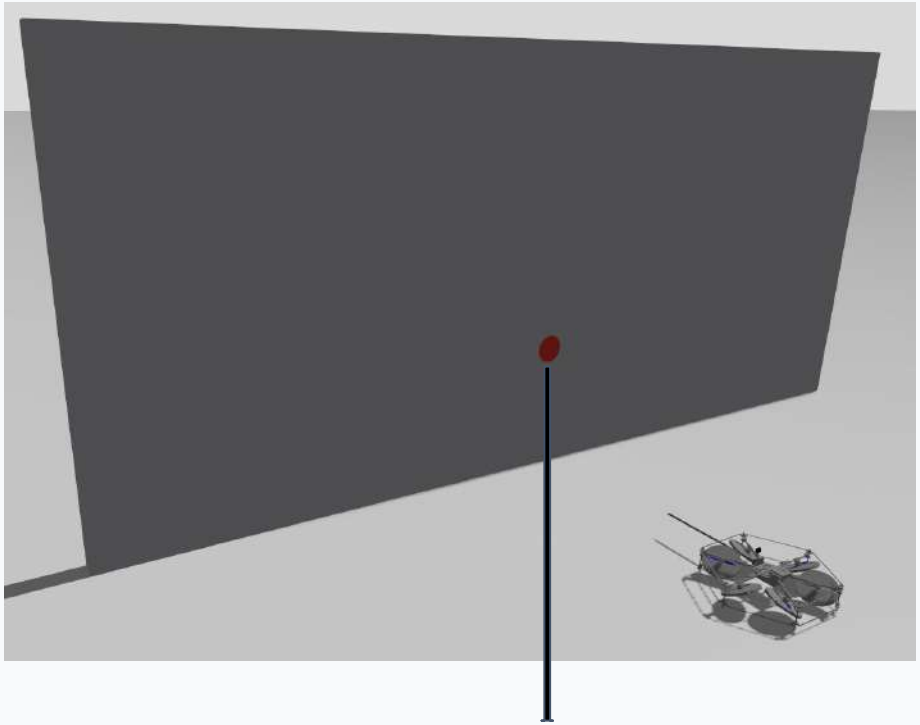
Near-Wall position holding

~0.3 m Away from the Wall
~1.5 m Flight Height
Hover for 30 s

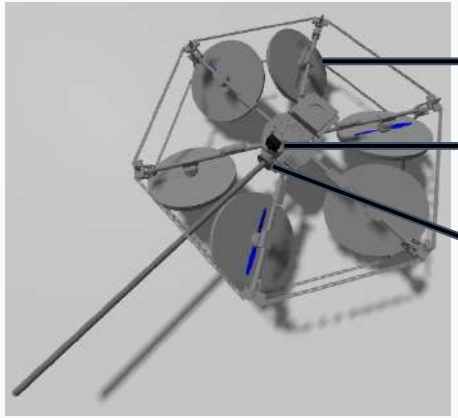


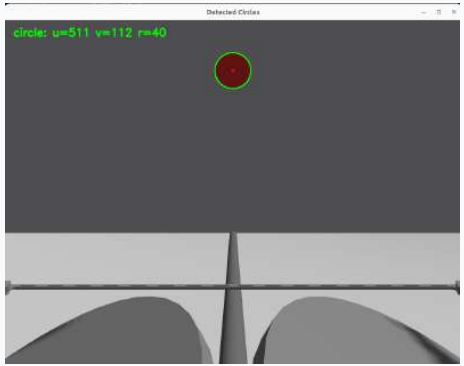


Simulation



Target Localization



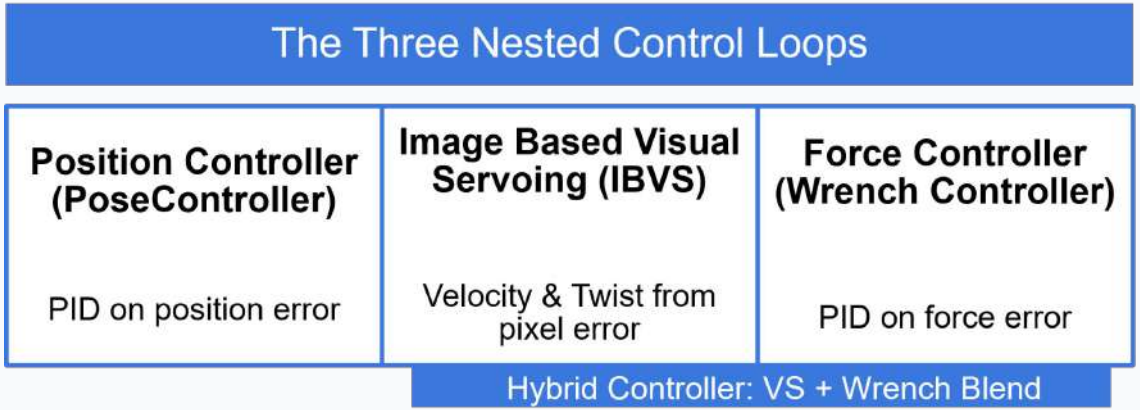


Simulation

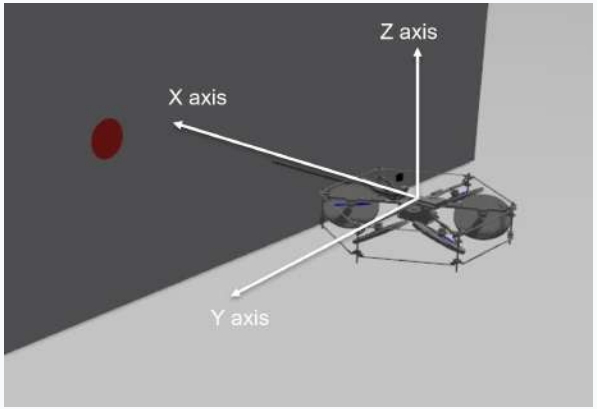
Mission Script:



The Blending: How the Three Loops Combine

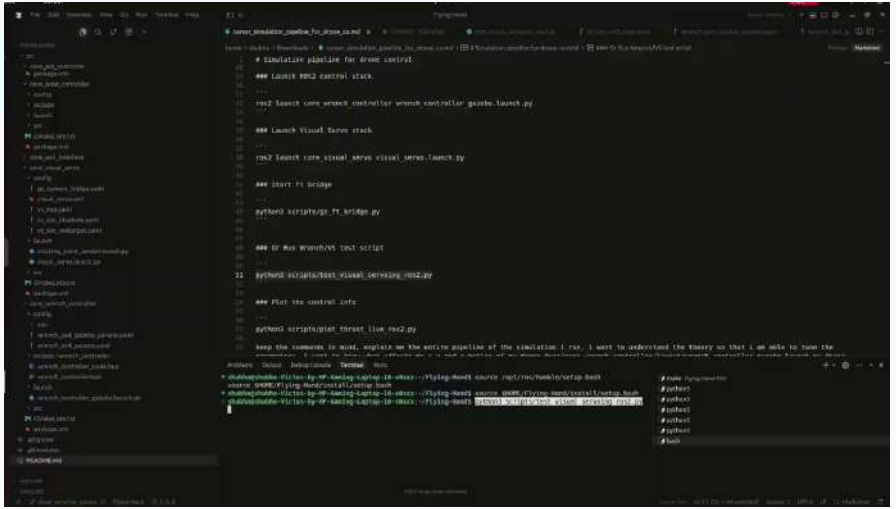


The Axis Control: What Affects X, Y, Z Motion



Simulation - SVD Performance Evaluation

- Effective Distance of Visual Servo Controller **> 2.5 m**
- Arm-end Contact Error **< 0.15 m**
- Force-convergence Time after Contact **< 3 s**
- Maintain a Constant Force **5±1 N**
- Duration of Force Application **≥ 15 s**



05

SVD Demonstration

Progress Video



SVD Conclusion

Manipulation Performance

- Fully-actuated drone successfully made contact with the target surface; force sensor accurately measured contact force and the Wrench Controller computed the desired thrust output.
- All performance criteria were met.

Full Pipeline Simulation

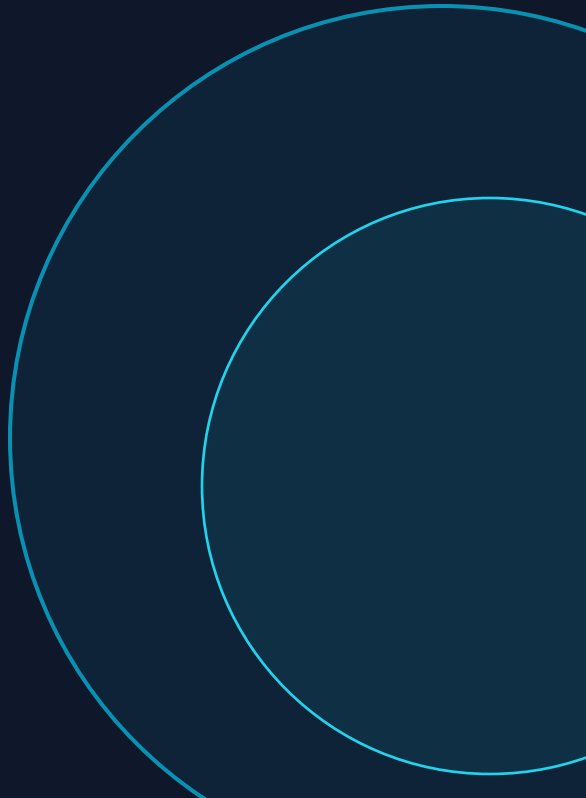
- Drone autonomously took off, detected the POI, and used visual servoing to guide approach; upon contact, the Wrench Controller applied a continuous 5 N force for over 10 sec.
- Simulation results confirmed overall system readiness.

VIO Localization Performance

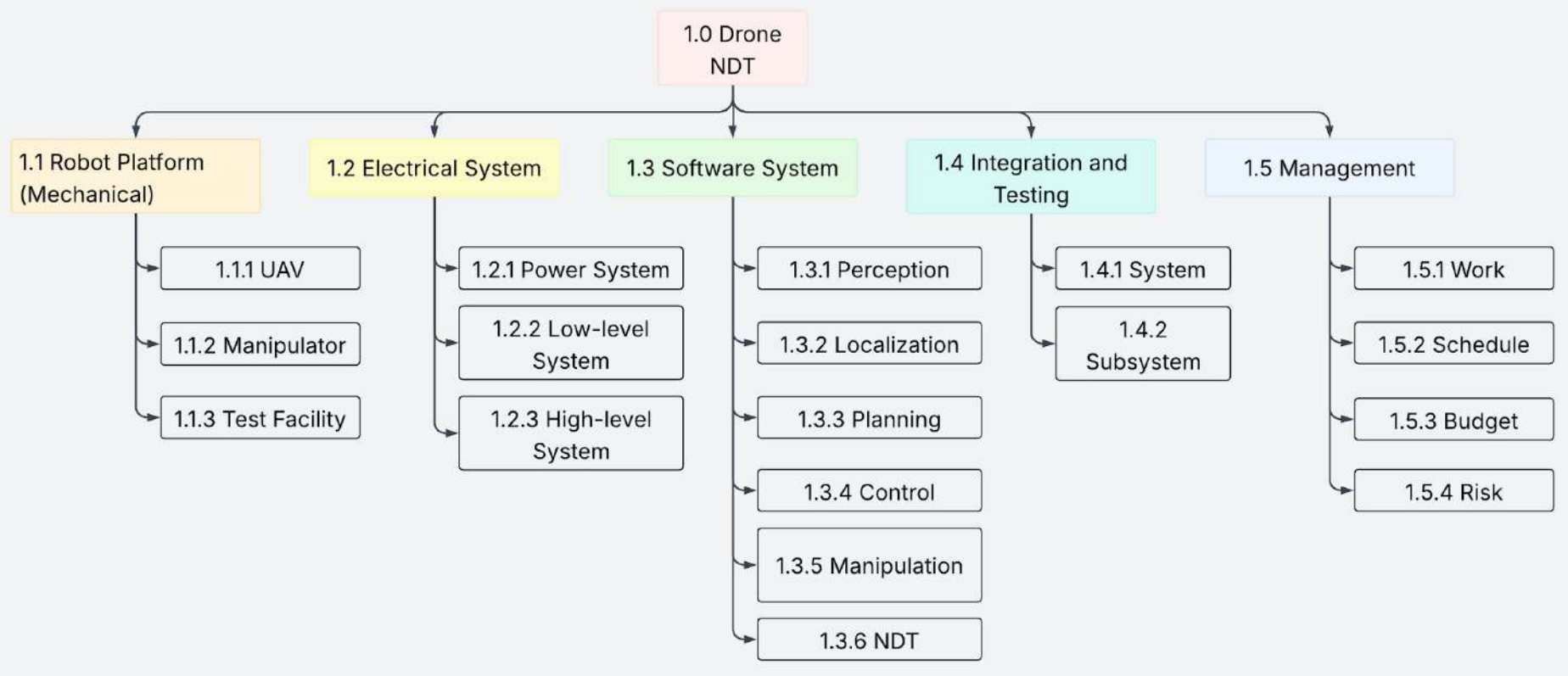
- **Strengths** Near-Wall Hover Test: Successfully maintained stable position hold (~0.3 m from wall, 1.5 m height) for the full 30-second duration.
- **Weakness:** Waypoint Navigation: In autonomous mode, PX4's EKF2 did not prioritize VIO over the accelerometer, causing localization drift and degraded wavepoint tracking accuracy— manual teleoperation was required mid-flight to recover. EKF2 fine tuning is required.

06

Project Management



Work Breakdown Structure



Spring Validation Demo

Spring Validation Demonstration	
Objective	Test 1: Demonstration of a fully-actuated drone, gps-denied localization, force application, and wrench control output during real flight Test 2: Demonstration of wrench control and visual servoing in simulation
Element	Flying Hand
Location	RIC Drone Cage/Near Mill 19
Equipment	(1) Tarot X6 Drone (2) Ground Control Station (3) LiPo Batteries (4) Futaba Transmitter (5) Measuring Scale (6) Gazebo Simulation
Personnel	Sang/Tanaya/Shubham/Chenyang/Shunxuan

Spring Validation Demo

Procedure
Test 1: 1. The drone is teleoperated to perform different maneuvers (forward and lateral movements) to demonstrate its fully actuated capabilities and ability to maintain position hold. The pilot then stops issuing commands for 10-20 seconds to illustrate position drift over time, after which the drone is landed. 2. The drone is teleoperated toward a mock wall. Once the probe is within close proximity (approximately 10cm), the pilot ceases input and demonstrates precise hovering near the wall for 20-30 seconds. 3. The drone is then teleoperated to make contact with the wall, applying an approximate 5 N, which is measured using the onboard force/torque sensor. 4. During the interaction, real-time force measurements and wrench control outputs are displayed. 5. After applying the force, the drone retreats and performs another contact maneuver, after which it is teleoperated to land. **Test 2:** 1. Launch the Gazebo simulation on the PC and initialize the relevant nodes while running the test script. 2. The drone, equipped with an F/T sensor, will automatically take off to a predefined height, navigate to the POI using the visual servoing subsystem, and apply a desired steady force on the wall via the wrench controller. 3. After completing the interaction, the drone will move away from the wall and land.

Spring Validation Demo

Verification Criteria
Test 1: 1. The drone autonomously lands within a 0.5m radius of the designated ground target. 2. During the 10-15 second NDT simulation, the drone holds its position accurately without drifting, keeping the target continuously inside the camera frame. 3. Real-time force measurements from the F/T sensor and wrench control outputs are correctly visualized on the Orin Nano with no data interruption. **Test 2:** 1. The drone will contact the POI on the wall, where the POI is defined as a circular target with a diameter of 300 mm, positioned at a height of 1.5 m. 2. The drone will then apply a steady desired force of 5 N, maintaining an error margin within ±1 N for a duration of 10 seconds.

Spring Test Plan

Test ID	Test Title	Test Description	Finish Before
T1	Under-Actuated Ground Test	Test airframe hardware integration and bench validation	PR1
T2	Ground VSlam Test	Validate GPS-denied navigation with VSlam on ground	PR2
T3	Under-Actuated Flight Test 1	Maiden flight in under-actuated configuration	PR2
T4	Under-Actuated Flight Test 2	PID tuning in under-actuated configuration	PR2
T5	Under-Actuated Flight Test 3	Flight with RTK in Under-Actuated Configuration	PR2
T6	Flight Failsafes Test	Validate hardware integrity of UAV and the failsafes	PR2

Spring Test Plan

Test ID	Test Title	Test Description	Finish Before
T7	Flight VSlam Test	Validate GPS-denied navigation with VSlam on flight	PR3
T8	Fully-Actuated Flight Test 1	Fully-actuated drone flight test under position control mode	PR4
T9	Fully-Actuated Flight Test 2	Fully-actuated drone flight test under force control mode	SVD
T10	Visual Servoing without UAV Test	Validate visual servoing pipeline without UAV flight, ensuring stable and correct command generation	PR3
T11	Optical Flow without UAV Test	Validate optical flow pipeline and motion estimation output	PR3
T12	Visual Servoing and Optical Flow Test	Validate integrated navigation pipeline, enabling the UAV to autonomously fly to the designated target	PR4

Fall Test Plan

Month	Capability Milestone	Tests	Validation
August	UAV quality assurance after summer break	1. Check all subsystems and units are working correctly 2. Improve PX4 EKF tuning	The UAV can complete all tasks from Spring
September	Integrate wrench controller and visual servoing on hardware	1. Test visual servoing accuracy 2. Tune PID gains for wrench controller	1. Visual servoing to publish correct goal pose in all conditions. 2. Hybrid controller holds a stable position and consistent contact

Fall Test Plan

Month	Capability Milestone	Tests	Validation
October	1. Integrate front facing obstacle avoidance 2. Integrate multi-DOF manipulator for improved dexterity	Dynamic Coupling and Disturbance Rejection Test, where the drone must maintain a stable, hover while the multi-DOF arm executes maneuvers across its full operational workspace.	The UAV remains stable during manipulation, end-effector reach a specific coordinate and maintain a steady, perpendicular contact.
November	Semi-autonomous contact	The drone must sequentially traverse five predefined (POI) coordinates find the best strategy to make contact.	Drone to reach all five points within a error ± 0.2m of the target coordinates and successfully hover for the time required to complete NDT data collection at each stop.

Fall Validation Demonstration

Objective	Demonstrate fully actuated drone with multi DOF arm to conduct NDT
Element	Flying Hand
Location	Mill 19/RIC Drone Cage
Equipment	1. Fully-actuated drone 2. Ground Control Station 3. Futaba Transmitter 4. Multi DOF custom-designed manipulator arm
Personnel	Sang/Tanaya/Shubham/Chenyang/Shunxuan

Procedure

1. Plan the flight to the asset location where contact-based NDT is to be performed.
2. The pilot/co-pilot performs pre-flight checks.
3. The UAV is armed and flies to a position near the asset under inspection.
4. The pilot selects appropriate inspection points on the asset using the controller touchscreen interface.
5. The UAV transitions to a semi-autonomous mode, moves toward the selected target location, and establishes contact (5-10sec).
6. The pilot teleoperates the UAV to the next inspection location, and steps 4–6 are repeated.
7. The UAV flight mode is changed to Return.

Verification Criteria

1. The end-effector probe marks a precise spot within 0.2m radius of the designated target area. (Ground truth data from Total Station)
2. The end effector applies a desired force required to maintain consistent contact.

Budget

Core Expenses

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

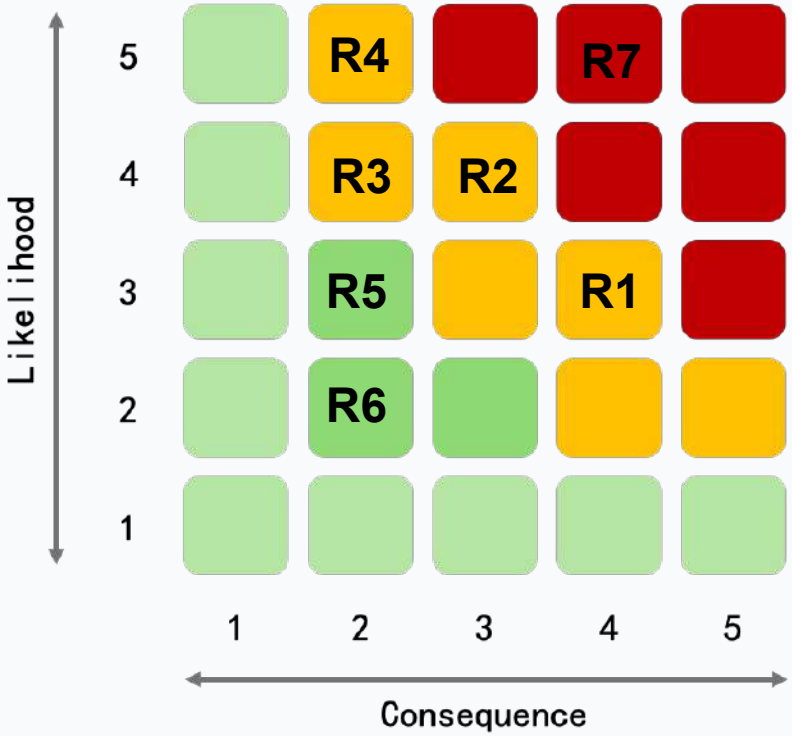








Risk Management



- R5- Component Arrival Delay
- R6- Version control confusion

- R1- Insufficient Advisor Guidance
- R2- Invalid Simulation Model
- R3- Lack of VIO Efficiency
- R4- Interface ATI F/T sensor with Orin

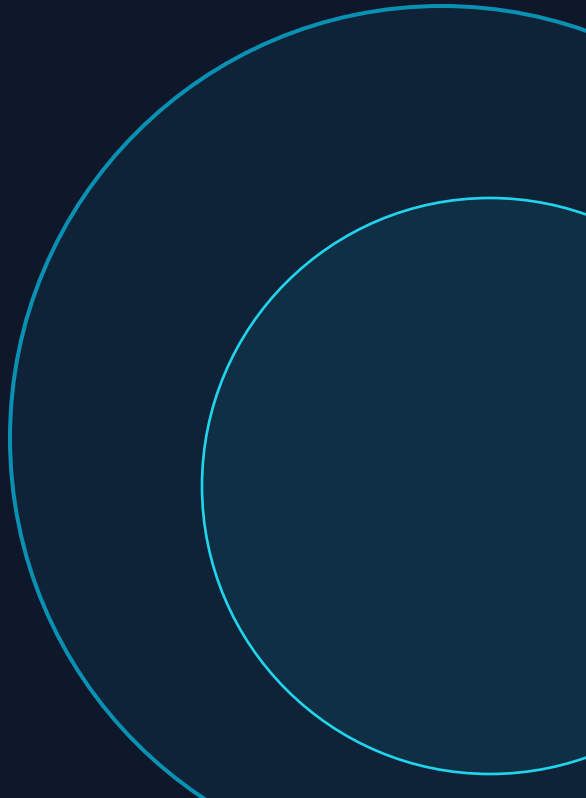
- R7- Drone Crash

Risk Management

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

07

Conclusion



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.

Key Fall Activities

- Integration and validation of the Wrench Controller and visual servoing
- Manipulator design and design modifications for CoG balancing
- Integration of manipulator with the UAV
- Lots of tuning and testing

Thank You!

TEAM C



