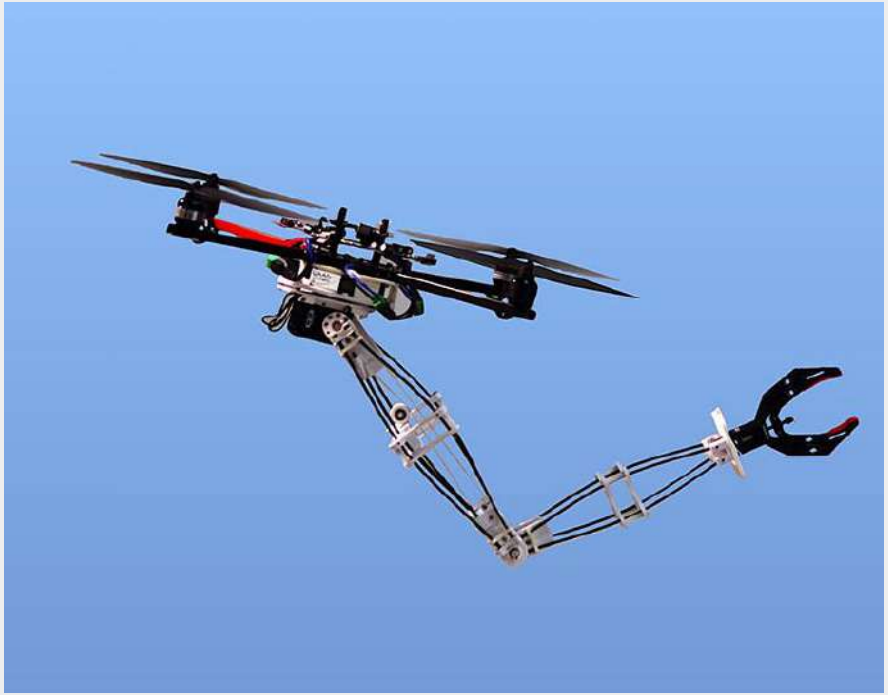
# Flying Hand

## Aerial Manipulator for Non Destructive Testing

**Team C**



**Sponsors:**

AIRLAB

LeCAR
Learning and Control for Agile Robotics Lab


**Sebastian Scherer,** **Guanya Shi**

**Advisors: Dimitrios Apostolopoulos**

**John Dolan**

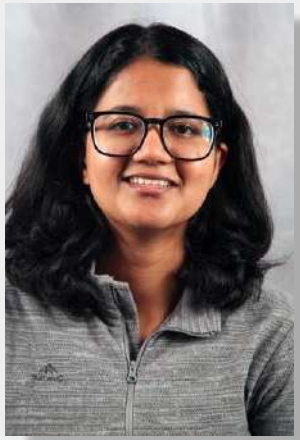
# Team Members



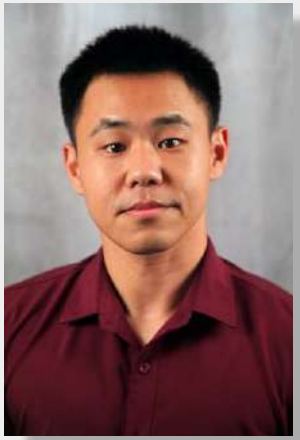
Chenyang Mao



Shunxuan Wang



Shubha Tanaya



Weerachai Sangiumpaisankij



Shubham Saboo

# 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.*

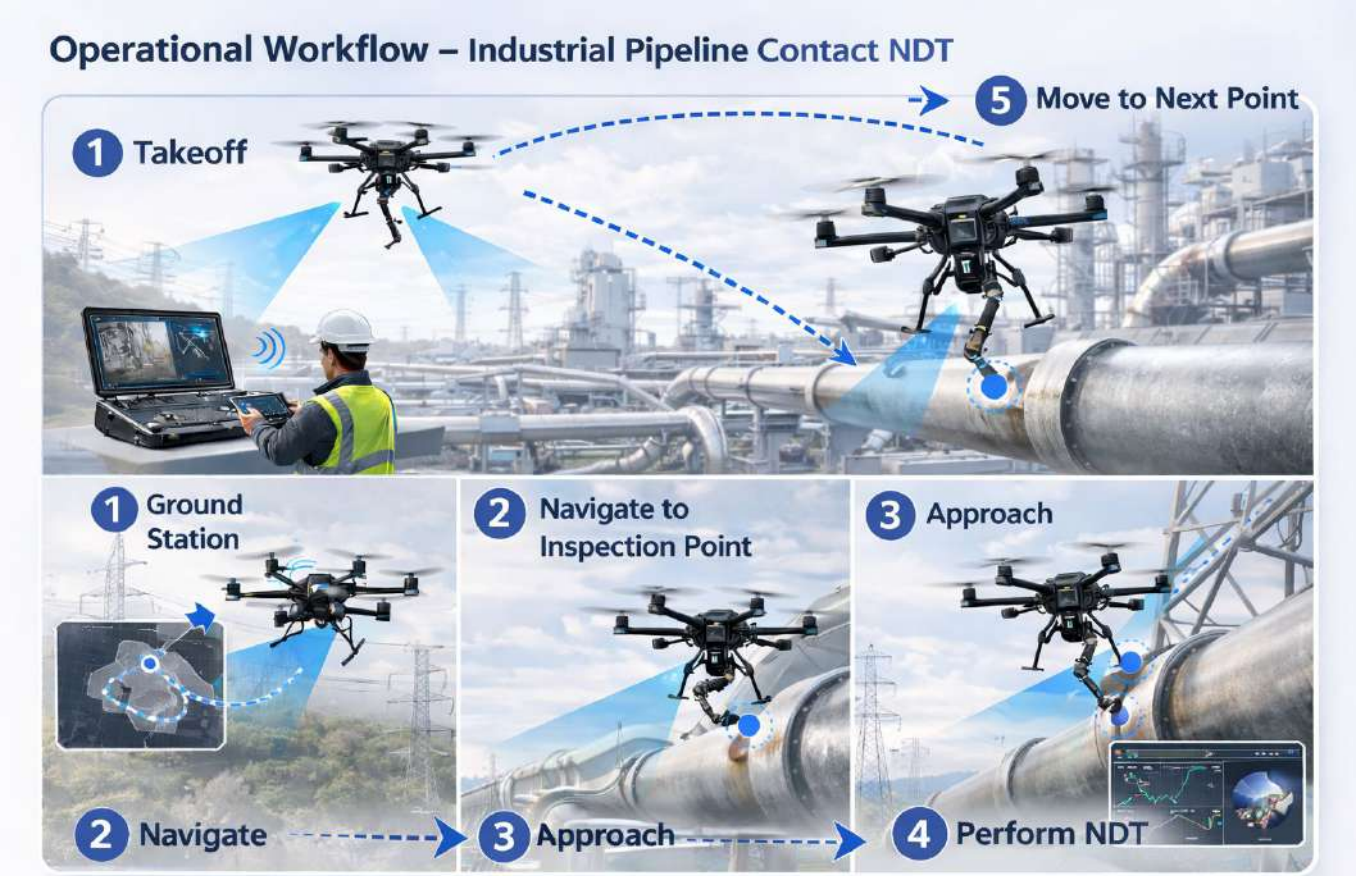
# 02
# Use Case

# 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**.

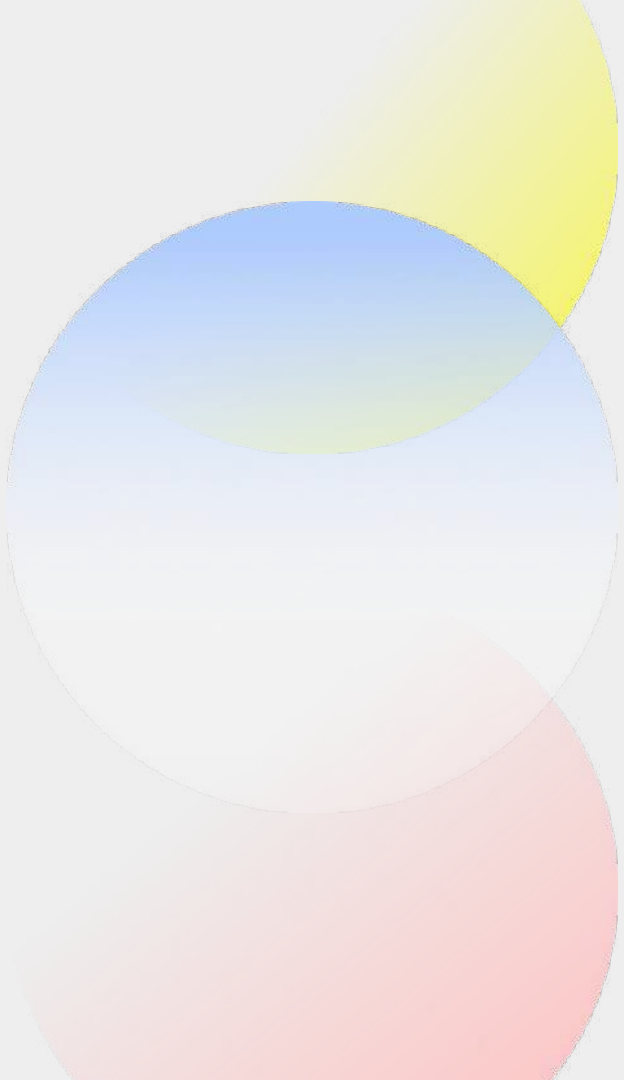


# Use Case




*Generated by AI

# 03
# 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 (RealSense)
- **Localize** itself within **5 cm** of true position (RTK/GNSS)
- **Navigate** the environment at the maximum speed of **1 m/s** (Tarrot X6)
- **Detect** POI from the distance of at least **60cm** (RealSense)
- **Communicate** with maximum latency in **100ms** (HereLink)
- **Sample** NDT data at **5** waypoints in a single flight
- **Maintain** end-effector positioning accuracy of **±0.5 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.
- **Transmit** video signals within **110-200ms**.

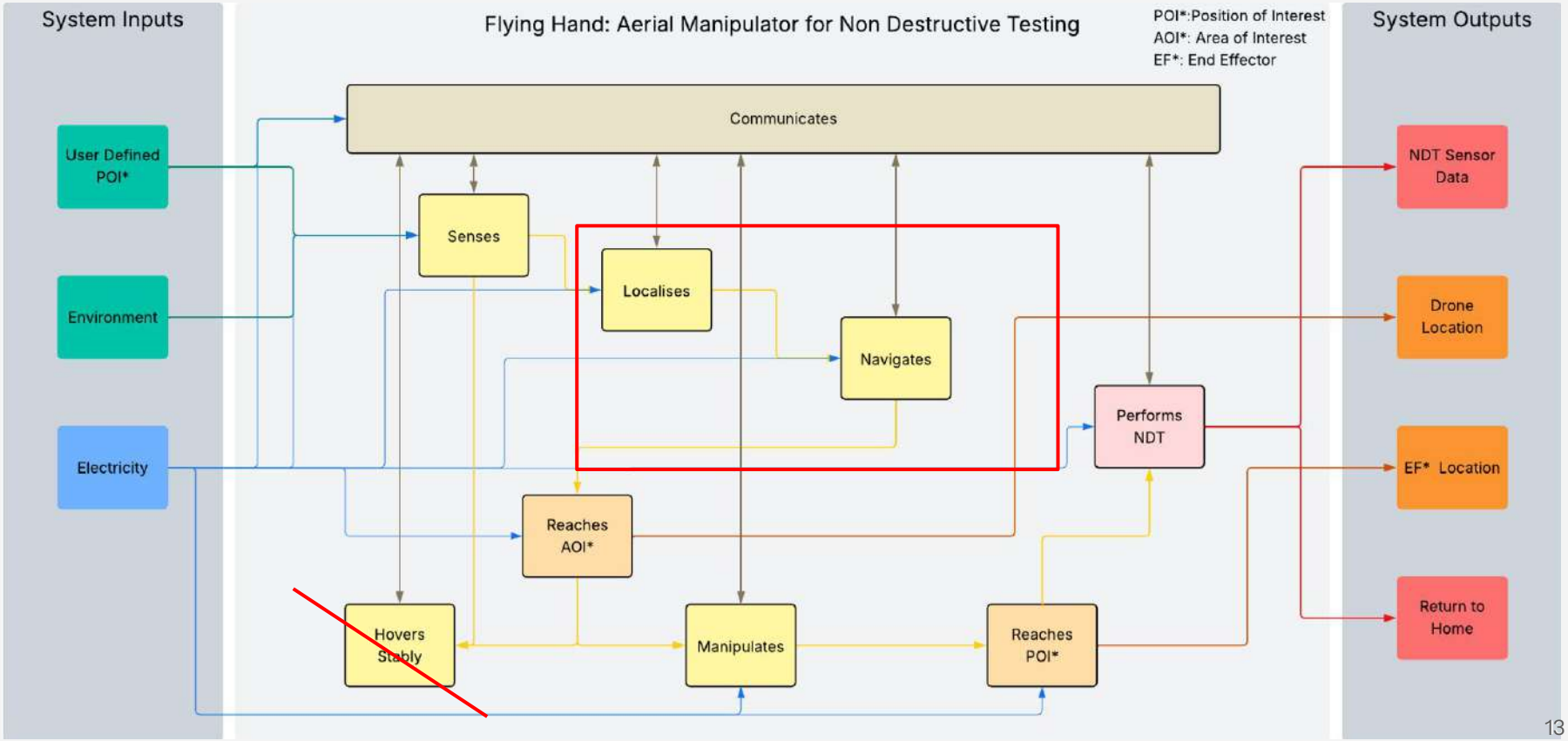
# Non-functional Requirements

**The Flying Hand WILL**

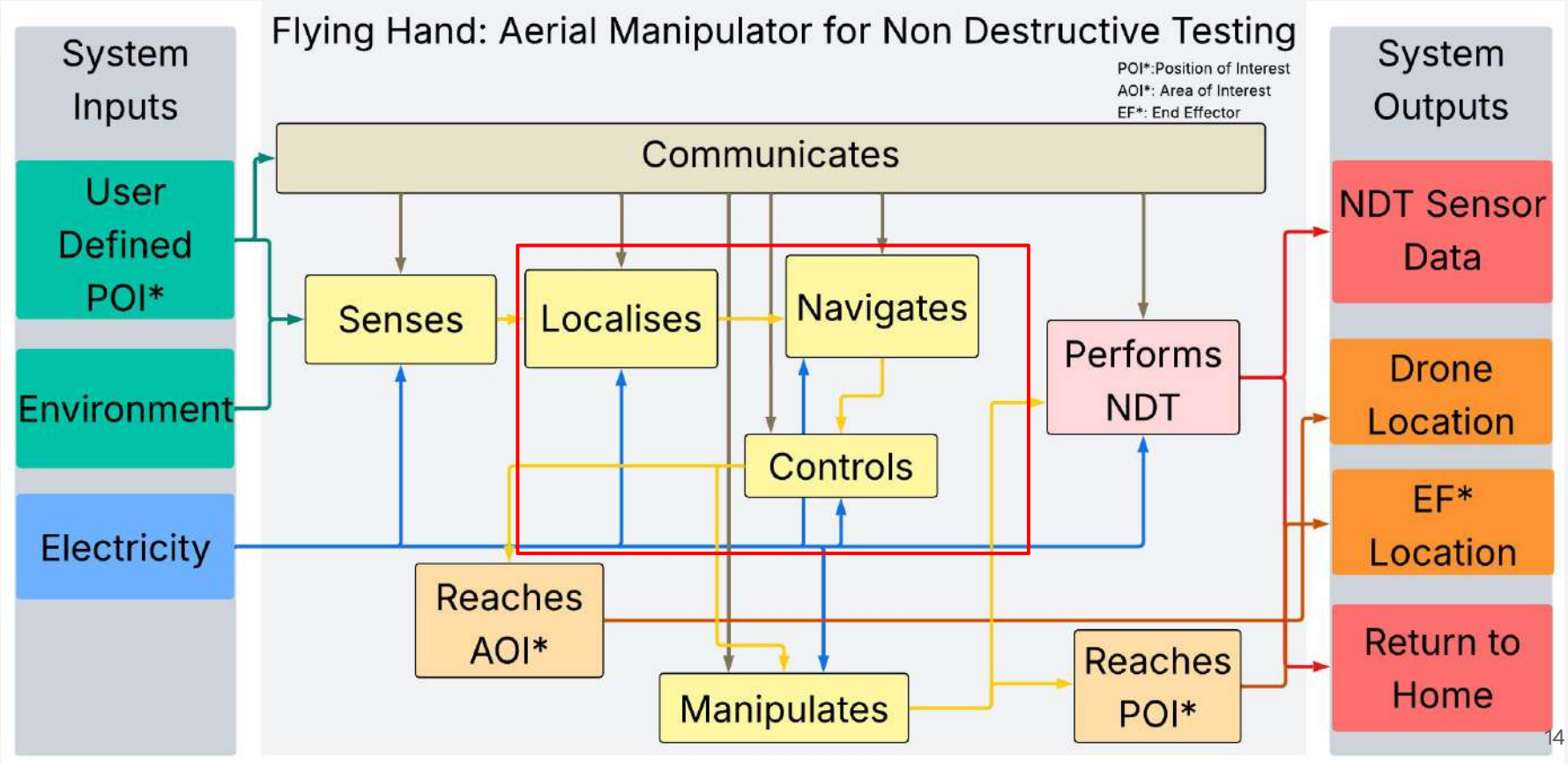
- **Be modular** (Quick probe replacement or end-effector module exchange)
- **Be lightweight** (Total take-off mass will no more than 15 kg)
- **Be easy to use** (Trained operator can plan the mission quickly)
- **Convey actionable information** (Store NDT data in standard formats)
- **Be compact** (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%)

# 04
# Architecture

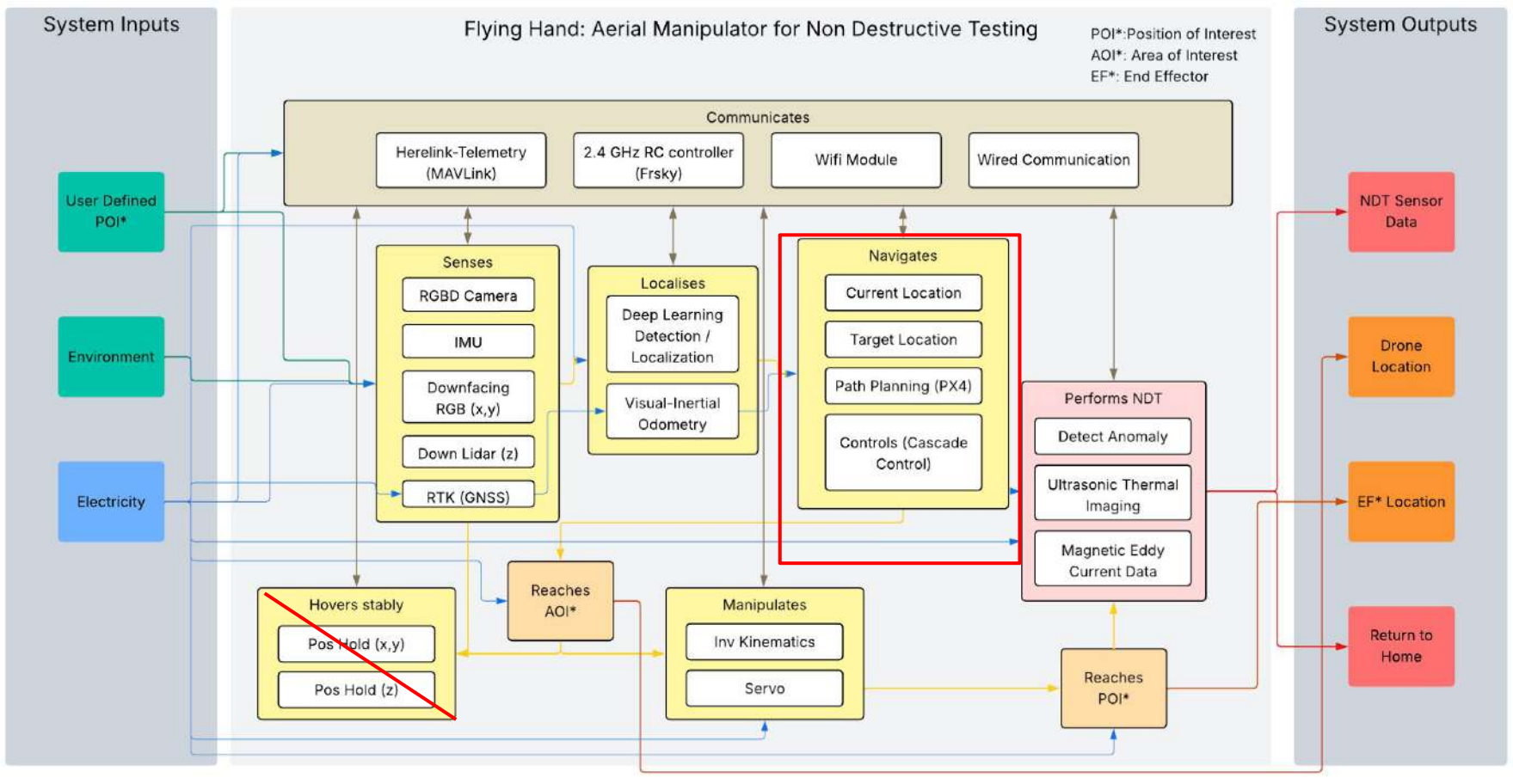
# Old-Functional Architecture



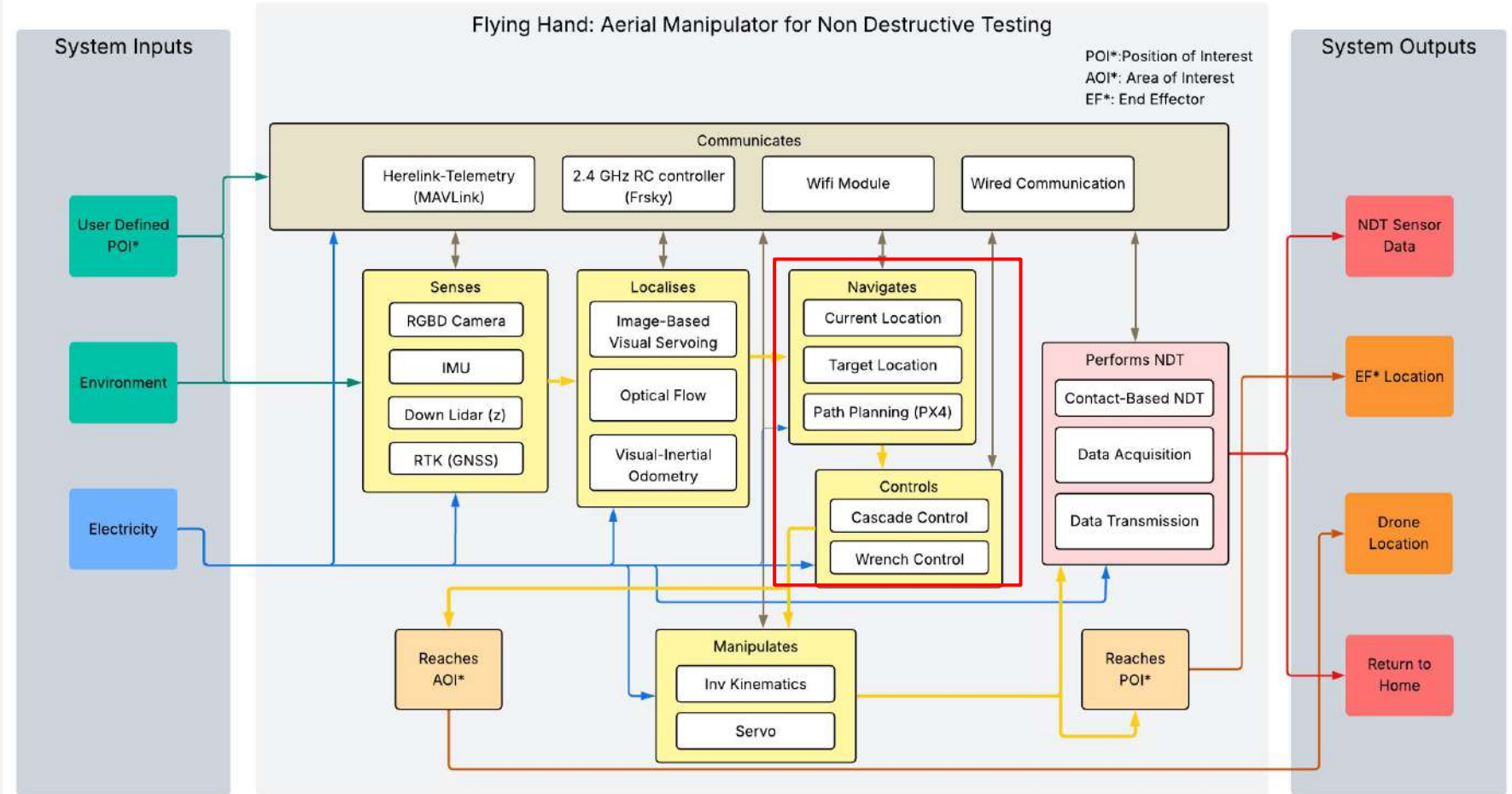
# New-Functional Architecture



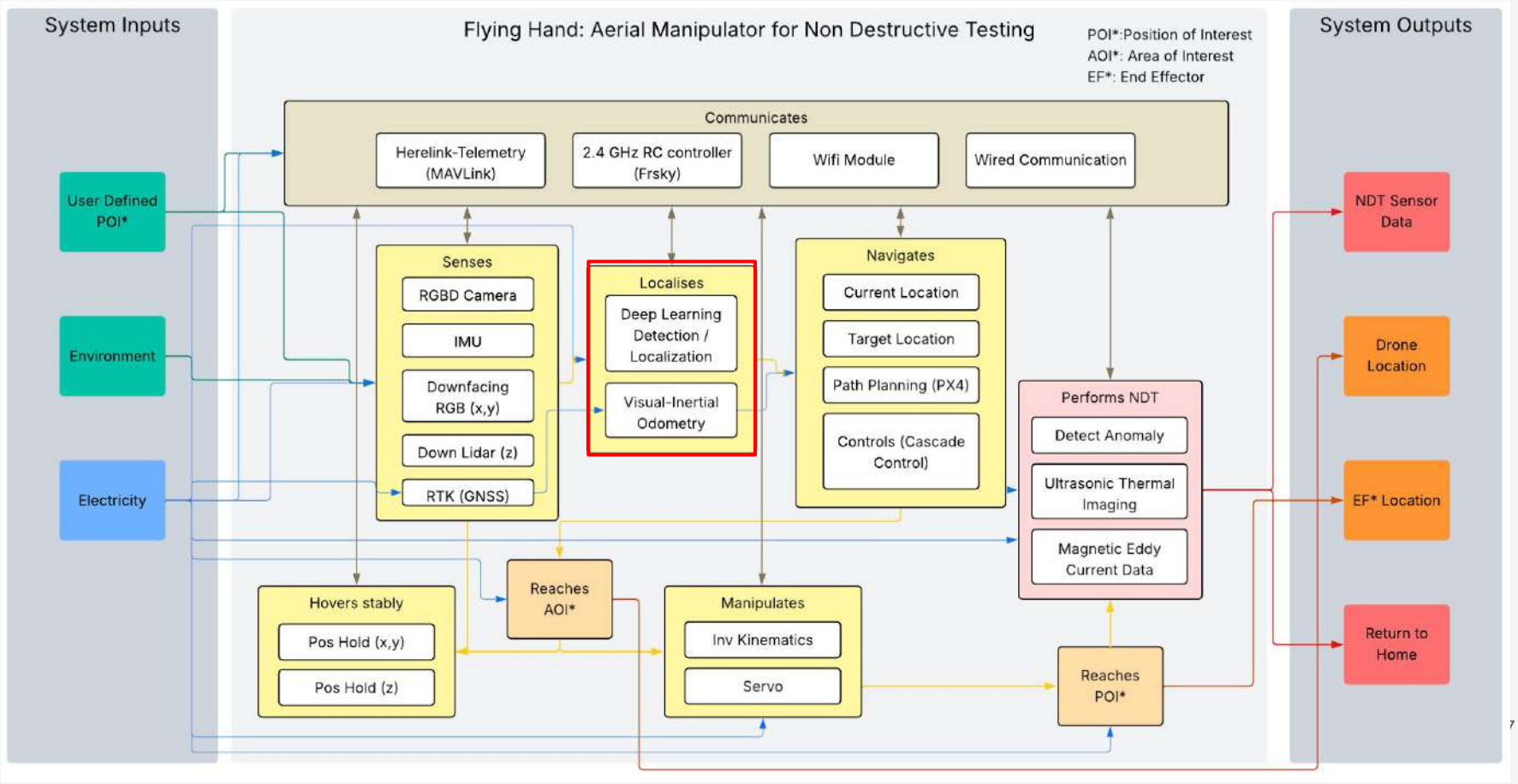
# Old - Cyber-Physical Architecture



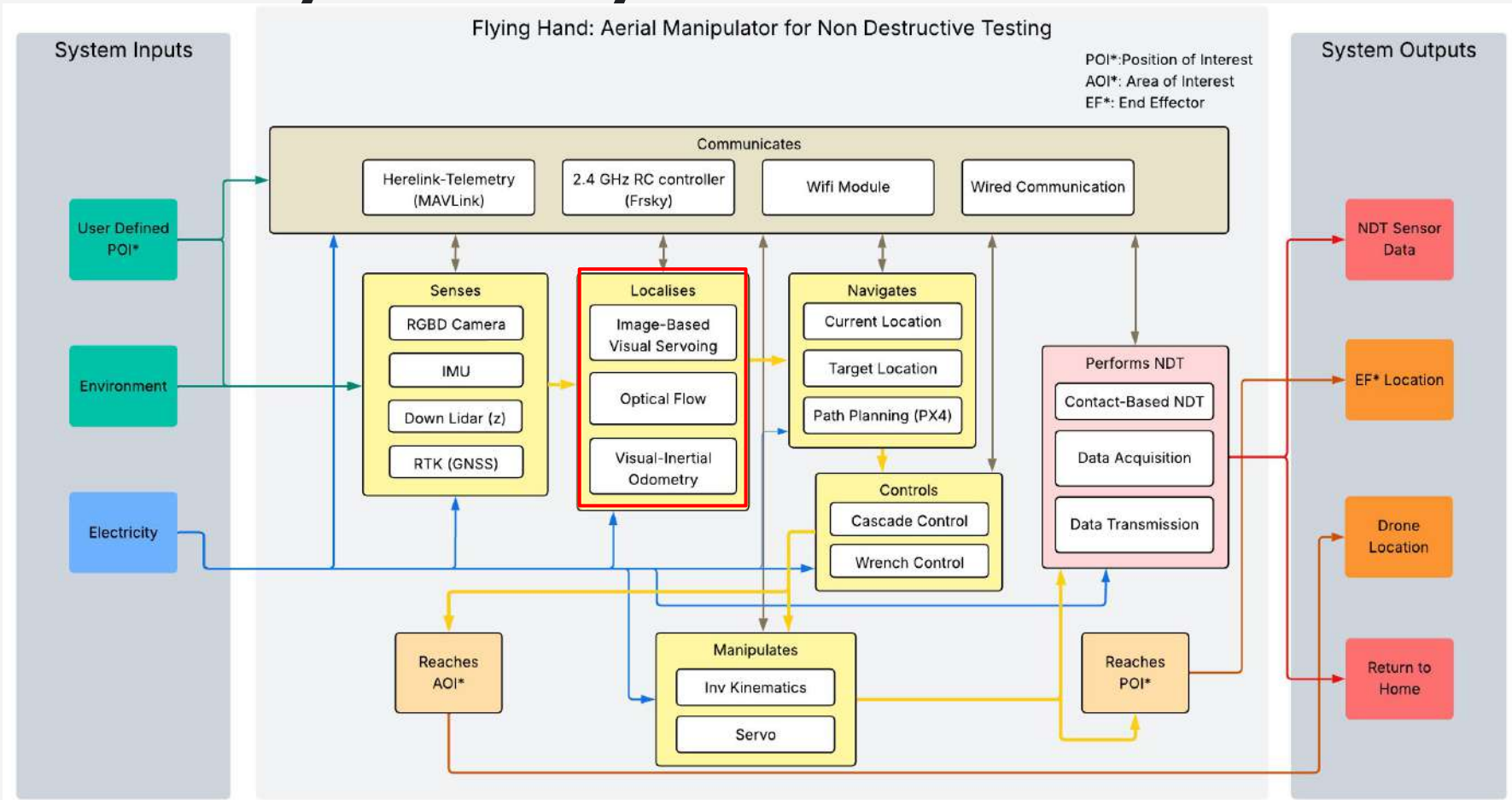
# New - Cyber-Physical Architecture



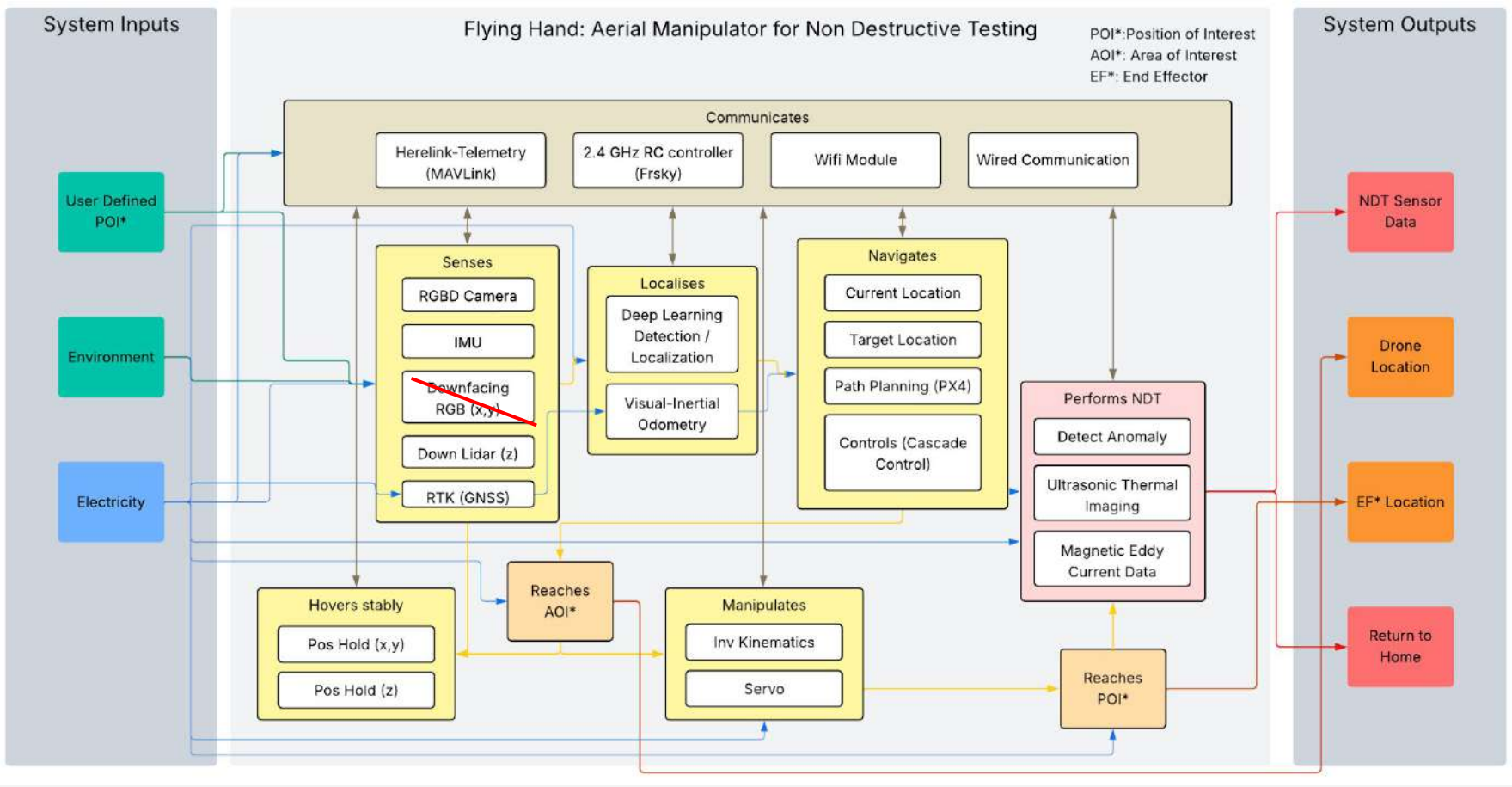
# Old - Cyber-Physical Architecture



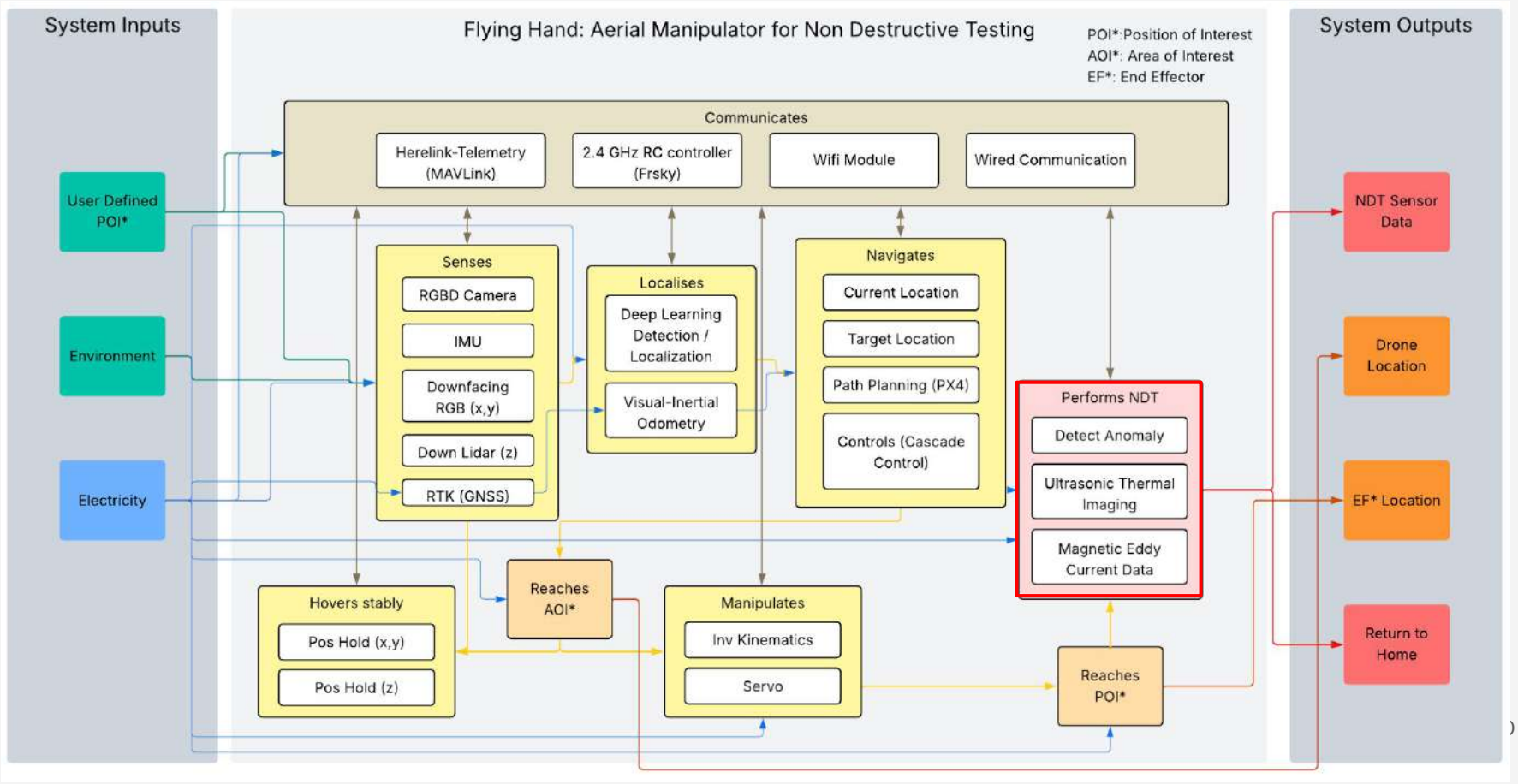
# New - Cyber-Physical Architecture



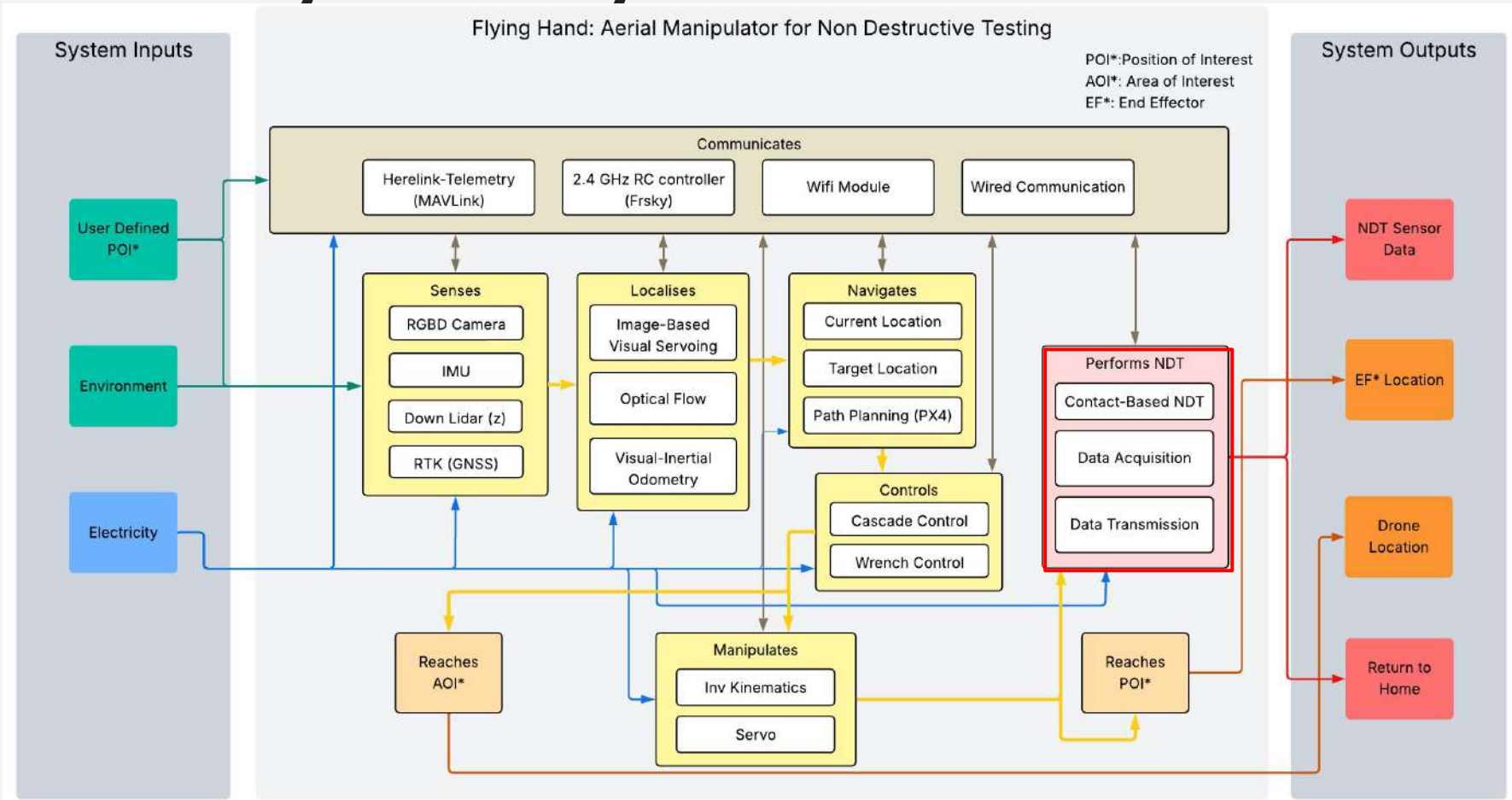
# Old - Cyber-Physical Architecture



# Old - Cyber-Physical Architecture

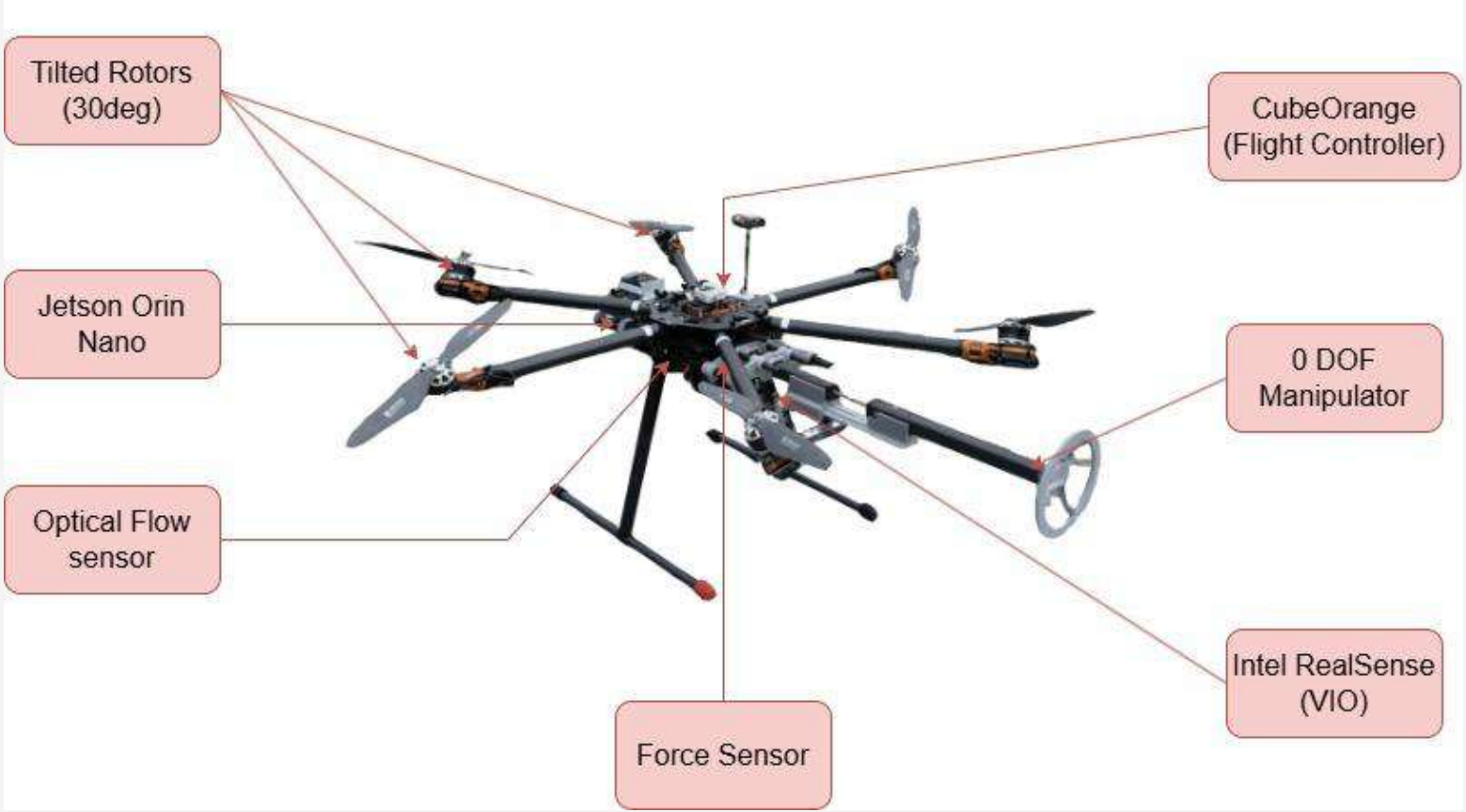


# New - Cyber-Physical Architecture

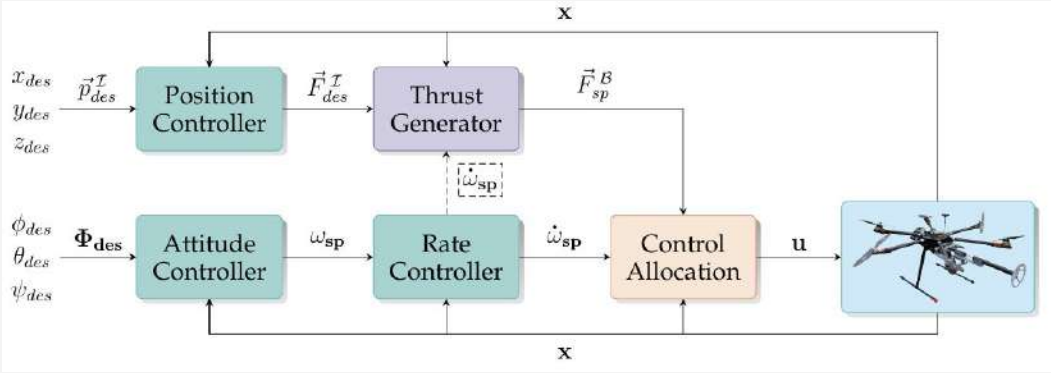


# 05
# System/Subsystem Description & Current System Status

# Overall System



# UAV Platform – Software/Controller



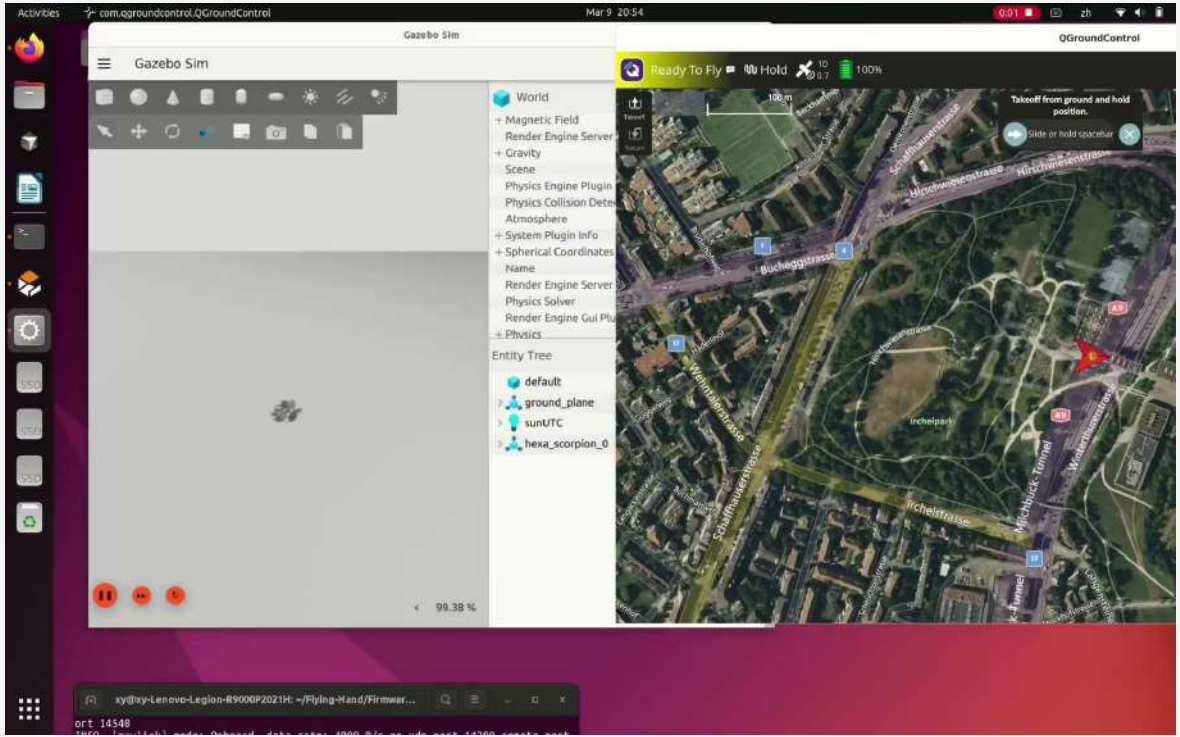

**Modifications Done to the PX4**

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 – Software




PX4-SITL with Gazebo to validate code modifications

# UAV Platform - Hardware



**Current Status:**

- Under-actuated hexa-rotor integrated with:
  1. PX4-Flight Controller
  2. Motors & Speed controller
  3. Other avionics
- Test flights



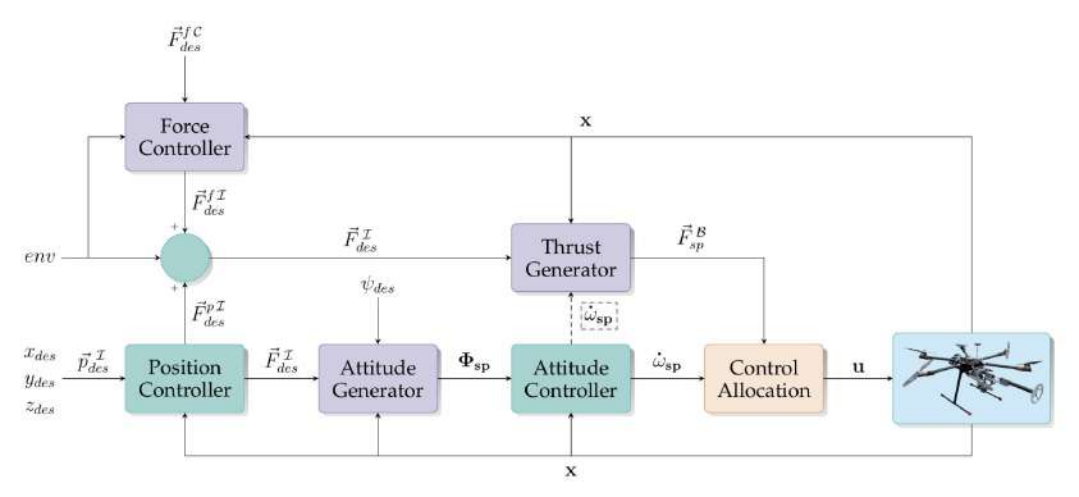
# UAV Platform - Hardware

**Final State:**
Hexa-rotor with:

1. Rotors tilted by 30 deg
2. Integrated with Localization hardware
3. Integrated with 0 Dof Manipulation hardware



# Manipulation Subsystem



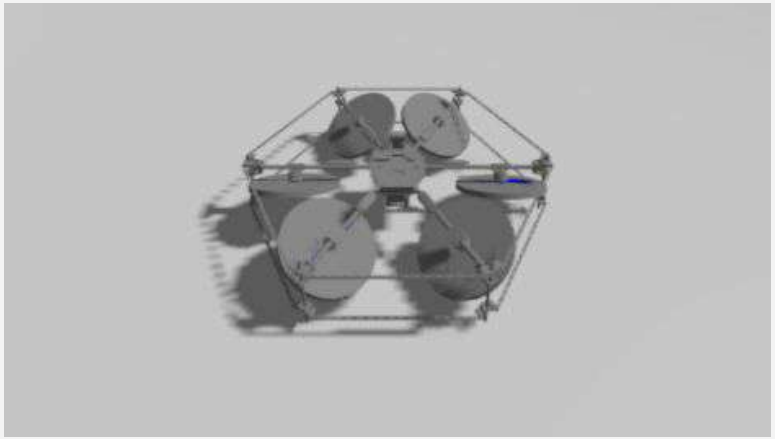

Hybrid Position-Force Controller

- This is an extension of the base architecture that adds a **Force Controller** running in parallel with the Position Controller.
- Their outputs are summed before hitting the Thrust Generator
- The environment feedback (*env*) closes the force loop - it tells the force controller what force is actually being applied so it can correct the error.



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

# Manipulation Subsystem - Software





**Current Status:**

1. Research & code Implementation and simulation: https://arxiv.org/pdf/2207.02856
2. Interfacing ATI F/T sensor with Jetson Orin(Ubuntu/ROS)

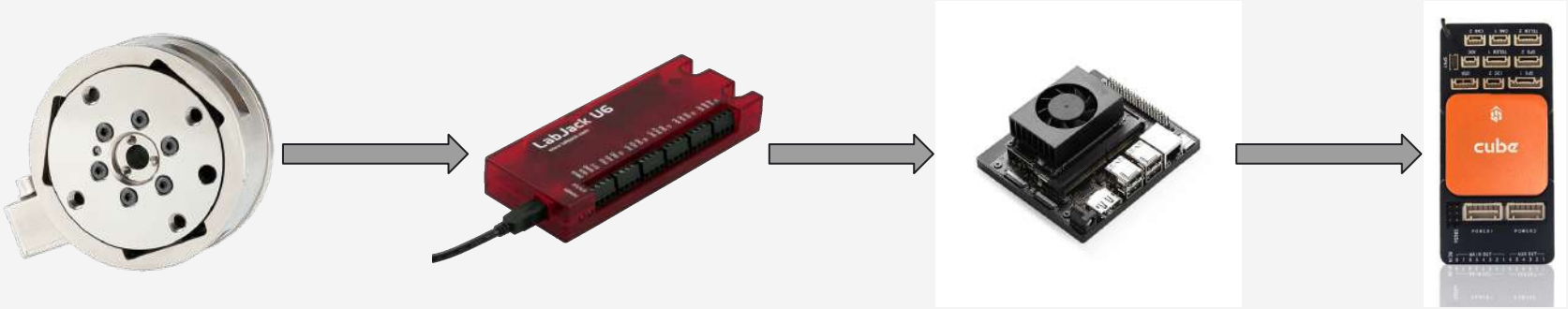
**Final Desired State:**

Sensor communicates with Orin Nano and Force controller is integrated with the Fully-actuated position controller.



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

# Manipulation Subsystem - Hardware




**Current Status:**

1. Interfacing F/T hardware with Orin Nano through a USB DAQ.

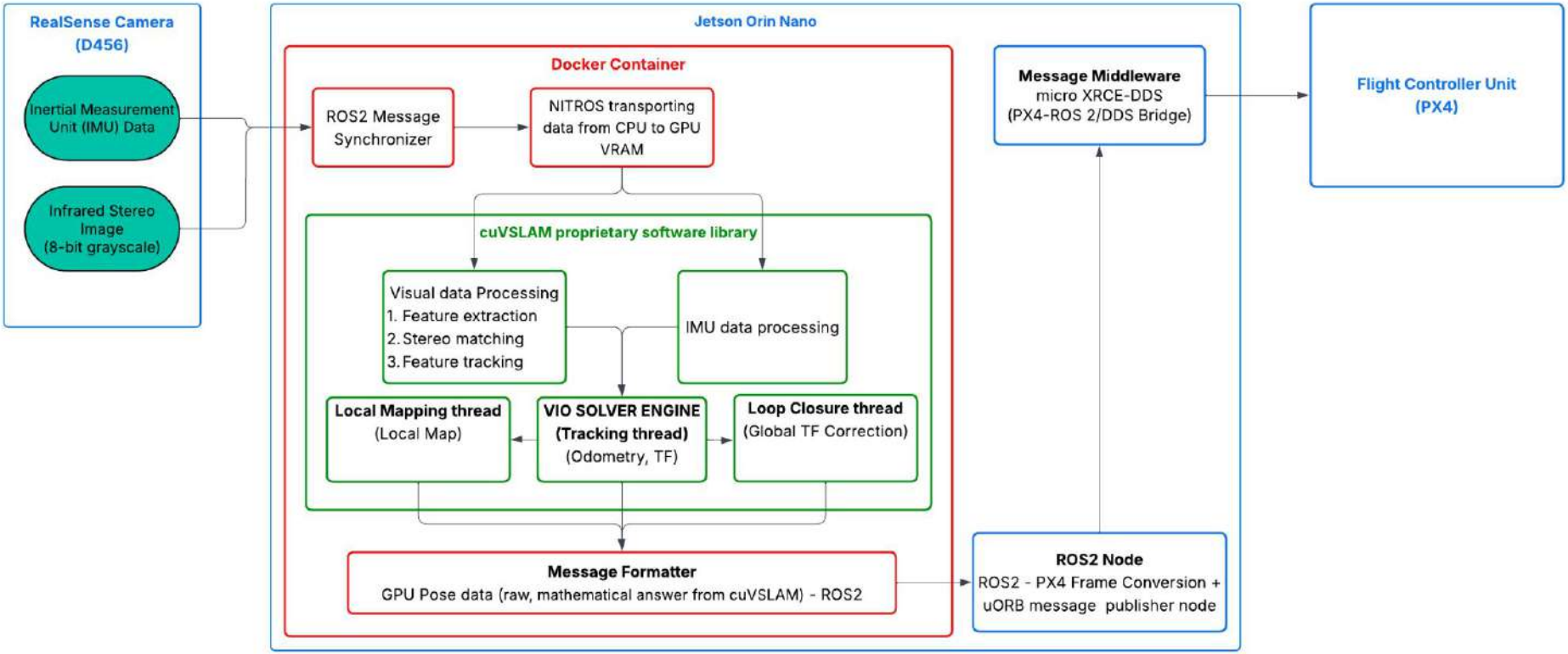
**Final Desired State:**

1. F/T sensor is mounted on the drone with a 0 DoF Manipulator

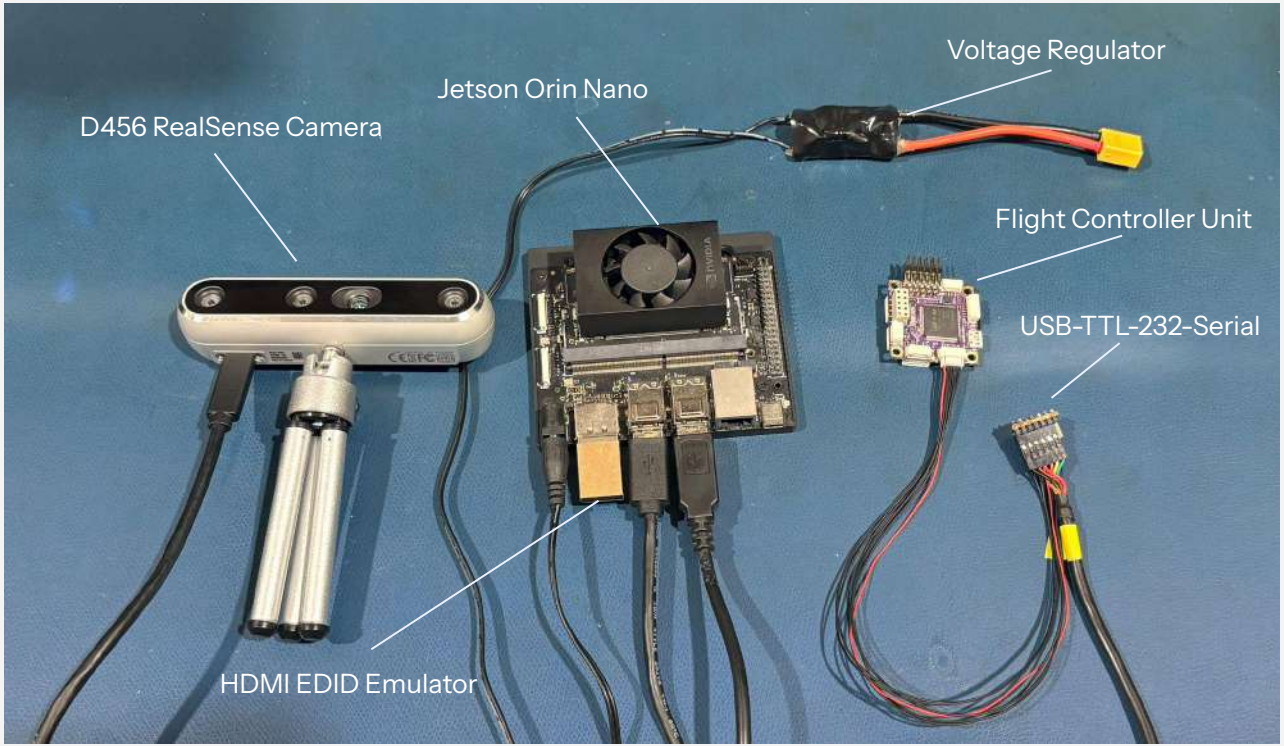


Image courtesy of Azarakhsh Keipour, CMU-RI, 2022. Used for academic purposes.

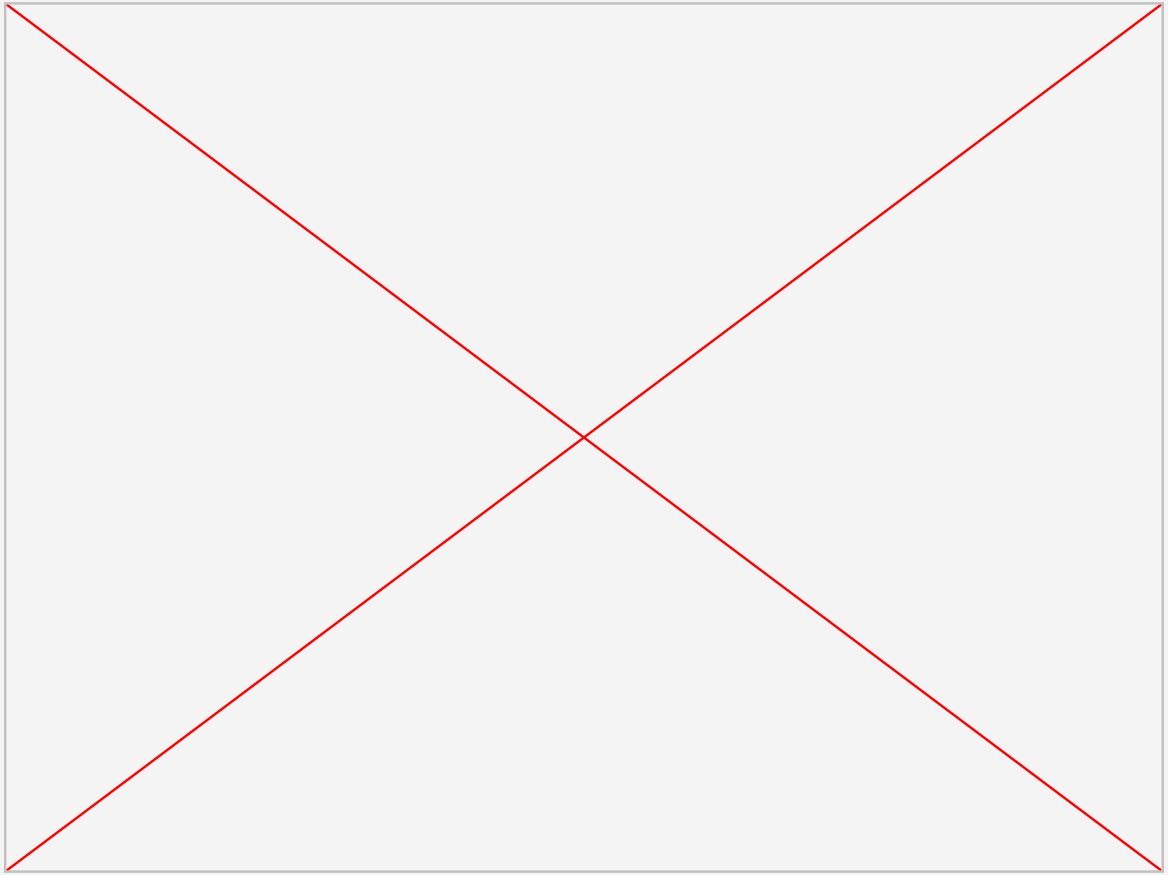
# Localization - VIO (Software Pipeline)



# Localization - VIO (Hardware Setup)



# Localization - VIO  (Current State)



**Current Status :**
VIO has been successfully set up between the Jetson Orin Nano and the RealSense camera. The system is calibrated, and the results fall within the acceptable criteria specified in the official documentation.

# Localization - VIO (Desired State)

**Final State:**
The VIO subsystem will be able to transmit data to the flight controller unit and serve as a visual sensor for odometry estimation.

# Localization – Optical Flow

**System Architecture:**




**PX4 Configuration:**

(Optical flow fusion enabled in EKF2 with UAVCAN sensor inputs.)

- Estimator Parameters
- UAVCAN Sensor Inputs
- Range Limits
- Sensor offset compensation

**System Validation (QGroundControl- Mission Planner):**

Key Diagnostic Messages on MAVLink Inspector-

- OPTICAL_FLOW_RAD
- DISTANCE_SENSOR
- LOCAL_POSITION_NED
- ESTIMATOR_STATUS

**Current State:**

Testing optical flow sub system - sensor validation rig with GPS-module for benchmarking.

**Desired State:**

Fully integrated optical flow fusion within the multi-sensor localization pipeline alongside VSLAM

*Optical flow integration provides robust short-term velocity estimation, improving localization stability and redundancy for GPS-denied aerial inspection tasks.*

# Localization - Optical Flow (H/W Test Setup)

GPS (GNSS) module

WiFi Module(for comms)

Pixracer Pro FC



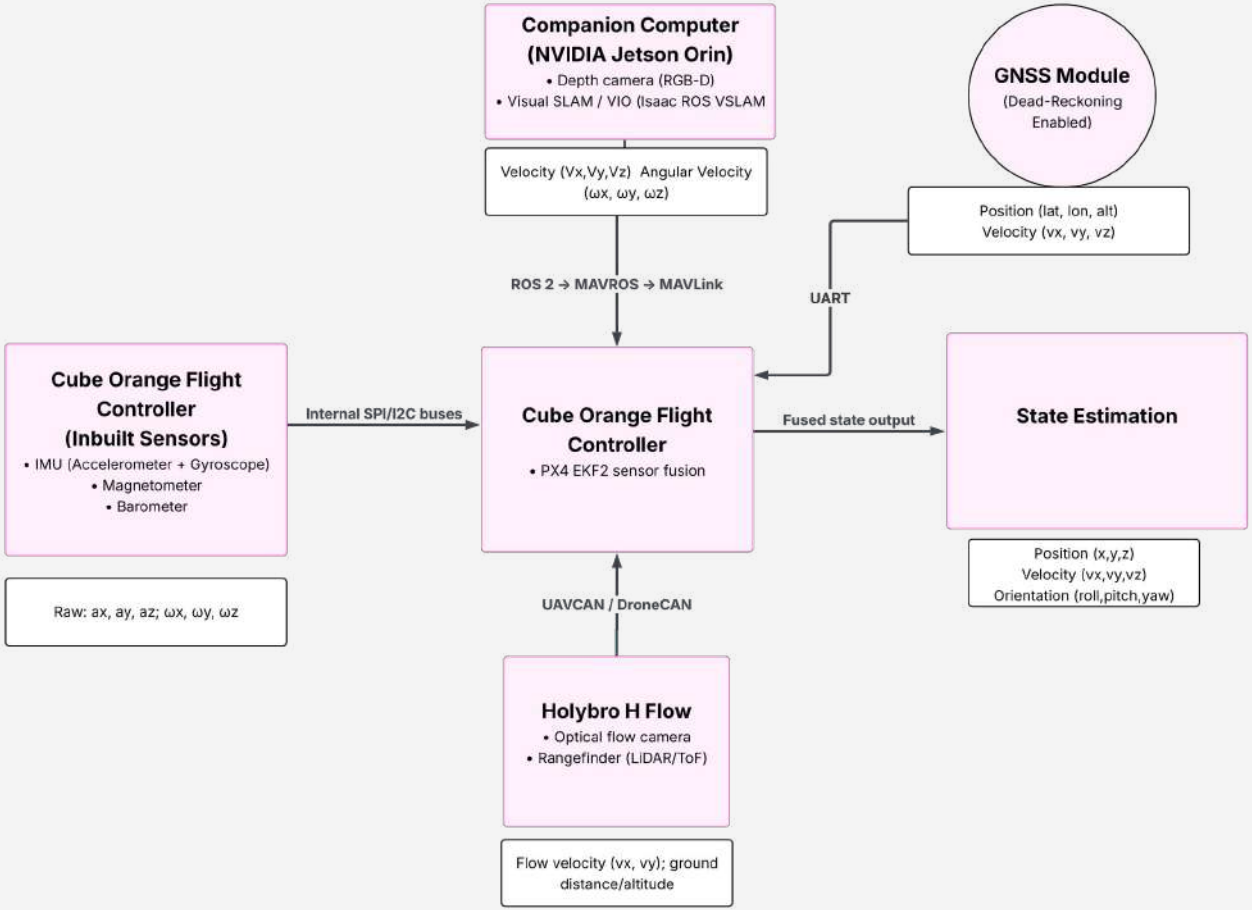
Front Side




Back Side

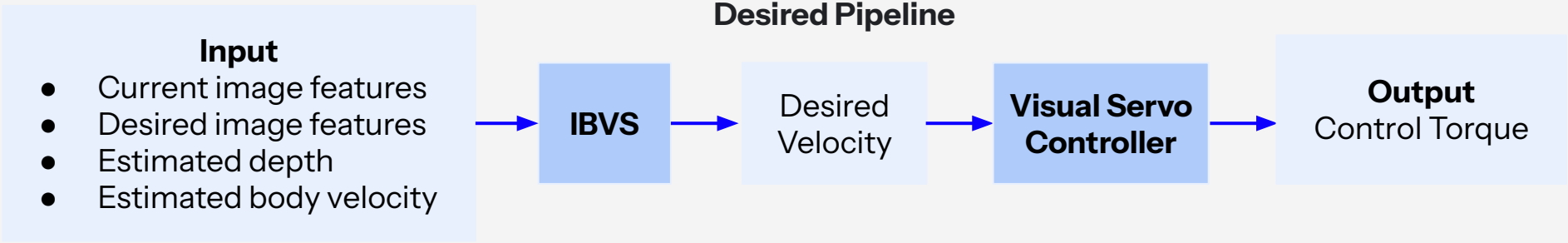
Holybro H Flow
Optical Flow + Rangefinder + IMU

# Localization – Sensor Fusion Pipeline



# Target Localization - Image-Based Visual Servoing

**Desired Pipeline**




**Hardware:**
Jetson Nano Orin
RealSense Depth Camera
UAV Platform

**Software:**
Perception Module
IBVS Control Law
ROS2

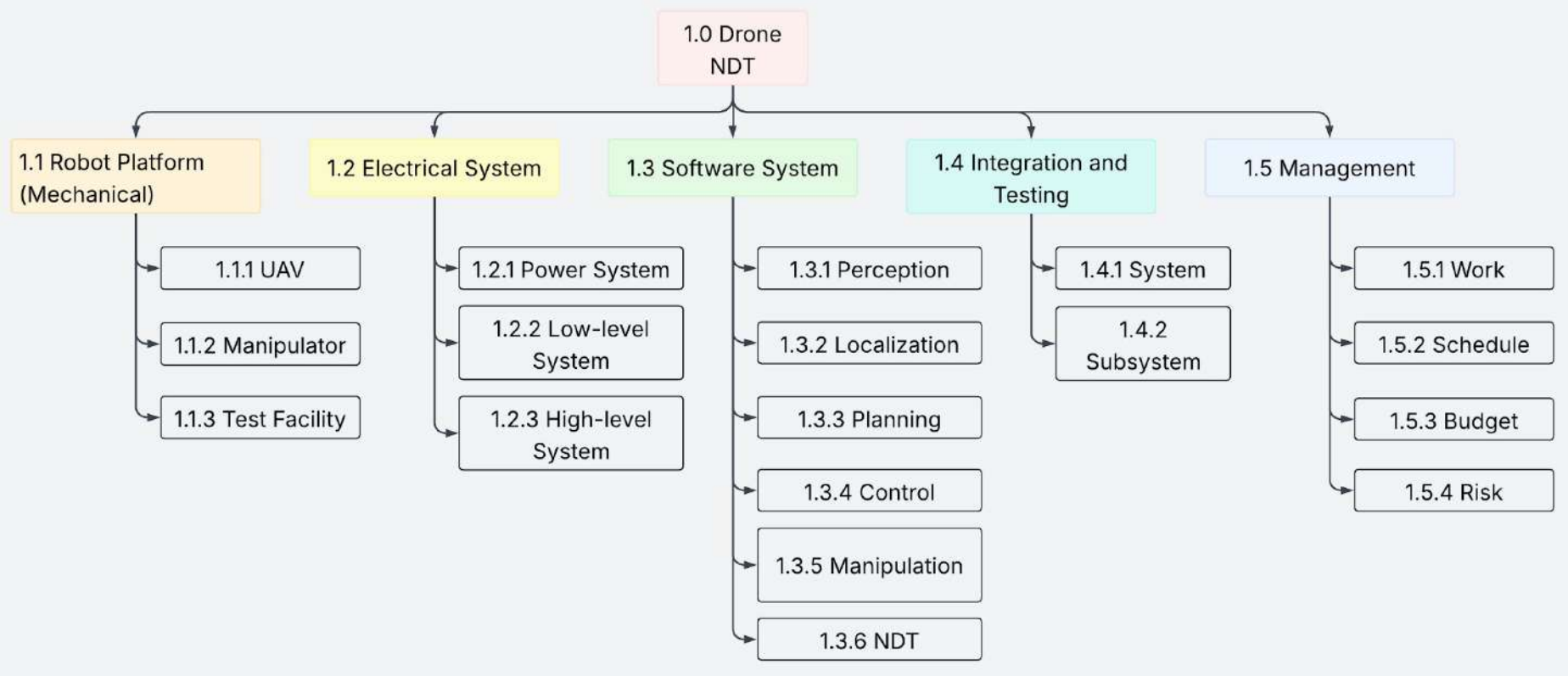
**Current Status:**
Finished researching the pipeline and identified a reference method for implementation.

**Final State:**
The IBVS subsystem will read images from the RealSense camera and velocity from Sensor Fusion module to generate control torque. This torque will be merged with the wrench controller and sent to PX4 for control allocation.

Reference: https://arxiv.org/pdf/2602.08251

# 06
# Project Management

# Work Breakdown Structure



# Milestone & Schedule

| Date | Identifier | Capability Milestone | Tests |
|---|---|---|---|
| 12-Feb | Progress Review 1 | Completed airframe hardware and under-actuated bench validation;<br>Validated an Isaac ROS-based VSLAM pipeline with RealSense;<br>Transferred AirLab's PX4 stack to PX4 v1.16,enabling QGroundControl-based simulation. | T1 |
| 26-Feb | Progress Review 2 | Validated GPS-denied perception & localization integrated RTK;<br>Completed under-actuated platform maiden flight test;<br>Verified key flight safety behaviors. | T2,<br>T3,<br>T4,<br>T5, T6 |

# Milestone & Schedule

| Date | Identifier | Capability Milestone | Tests |
|---|---|---|---|
| 19-Mar | Progress Review 3 | **Demonstrated on-platform GPS-denied localization feasibility** by evaluating in-flight VSLAM trajectory accuracy against RTK-GPS reference data; **Bench-validated the visual servoing pipeline**; **Bench-validated the optical flow pipeline** for motion estimation, verifying stability, directional correctness, and low drift when static. | T7, T10, T11 |
| 2-Apr | Progress Review 4 | **Verified the fully-actuated UAV platform and PX4-based control stack** by demonstrating stable manual takeoff/landing and position-hold flight performance; **Completed integration of onboard perception** with optical flow and **validated fused localization** for UAV navigation: autonomously reached the designated NDT target pose and maintained stable hover using the fused estimate. | T8, T12 |
| 16-Apr | SVD | **Demonstrated fully-actuated wall interaction** via closed-loop force control; Tracked contact force. | T9 |
| 23-Apr | SVD Encore | Optimized issues encountered in SVD | SVD |

# Spring Validation Demo

| | |
|---|---|
| **Objective** | Demonstrate end-to-end readiness of the Flying Hand UAV platform by validating hard-ware integration, fully actuated capability, GPS-denied localization and asset interaction capability |
| **Element** | Flying Hand |
| **Location** | RIC Drone Cage (Video recording) |
| **Equipment** | Tarot X6 Airframe<br>Intel RealSense Depth Camera<br>NVIDIA Jetson Orin Nano<br>Cube Orange Flight Controller<br>EMLID RTK GNSS Receiver<br>Futaba Receiver and Transmitter |
| **Personnel** | Sang/Tanaya/Shubham/Chenyang/Shunxuan |

# Spring Validation Demo

| Procedure |
| --- |
| 1. Plan the flight to the asset location where contact-based NDT is to be performed.<br>2. The pilot/co-pilot performs pre-flight checks.<br>3. The UAV is armed and teleoperated to a position near the asset under inspection.<br>4. The pilot selects appropriate inspection points on the asset using the controller touchscreen interface.<br>5. The UAV transitions to a semi-autonomous mode, moves toward the selected target location, establishes contact, and applies the desired contact force.<br>6. Once data collection is complete, the operator receives a notification on the GCS.<br>7. The pilot teleoperates the UAV to the next inspection location, and steps 4–6 are repeated.<br>8. After all inspection data is collected, the UAV flight mode is changed to Return. |
| **Verification Criteria** |
| 1. The end-effector probe marks a precise spot within 50cm radius of the designated target area.<br>2. The end effector applies a proportional force threshold according to the selected NDT sensor. |

# 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 | Check all subsystems and units are working correctly | The UAV can complete all tasks from Spring |
| September | Integrate 3 DOF manipulator for improved dexterity | Dynamic Coupling and Disturbance Rejection Test, where the drone must maintain a stable, hover while the 3DOF 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 force |
| October | Autonomous the data collection | The drone must sequentially traverse five predefined (POI) coordinates find the best strategy to make contact and collect data. | Drone to reach all five points within a spherical error ± 0.5m of the target coordinates and successfully trigger the NDT data collection window at each stop. |
| November | Integrate the system with NDT probe | NDT Integration and Data Transmission Test evaluates the end-to-end signal chain, from the physical contact of the sensor to the live visualization on the operator's UI. | Digital readout on the Ground Control Station (GCS) matches the physical NDT sensor output with data integrity across the 5-point mission. |

# Budget



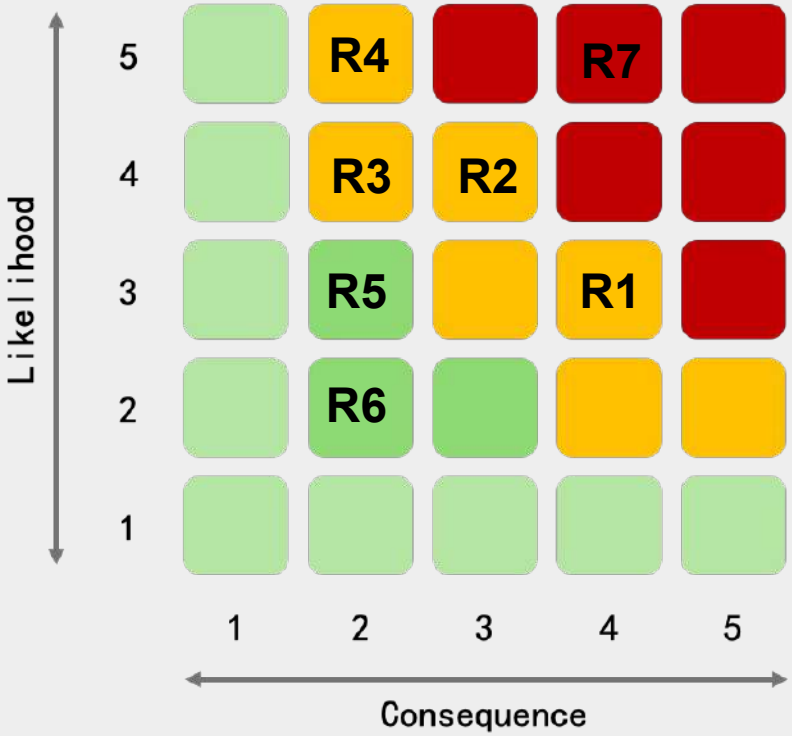






| No. | Date | Part Name | Quantity | Price | Shipping |
|---|---|---|---|---|---|
| #1 | 02/09/26 | M1.6 x 0.35 mm Thread, 14 mm Long | 1 | $6.7 | $10.22 |
| #2 | 02/09/26 | Super Glue | 2 | $12.66 | |
| #3 | 02/23/26 | Eolo Carbon Fiber Reinforced Nylon UAV Propellers | 6 | $107.94 | $0 |
| #4 | 02/23/26 | Holybro H-Flow Optical Flow and Distance Sensor Module | 1 | $145 | $0 |
| #5 | 02/11/26 | Cube Orange Standard Set ADS-B | 1 | Sponsored | |
| | | **Total Budget** | | **$282.52** | |

# 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 |

# Thank you !

