

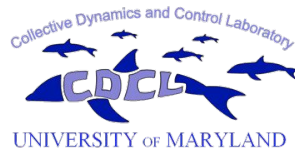
# Autonomous Hybrid Aerial-Terrestrial Transport and Retrieval for In-Situ Collection

**Madelyne G. Rossmann**

M.S. Thesis Defense

17 April 2025

Department of Aerospace Engineering - University of Maryland



# Acknowledgements

For funding my graduate studies and research endeavors, I'd like to thank Microsoft (funding for 2023-24) and the Maryland Robotics Center (funding for 2024-25).

Gratitude is due to my fellow CDCL labmates that have given me advice and support the past two years, as well as my two undergraduate collaborators: Mahima Thirukkonda and Sabrina Zaleski.

I am also appreciative of my thesis committee, who have offered me their time and input through this process.

Finally, thank you to my family and friends for always encouraging me as I've pursued this degree. I would not be where I am today without them.

# Presentation Outline

1. Research Introduction
2. Vehicle Hardware Design and Assembly
3. Design and Implementation of Autonomy Architecture
4. Experimental Evaluation

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# Objective of Thesis Research

*The objective of this research is to create an autonomous Earth-analog to the Sample Recovery Helicopter, this is accomplished by:*

- Augmenting a commercial off-the-self (COTS) quadcopter drone with a custom-built terrestrial platform, including a gripper
- Designing an autonomous state machine for sample search and collection, using fiducial markers to signify points of interest



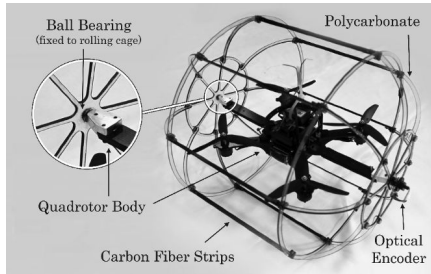
ModalAI VOXL 2 m500 quadcopter platform  
[Credit: ModalAI]



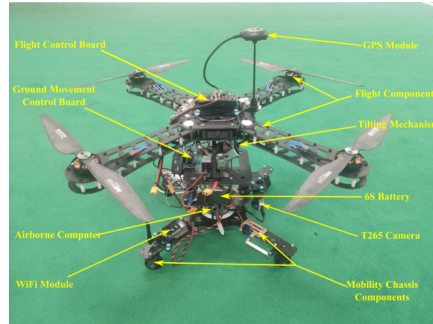
A-HAT-TRIC vehicle designed for this thesis

# Relation to State of the Art

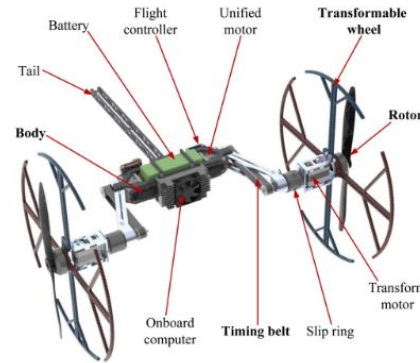
- Most prior research focuses on introducing terrestrial capability to increase operating efficiency for a rotary-wing drone near the ground



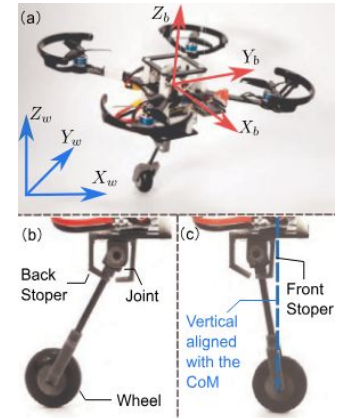
Hybrid terrestrial/aerial quadrotor [Kalantari, 2014]



Autonomous quadrotor tilting hybrid robot [Zhang, 2024]



Morphable terrestrial-aerial robot [Shi, 2024]



Wheel-on-leg quadcopter design [Yu, 2025]

*This thesis aims to showcase a specific application of this vehicle type rather than optimize vehicle design.*

# Technical Approach of Thesis Research

## 1. Augment Commercial Aerial Platform

- Design and manufacture a custom terrestrial platform for mounting to airframe
- Establish communication link between aerial and terrestrial platforms

## 2. Adapt Existing Flight Software for Autonomy

- Leverage existing framework for accessing critical information regarding vehicle performance
- Modify pipeline for parsing camera data prior to use in autonomous algorithm

## 3. Develop Autonomous State Machine for Sample Collection

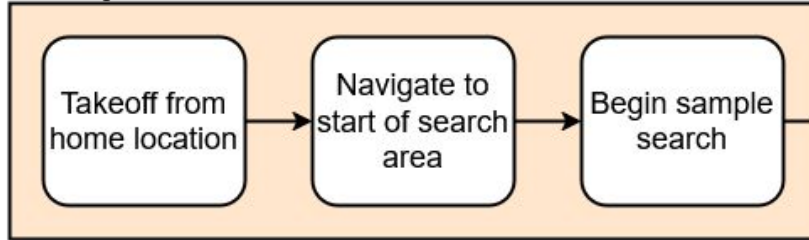
- Create decision-making structure for state transitions
- Implement all required logic in robotic software for vehicle commanding

## 4. Test in Simulation and Laboratory Environment

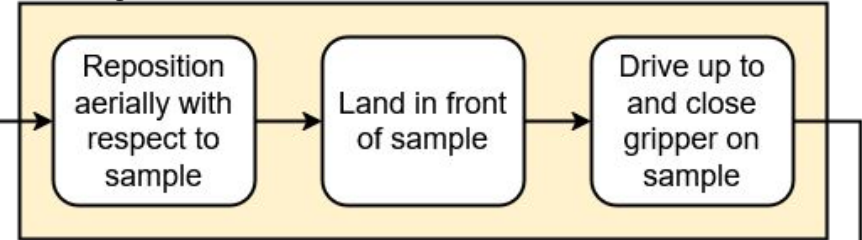
- Verify virtual vehicle performance prior to deployment on real vehicle
- Perform end-to-end demonstration in lab for analysis

# Concept of Operations

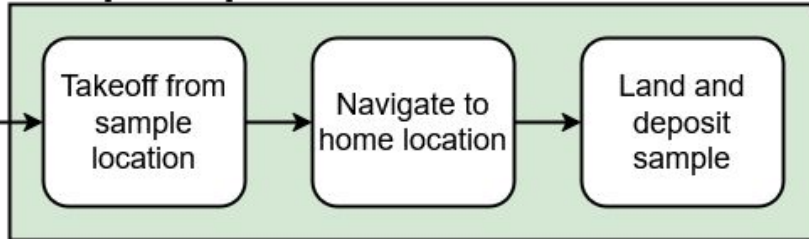
## Sample Search



## Sample Collection

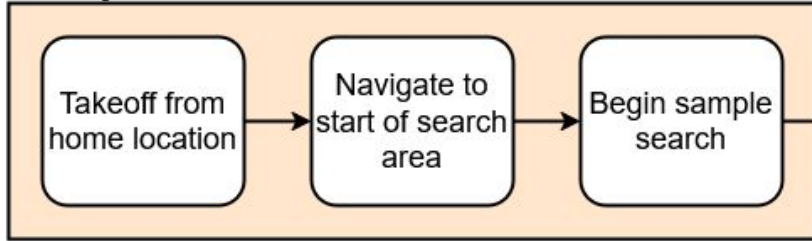


## Sample Deposit

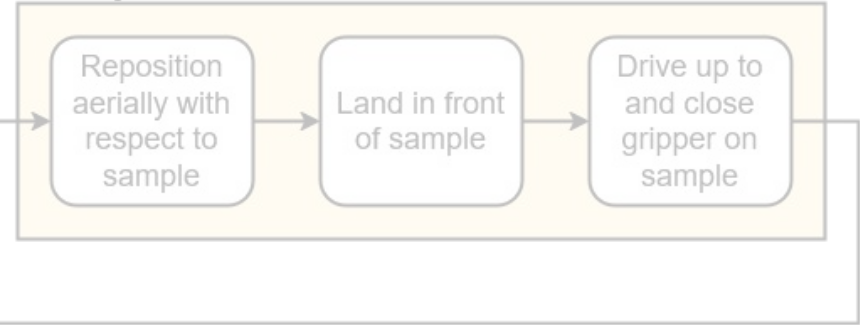


# Concept of Operations

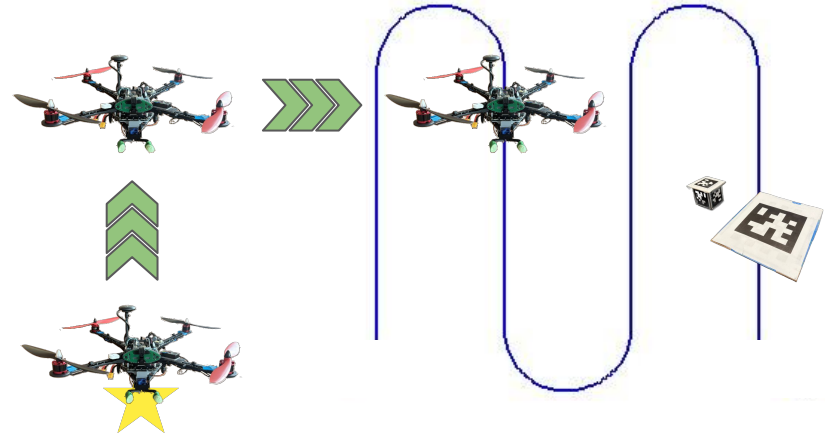
## Sample Search



## Sample Collection



## Sample Deposit

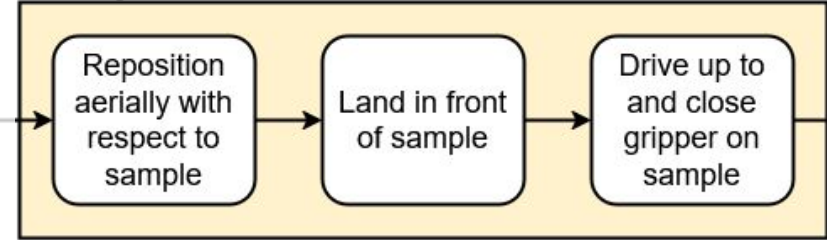


# Concept of Operations

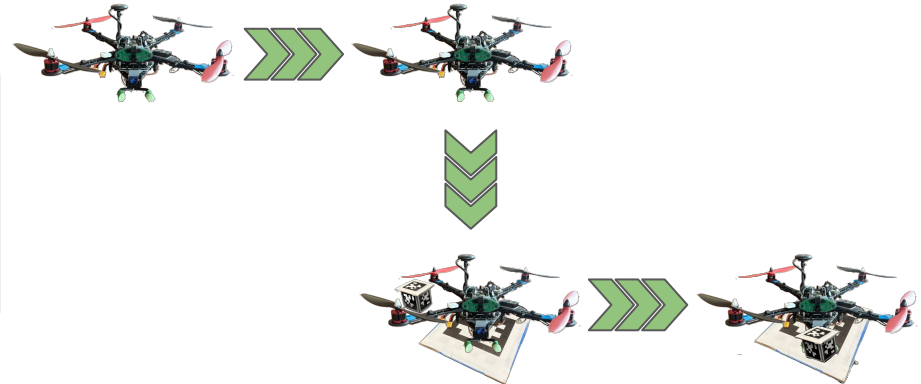
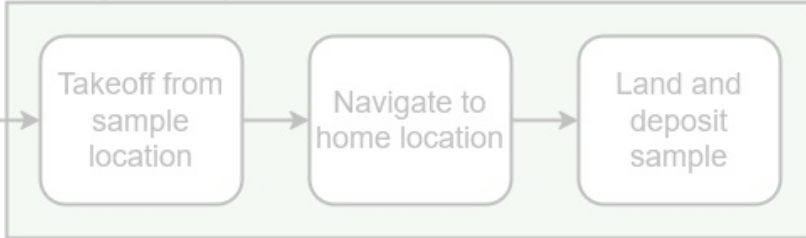
## Sample Search



## Sample Collection



## Sample Deposit

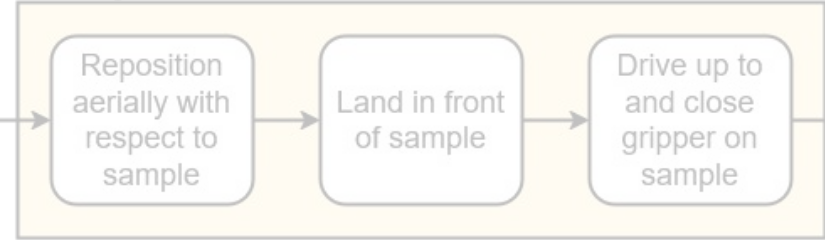


# Concept of Operations

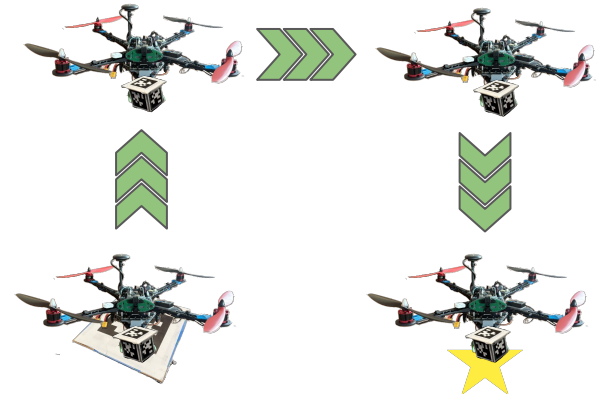
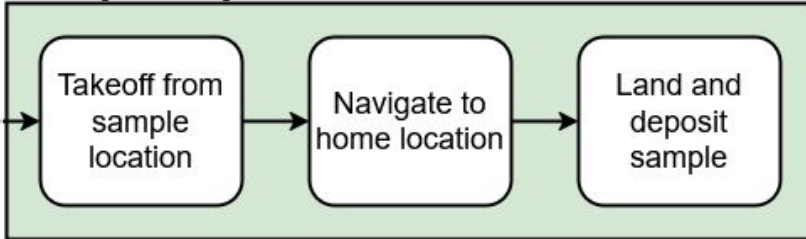
## Sample Search



## Sample Collection



## Sample Deposit






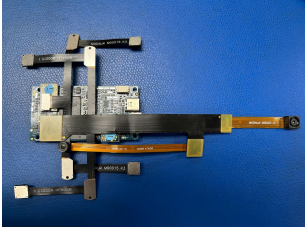
# Contributions of Thesis

- **Simple hybrid aerial-terrestrial vehicle design**
  - Commercial airframe outfitted with custom terrestrial platform
  - Greater emphasis placed on software development
- **Mission commanding from primary computer**
  - Each platform controlled by its own respective device
  - Primary device executes the autonomous algorithm and communicates relevant commands to the secondary device
- **Sample collection routine requiring minimal operator input**
  - Commands the vehicle at all stages of the sample collection mission
  - Only requires the operator to arm the vehicle and provide search parameters
- **Experimental analysis of sample collection mission**
  - Vehicle design tested in multiple laboratory demonstrations
  - Tests vehicle performance and determines viability for further research

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1. Research Introduction
- 2. Vehicle Hardware Design and Assembly**
3. Design and Implementation of Autonomy Architecture
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# Selected Commercial Aerial Platform

KEY COMPONENTS			
Flight Computer	Flight Controller	Airframe	Cameras
 <p>[Credit: ModalAI]</p>	 <p>[Credit: PX4]</p>	 <p>[Credit: Readytosky]</p>	 <p>[Credit: ModalAI]</p>
ModalAI VOXL 2	PX4-Autopilot	S500 Quadcopter Frame	Front Stereo Tracking High-Resolution Rear Stereo

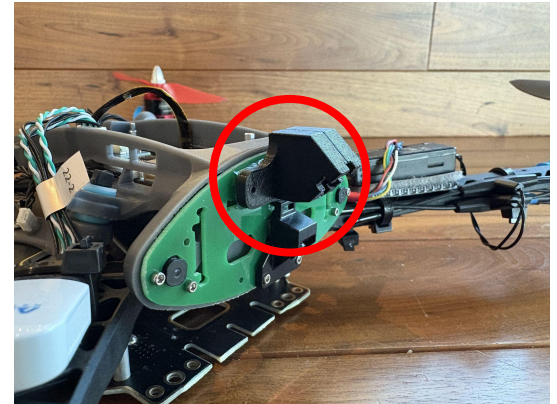
# Hardware Design Goals

*To successfully complete the sample collection mission, additions and modifications to the commercial airframe must include:*

- A mount for the high-resolution image sensor to increase the distance from which A-HAT-TRIC can detect fiducial markers on the ground
- A computer for commanding A-HAT-TRIC terrestrial platform motors
- A simple gripper to enable A-HAT-TRIC to pick up and deposit samples
- A ground chassis to allow A-HAT-TRIC to drive on the ground for repositioning prior to sample retrieval

# Hi-Res Image Sensor Mount

- Pitches hi-res sensor 45 degrees downwards to include ground in field of view
- Extrudes sensor beyond commercial tracking camera mount to ensure a minimally-obstructed image
- Increases range in which detections of fiducial markers are possible due to greater resolution of hi-res sensor as compared to tracking camera

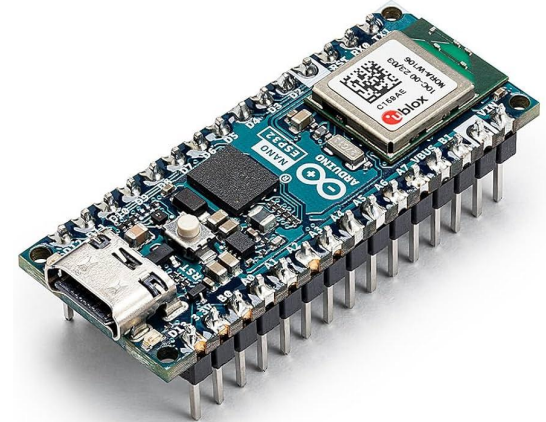


Hi-res mount on flight deck

# Selected Terrestrial Platform Computer

## Arduino Nano ESP32 Microcontroller

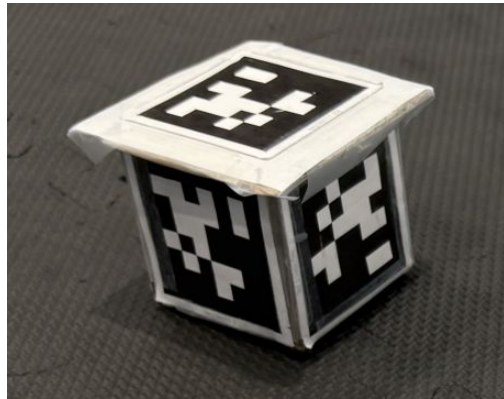
- WiFi-enabled for communication with flight computer
- Simple programming environment for rapid testing and development of code
- Offers pulse-width modulation pins for motor commanding
- Able to operate using power provided by flight battery



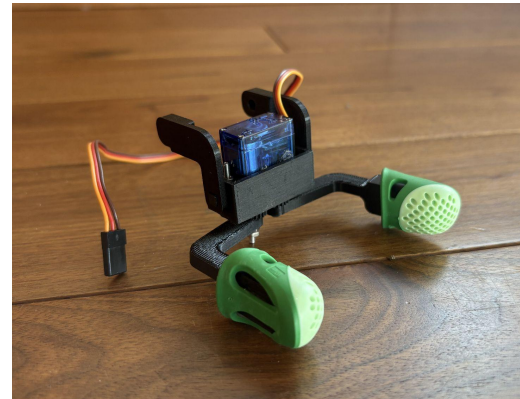
Arduino Nano ESP32  
[Credit: Arduino]

# Simple Gripper for Sample Grasping

- Designed for the cube-shaped samples used in this research
- One arm articulated using a micro servo, other arm rigidly fixed in closed position
- Rubber thimbles added to increase friction between gripper and sample



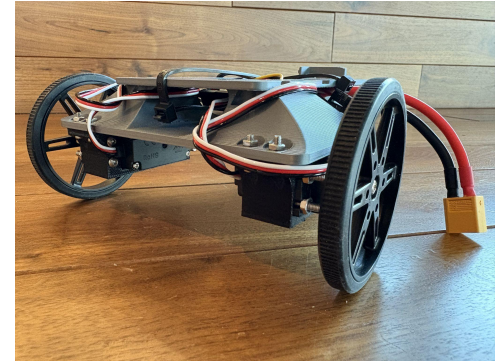
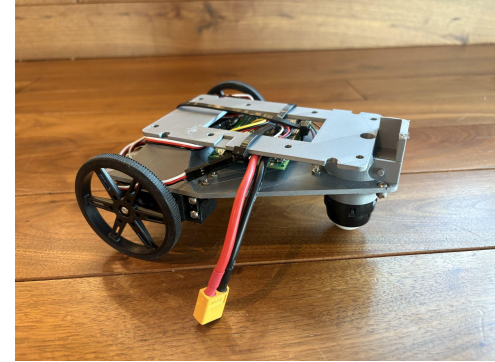
Sample shape



Final gripper design

# Ground Chassis for Terrestrial Locomotion

- Specifically designed to attach to the selected airframe
- Upper deck for mounting, lower deck for housing circuit board
- Rear-wheel drive design with caster ball providing multi-directional movement in the front
- Mounting point for gripper included at front of chassis



Final ground chassis design

# Challenge Encountered with Locomotive Motors

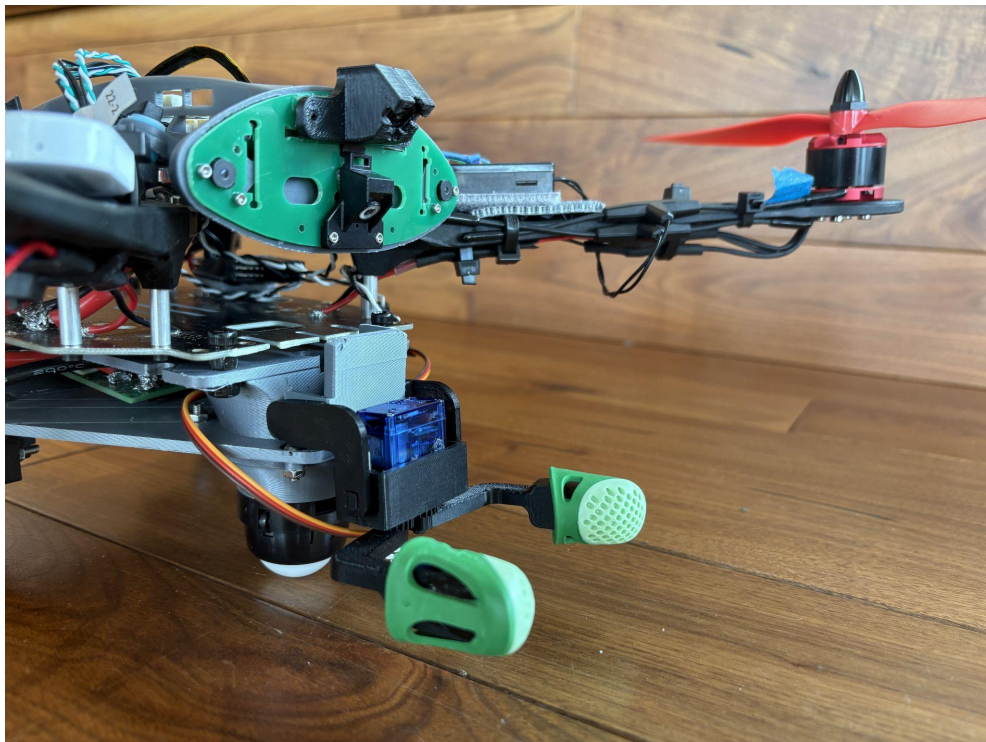
## Problem:

Motors unable to provide precise position control necessary for orienting the vehicle with respect to the sample. Additionally, the field of view of both detecting cameras were insufficient for complex navigation with respect to AprilTags on the ground.

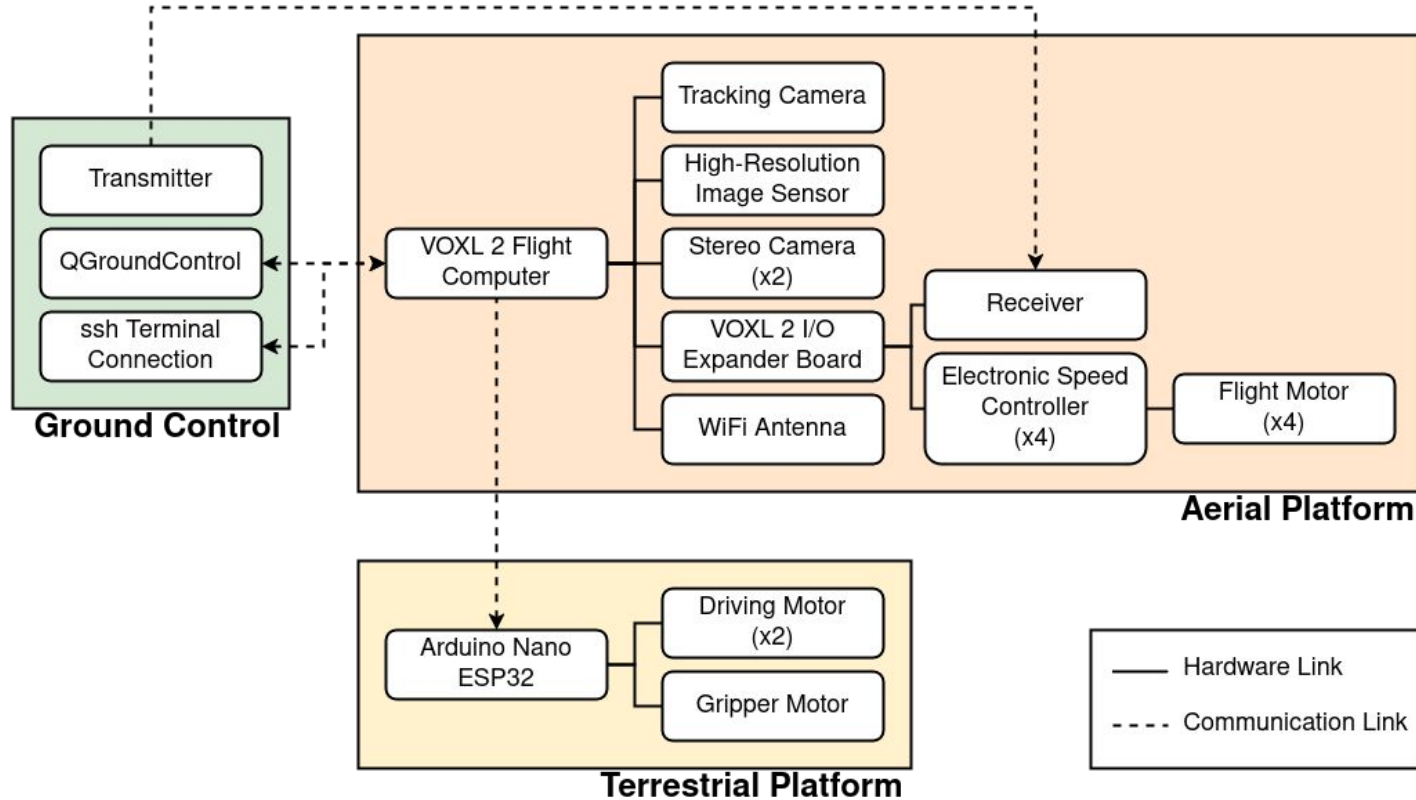
## Solution:

Perform all repositioning with respect to AprilTags aerially to leverage greater position control offered by flight motors and keep AprilTags within the field of view of detecting cameras.

# A-HAT-TRIC Vehicle

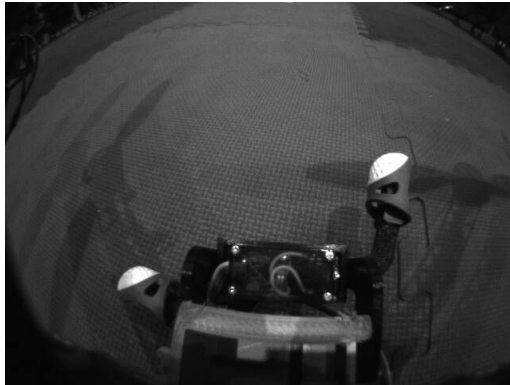


# A-HAT-TRIC Component Diagram

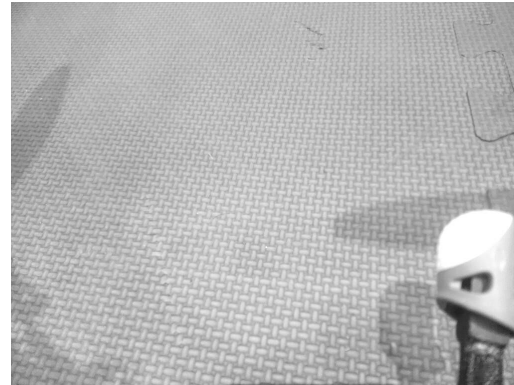


# A-HAT-TRIC Camera Operations

- Tracking camera and hi-res image sensor utilized for fiducial marker detection in sample search due to their position at the front of the flight deck
- Rear stereo cameras utilized for visual-inertial odometry (VIO) inertial position estimation due to being wholly unobstructed by additions to airframe



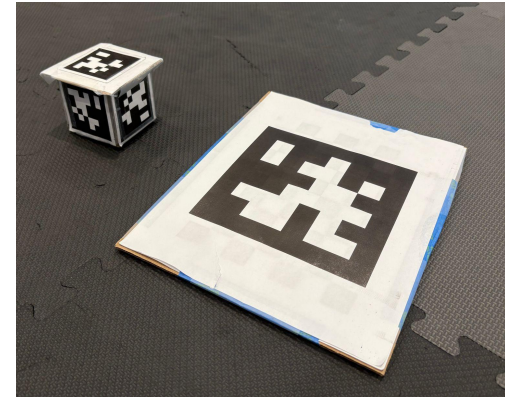
Tracking camera  
field of view



Hi-res image sensor  
field of view

# Fiducial Markers Utilized in Mission Execution

- Two AprilTags needed for mission execution:
  1. Landing site AprilTag
  2. Sample AprilTag
- AprilTag for landing is a 15.5 centimeter square, enabling detections at selected search flight altitude of 1 meter
- AprilTag on sample is a 5.2 centimeter square, which can be detected at a reduced flight altitude of 40 centimeters



Sample (left) and landing (right) AprilTags utilized

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# Sample Collection Mission Overview

Three main phases to the mission:

1. **Sample search**
2. **Sample collection**
3. **Sample deposit**

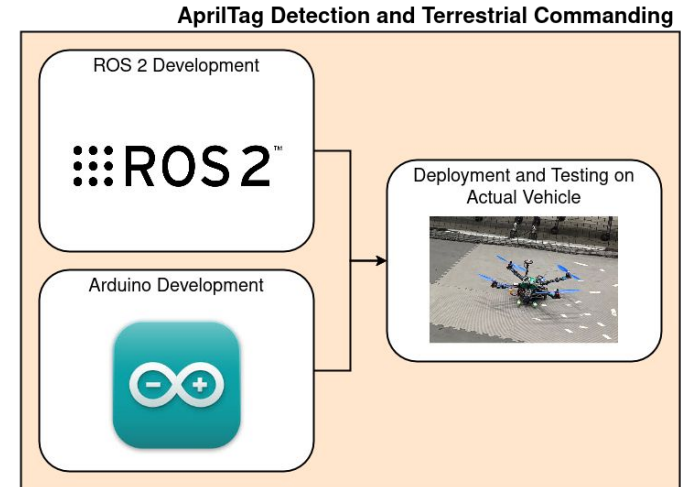
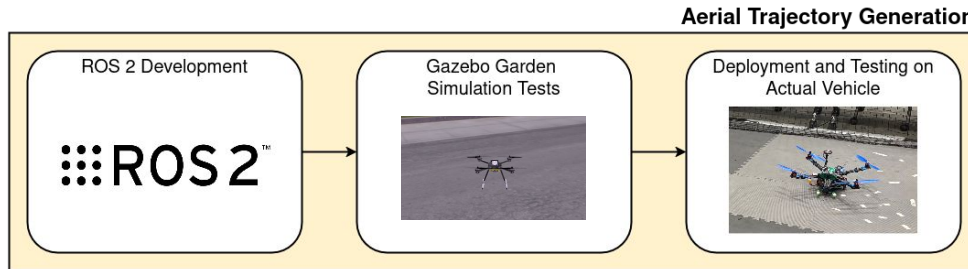
Further granularity required to successfully implement a state machine for mission commanding, necessitating the development of:

- A map of all steps required for mission completion
- Precise logic to determine state transitions

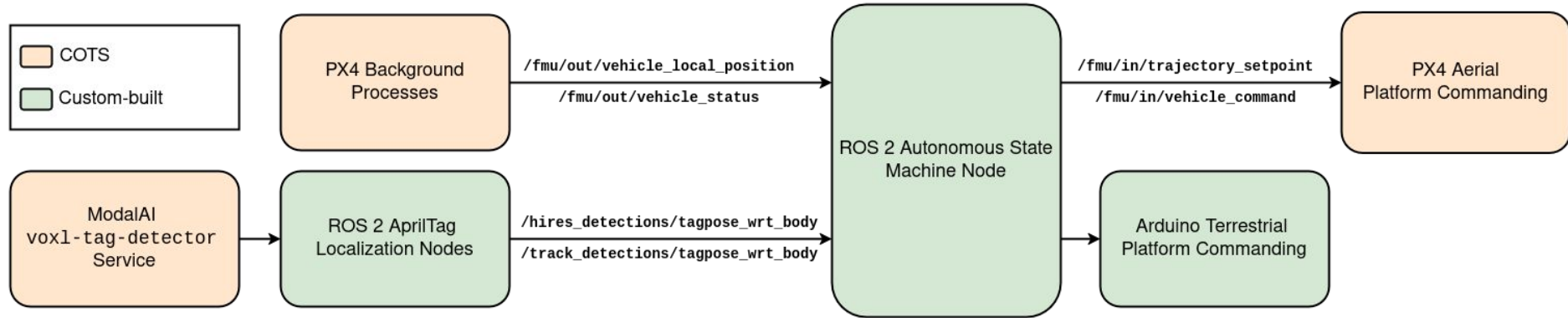


# Robotic Software and Workflow

- Autonomous state machine written using Robot Operating System 2 (ROS 2)
- Terrestrial commanding programmed in Arduino coding language
- Gazebo Garden utilized as high-fidelity computer simulation environment



# ROS 2 Command Architecture



`/fmu/out/vehicle_local_position`: estimate of current vehicle inertial coordinates and heading

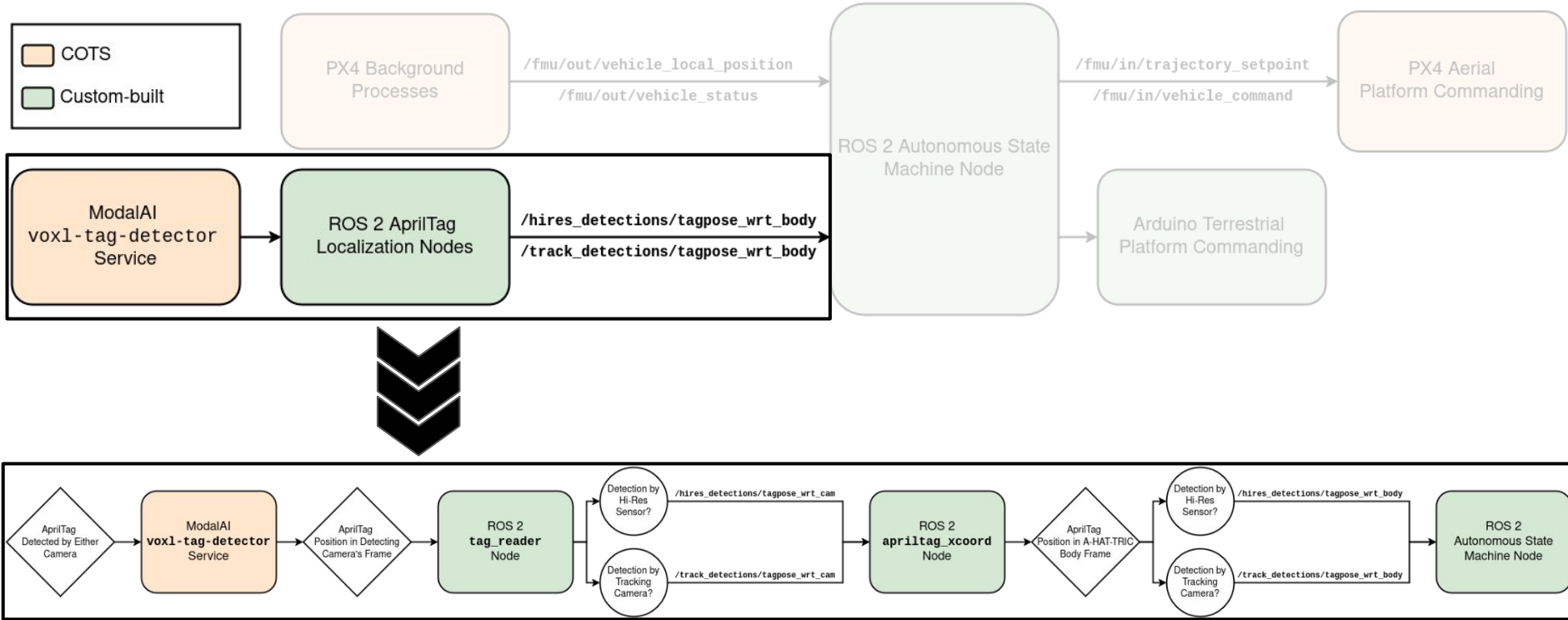
`/fmu/out/vehicle_status`: information about current vehicle status (i.e., armed vs. disarmed)

`<>_detections/tagpose_wrt_body`: position of AprilTag in body frame as estimated by detecting camera

`/fmu/in/trajectory_setpoint`: generated command for vehicle aerial maneuvering

`/fmu/in/vehicle_command`: message for changing vehicle mode (i.e., position vs. offboard)

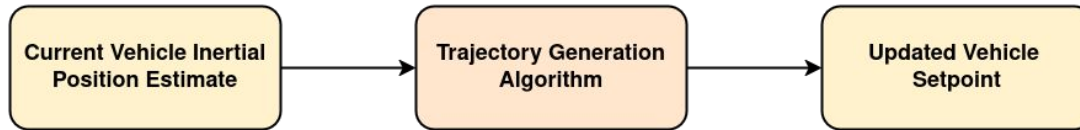
# AprilTag Detection Routine



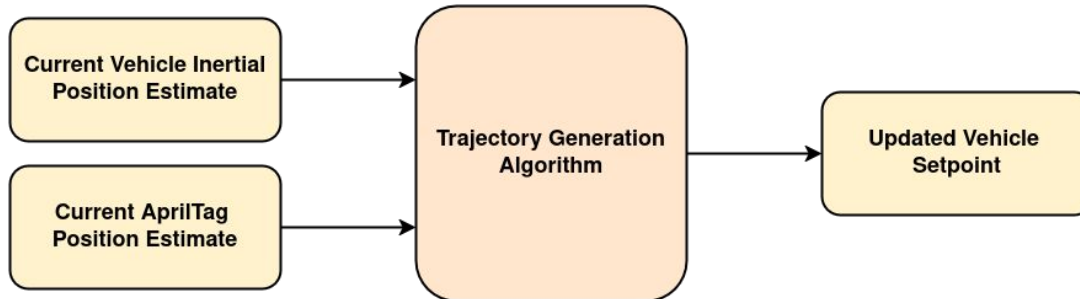


# Autonomous Trajectory Generation

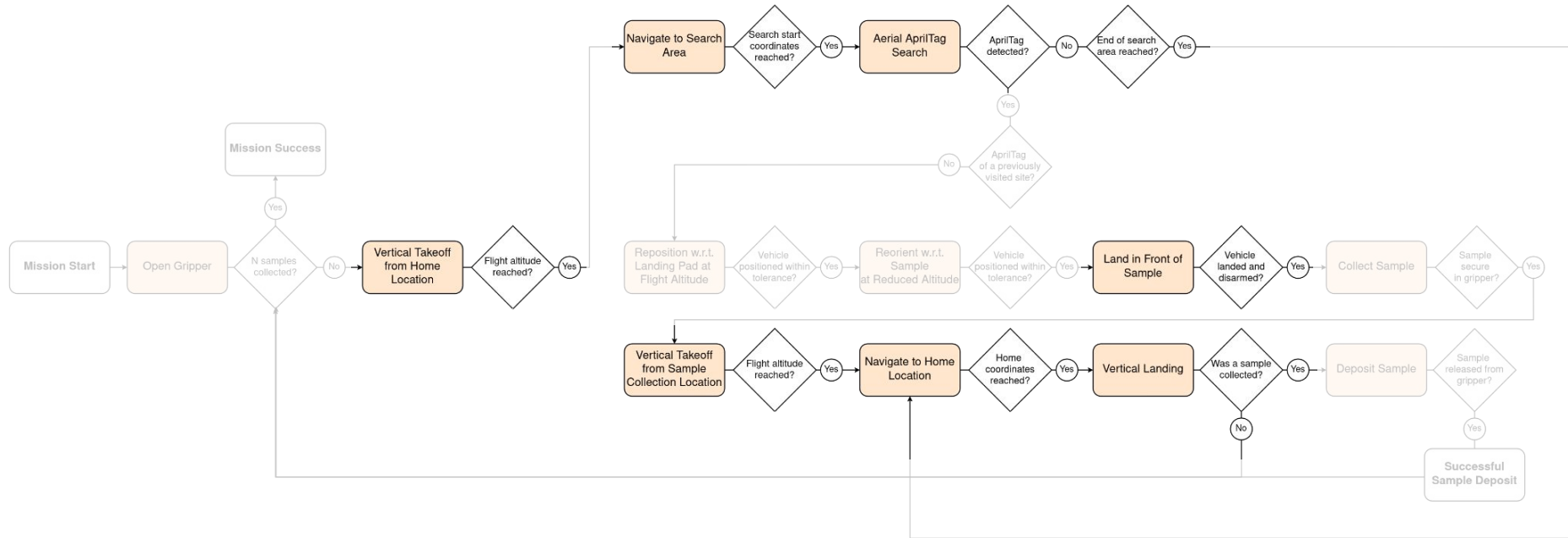
- Path to follow calculated as vehicle is maneuvering through inertial space
- Next commanded setpoint relies on current vehicle inertial position



- If AprilTag detections utilized for setpoint generation, commanded setpoint also depends on the coordinates of the marker



# States Utilizing Autonomous Trajectory Generation Logic

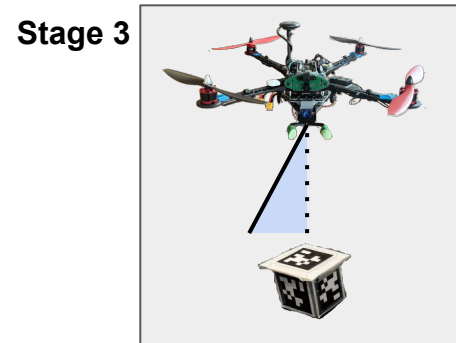
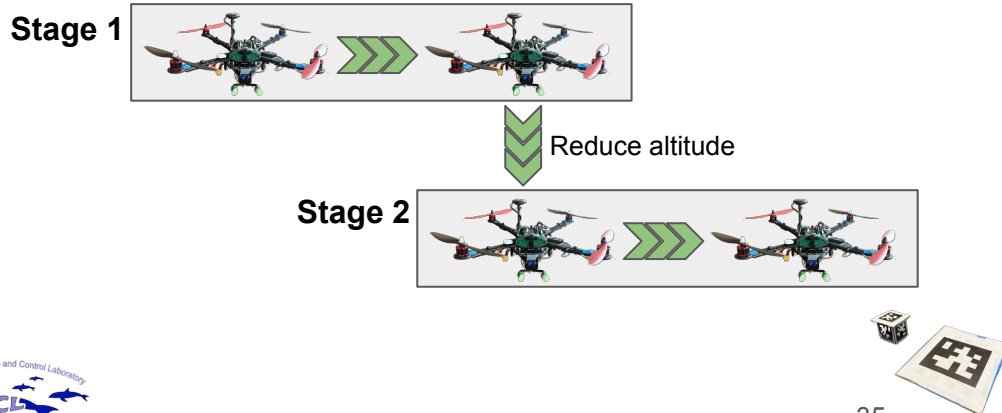


\*AprilTag-based navigation not included.

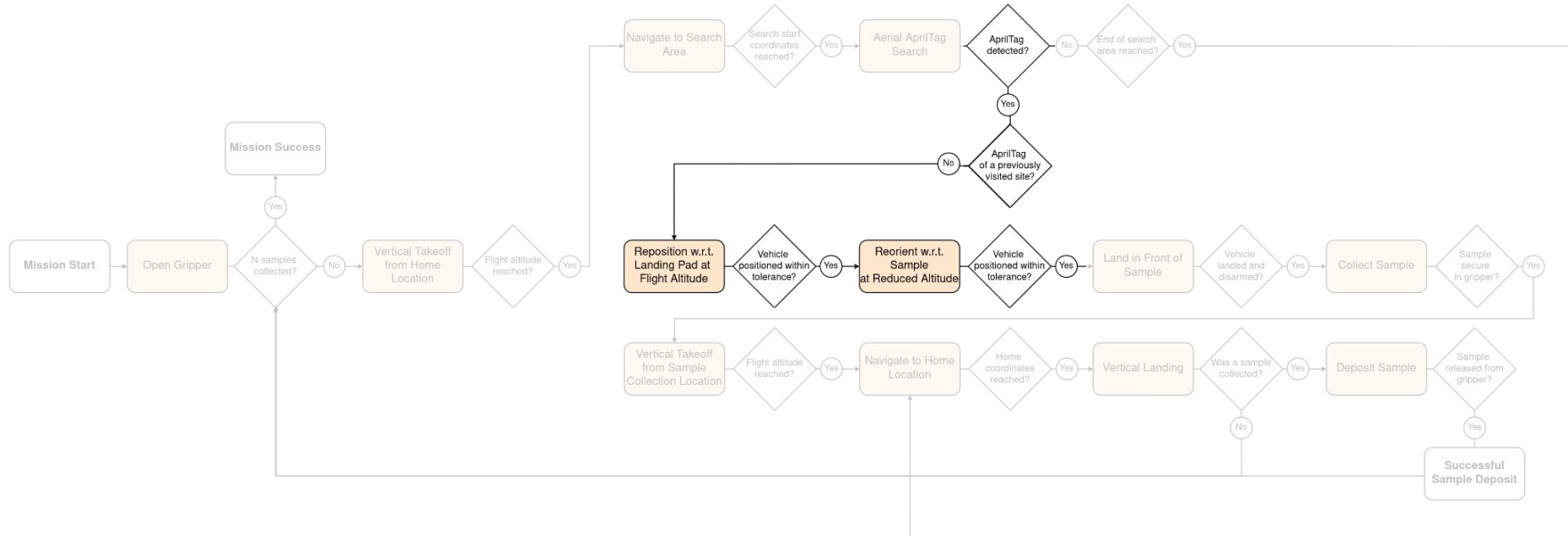
# AprilTag Detection and Vehicle Positioning

Positioning relative to AprilTags occurs in three stages:

1. Planar approach of landing AprilTag at search flight altitude of 1 meter
2. Planar approach of landing AprilTag at reduced flight altitude of 40 centimeters
3. Heading alignment with respect to sample AprilTag at reduced flight altitude of 40 centimeters



# States Utilizing AprilTag Detection Logic



# Terrestrial Maneuvering for Sample Grasping

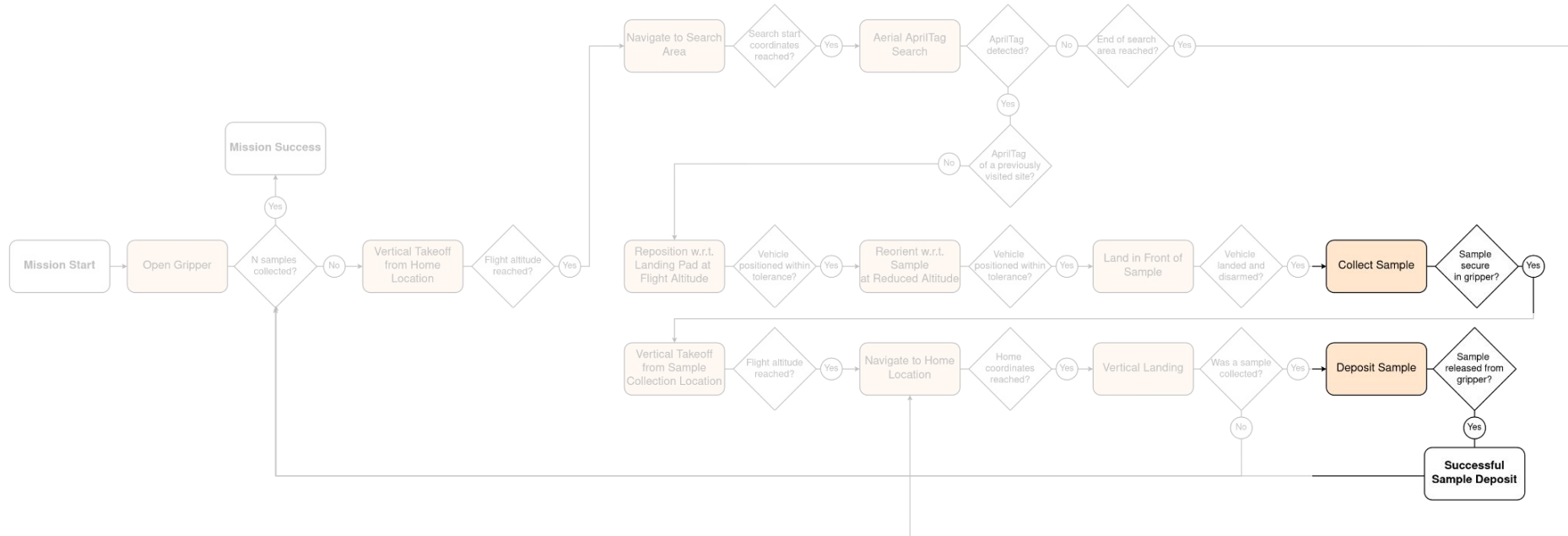
For sample collection:

1. Drive forward then record current sample AprilTag coordinates
2. Close gripper
3. Drive backward then compare current sample AprilTag coordinates with those from step 1
4. If distance of AprilTag from vehicle remains constant, sample has been *successfully collected*

For sample deposit:

1. Open gripper, record current sample AprilTag coordinates
2. Drive backward then compare current sample AprilTag coordinates with those from step 1
3. If distance of AprilTag from vehicle increases, sample has been *successfully deposited*

# States Utilizing Sample Grasping Logic

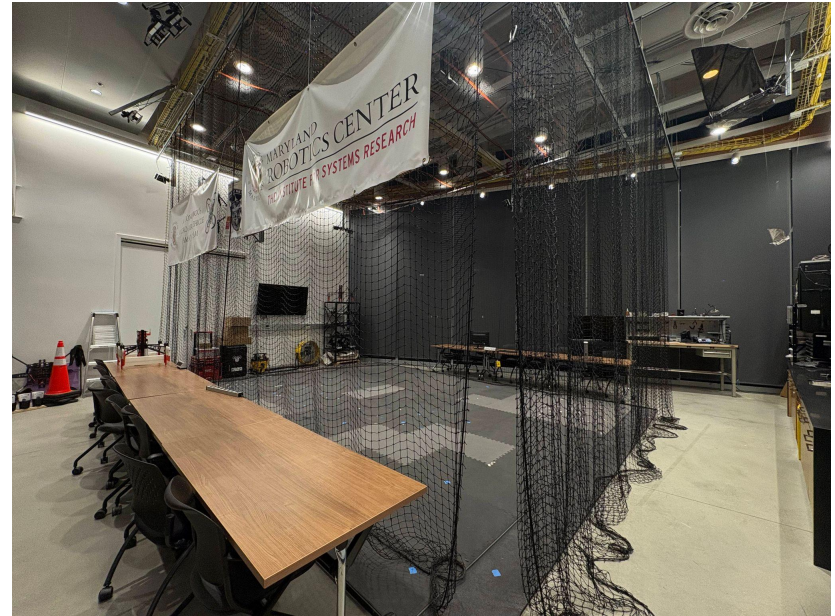


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# Facility Utilized for Experimentation

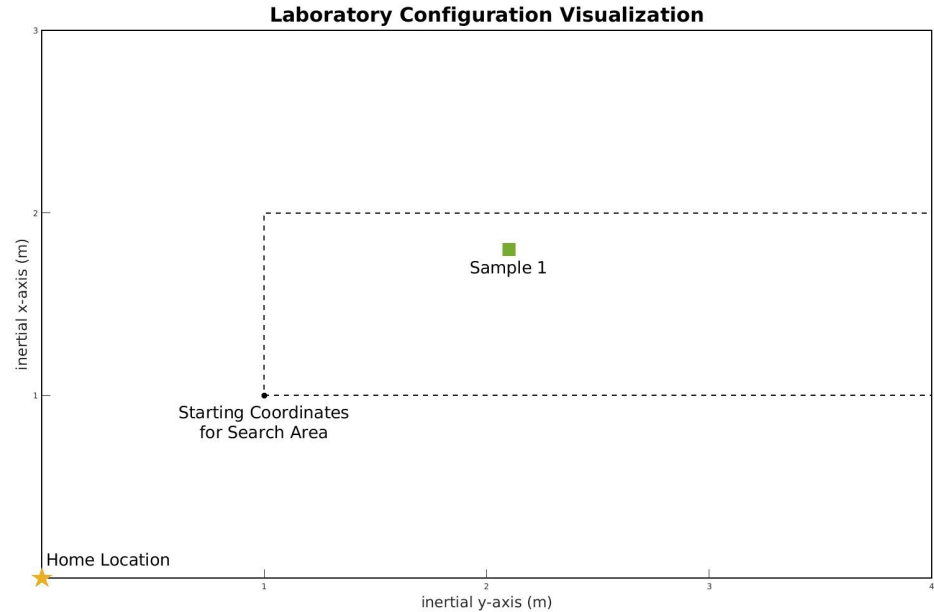
- Brin Family Aerial Robotics Lab utilized for vehicle testing
- Indoor 430 square foot netted facility with padded floor
- Maintained by Maryland Robotics Center



Brin Family Aerial Robotics Lab

# Mission Parameters and Laboratory Visualization

<b>Search Area Starting Coordinates</b>	(1, 1)
<b>Search Area Length</b>	3 meters
<b>Search Area Width</b>	1 meter
<b>Number of Samples</b>	1
<b>Sample Location in Inertial Frame</b>	(1.8, 2.1)



Graphical depiction of laboratory setup

# A-HAT-TRIC Testing Methodology

Testing of the vehicle was performed in two stages:

1. **Verification of autonomous trajectory generation** without samples present in the search area to determine accuracy of vehicle navigation routine
2. **Experimental evaluation of full end-to-end demonstration** to verify AprilTag detection and repositioning scheme, as well as terrestrial maneuvering capabilities

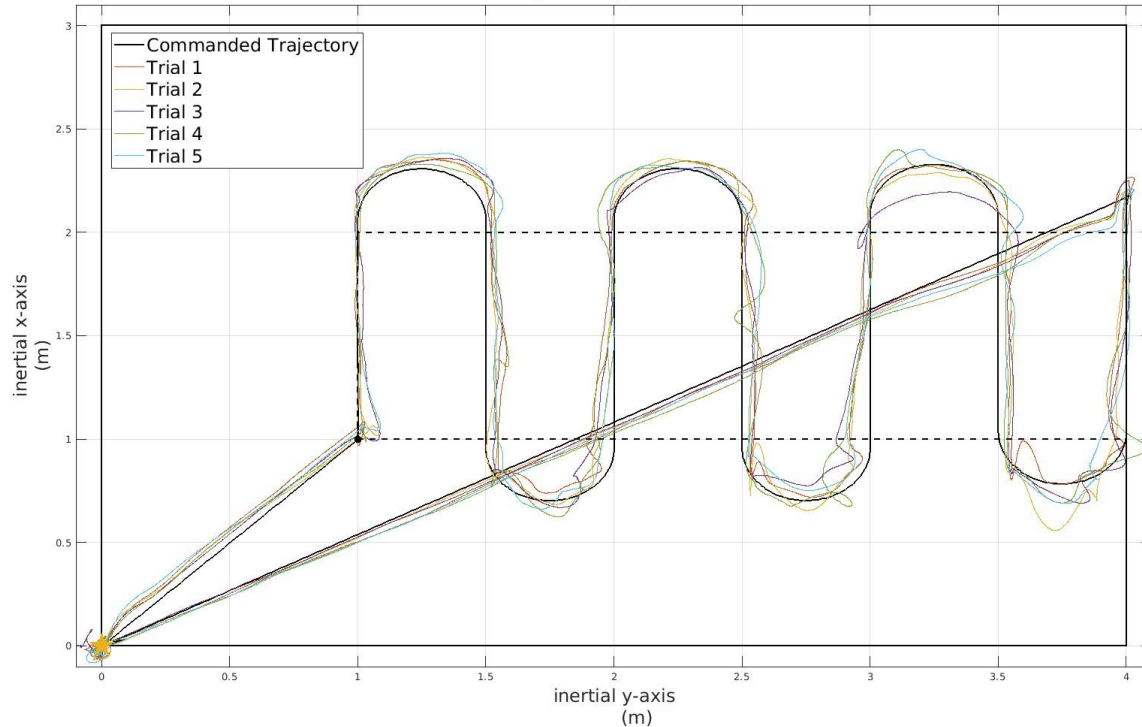
# Autonomous Trajectory Generation Demonstration

Five trials performed *without sample* placed in laboratory environment

Trial	Completion Time	Executed in Full?
1	131 seconds	yes
2	133 seconds	yes
3	128 seconds	yes
4	129 seconds	yes
5	132 seconds	yes

# Autonomous Trajectory Generation Test Data

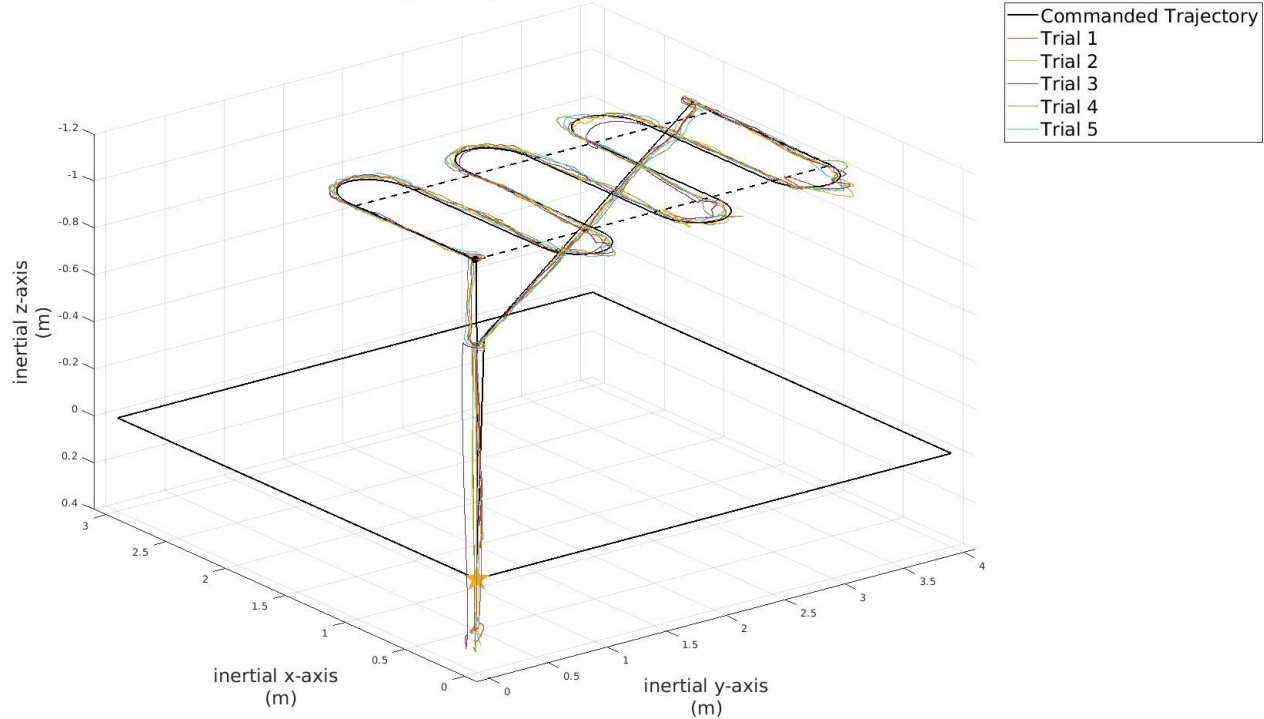
## Real-World Planar Trajectory Generation and Execution



Planar inertial view of A-HAT-TRIC trajectory

# Autonomous Trajectory Generation Test Data

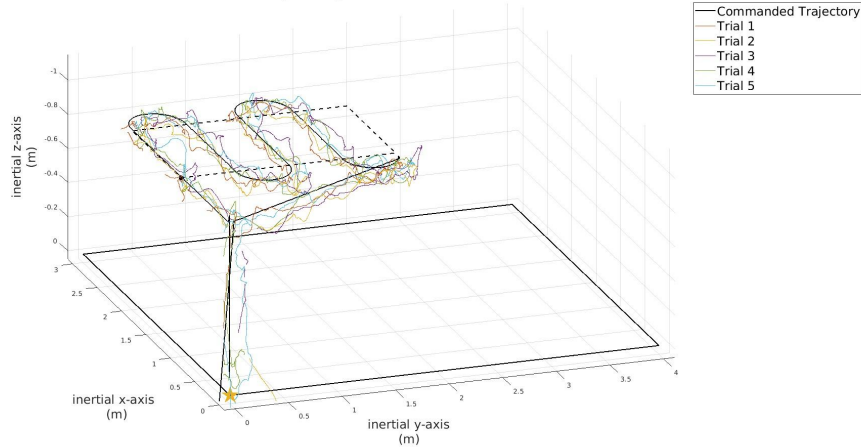
## Real-World Trajectory Generation and Execution



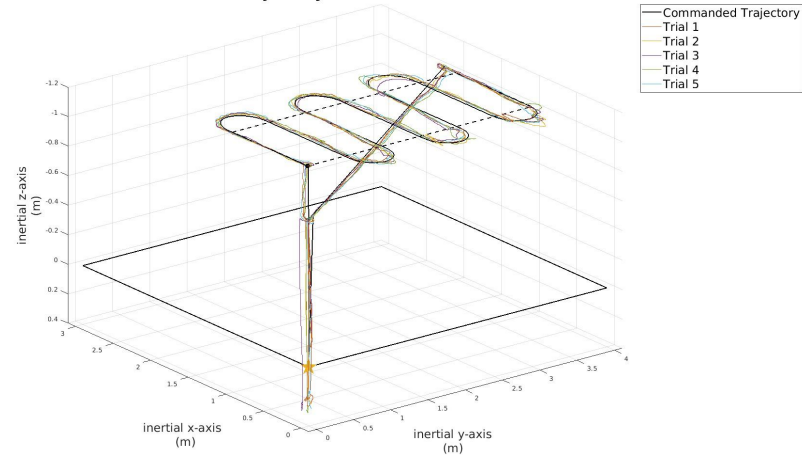
3D inertial view of A-HAT-TRIC trajectory

# Performance Improvement From Simulation Tests

Simulated Trajectory Generation and Execution



Real-World Trajectory Generation and Execution



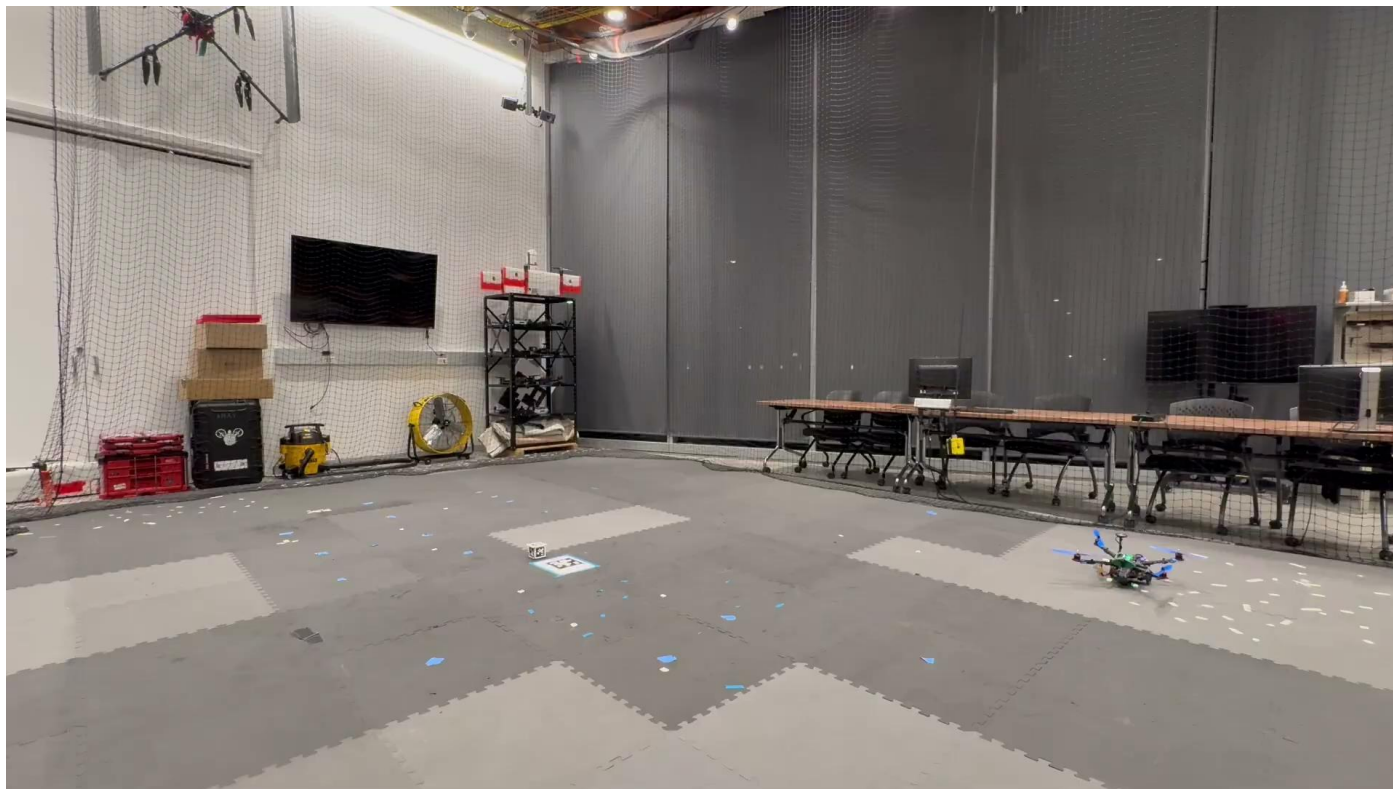
- Gazebo Garden is a non-deterministic simulator, resulting in significant variation in performance between runs
- Actual drone has more predictable behavior with greater repeatability between trials
- Marked improvement in trajectory-following capabilities between simulation and laboratory tests

# Autonomous Sample Collection Mission Demonstration

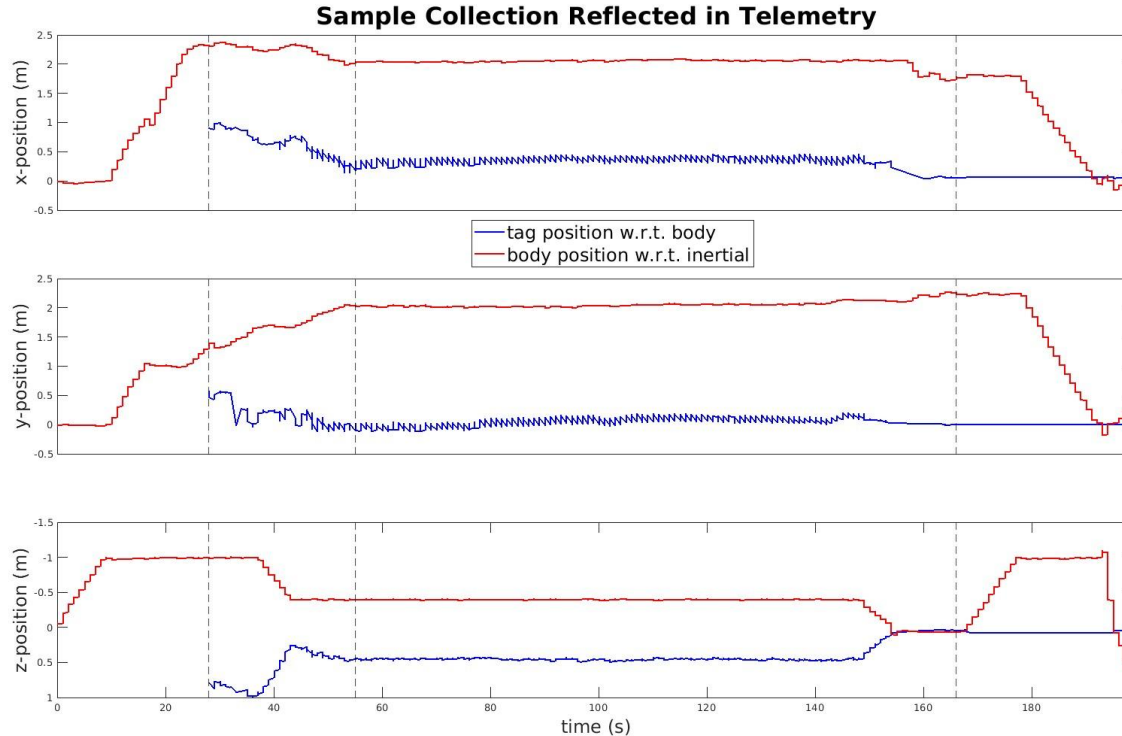
Five trials performed *with one sample* placed in laboratory environment

Trial	Completion Time	Sample Collected?
1	137 seconds	yes
2	106 seconds	yes
3	196 seconds	yes
4	123 seconds	yes
5	170 seconds	yes

# Selected End-to-End Demonstration Video



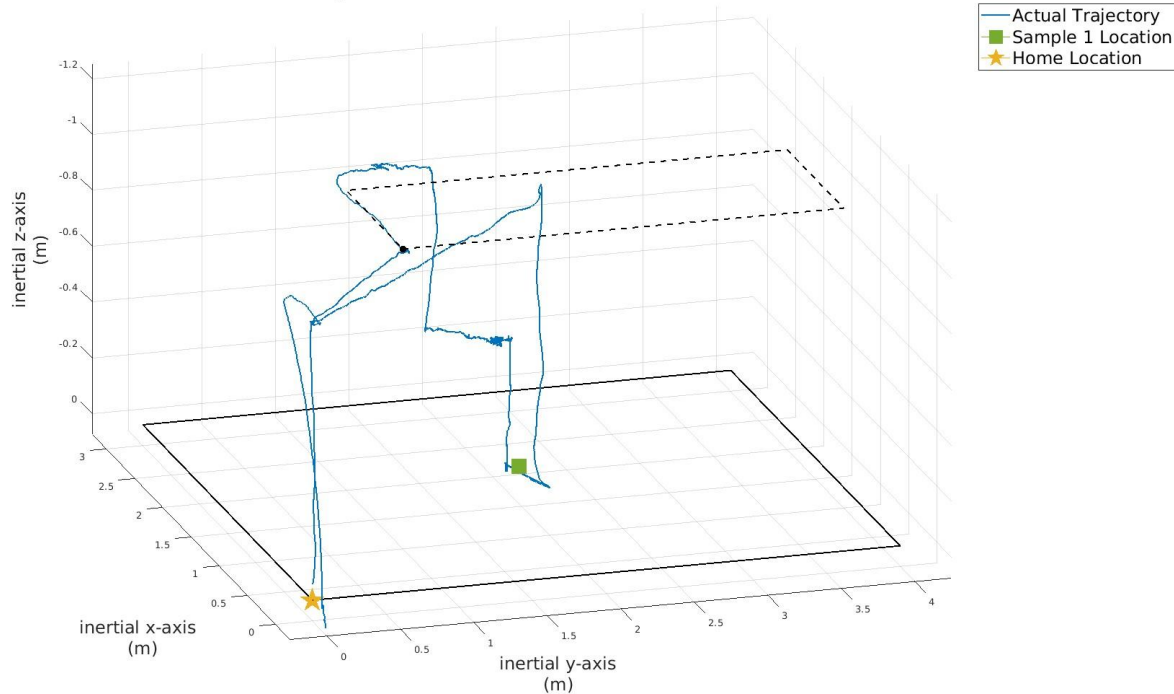
# Sample Collection Observed in Vehicle Telemetry



Plots detailing sample position relative to body frame as vehicle navigates in inertial space

# Selected End-to-End Demonstration Vehicle Trajectory

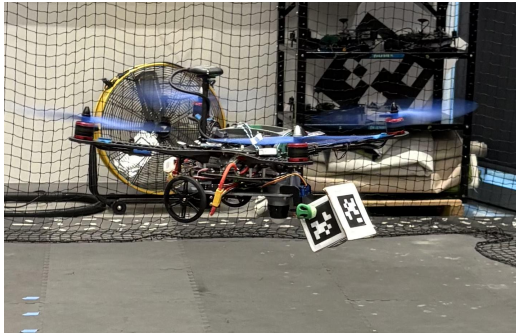
## Sample Collection from Aerial Search



3D inertial view of A-HAT-TRIC trajectory

# Noteworthy Observations from Mission Trials

- Trials 3 and 5 included one complete pass across width of search area prior to sample detection
- Trial 5 resulted in the sample being collected in an inverted position, which ultimately did not affect the vehicle's ability to determine it had been collected



A-HAT-TRIC in flight with sample



Inverted sample collection position (left) and nominal sample collection position (right) as viewed by hi-res sensor

# Challenges in Laboratory Implementation

- Sensitive camera estimates
  - Effects of external light sources infringed upon cameras' abilities to detect AprilTags
  - Impacted consistency in detecting and navigating relative to AprilTags between tests
- Flight battery capacity
  - Increased vehicle weight due to terrestrial platform impacted battery runtime
  - Resulted in limited time for testing, as well as several aborted attempts due to unsafe power levels remaining
- Degradation of VIO during extended operations
  - Position estimation consistently failed when missions with multiple samples were attempted
  - Resulted in origin of inertial frame being reset mid-mission, preventing successful completion

# Summary of Contributions

- **Simple hybrid aerial-terrestrial vehicle design**
  - Custom vehicle platform designed that integrates terrestrial capabilities into a commercial quadcopter UAV platform
  - Demonstrated ability to fly, drive, and grasp samples in laboratory tests
- **Mission commanding from primary computer**
  - Communication link between primary device, defined as flight computer, and secondary device, defined as terrestrial microcontroller, established
  - Autonomous algorithm developed executed on primary device, with terrestrial commands sent to secondary device
- **Sample collection routine requiring minimal operator input**
  - Autonomous state machine, only requiring operator to arm vehicle and provide sample search parameters, developed
  - Shown in laboratory tests to be capable of commanding vehicle through multiple executions of sample collection mission
- **Experimental analysis of sample collection mission**
  - Multiple successful laboratory demonstrations performed that verify vehicle's performance in two stages
  - Vehicle telemetry gathered to showcase and support successful mission execution

# Suggested Future Work

- Enhancement of terrestrial locomotive capabilities
  - Vehicle dynamics more stable on the ground versus in the air
  - Results in more accurate and precise AprilTag position estimates for repositioning
- Increasing gripper utility
  - Current gripper only optimized for cube-shaped samples
  - A universal gripper mount would allow for end effectors to be changed out depending on the shape of the sample being collected
- Utilization of object detection in place of AprilTags
  - Increases algorithm's versatility for applications where samples do not have fiducial markers
  - Requires the addition of new software to facilitate object detection and localization
- Implementation in an outdoor environment
  - Outdoor applications are more realistic for demonstrating the A-HAT-TRIC as an earth-analog to the Sample Recovery Helicopter, which is designed to operate on the Martian surface
  - Incorporate the GPS sensor and magnetometer, removing need for VIO-based navigation

# Presentation Citations

A. Kalantari and M. Spenko. Modeling and Performance Assessment of the HyTAQ, a Hybrid Terrestrial/Aerial Quadrotor. *IEEE Transactions on Robotics*, 30(5):1278–1285, October 2014.

D. Zhang, M. Xu, P. Zhu, C. Guo, Z. Zhong, H. Lu, and Z. Zheng. The development of a novel terrestrial/aerial robot: autonomous quadrotor tilting hybrid robot. *Robotica*, 42(1):118–138, 2024.

K. Shi, Z. Jiang, L. Ma, L. Qi, and M. Jin. MTABot: An Efficient Morphable Terrestrial-Aerial Robot With Two Transformable Wheels. *IEEE Robotics and Automation Letters*, 9(2):1875–1882, 2024.

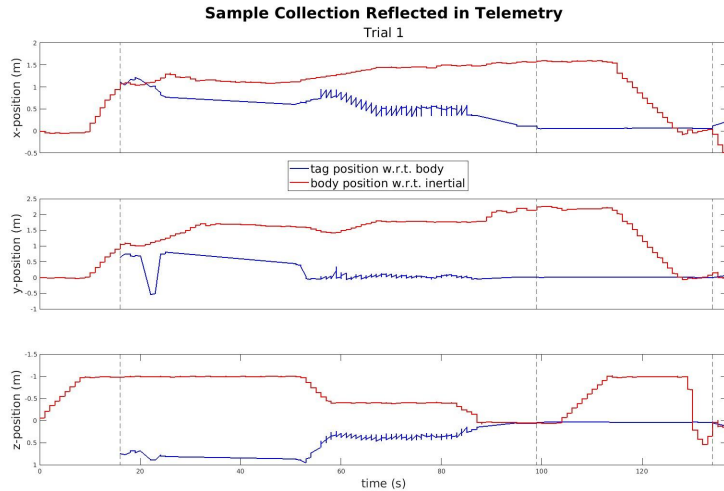
S. Yu, B. Pu, K. Dong, S. Bai, and P. Chirarattananon. A Hybrid Quadrotor With a Passively Reconfigurable Wheeled Leg Capable of Robust Terrestrial Maneuvers. *IEEE Robotics and Automation Letters*, 10(4):3486–3493, 2025.

*\*Full list of sources utilized available in thesis document.\**

# Backup Slides

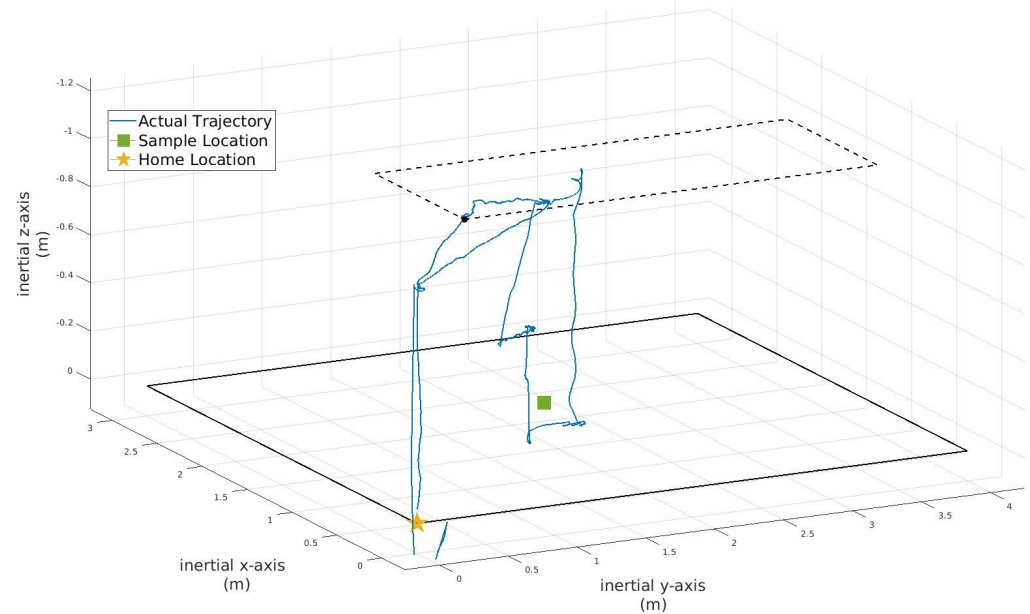
# End-to-End Demonstration: Trial 1

Time to complete: 137 seconds



Telemetry showing sample position w.r.t. vehicle

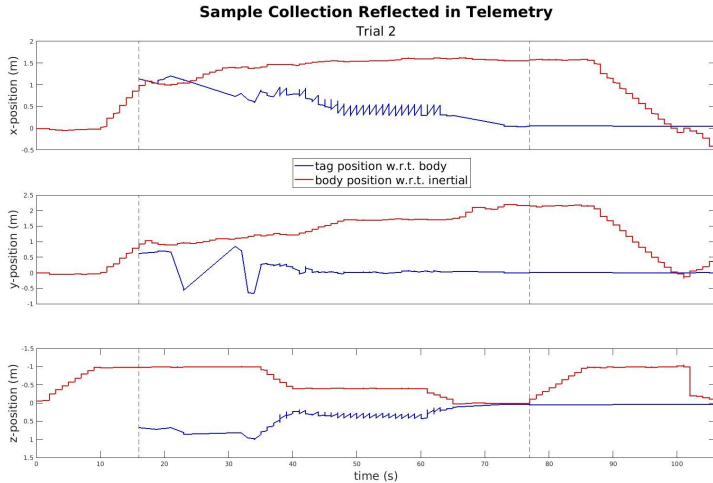
**Sample Collection from Aerial Search**  
Trial 1



3D inertial view of A-HAT-TRIC trajectory

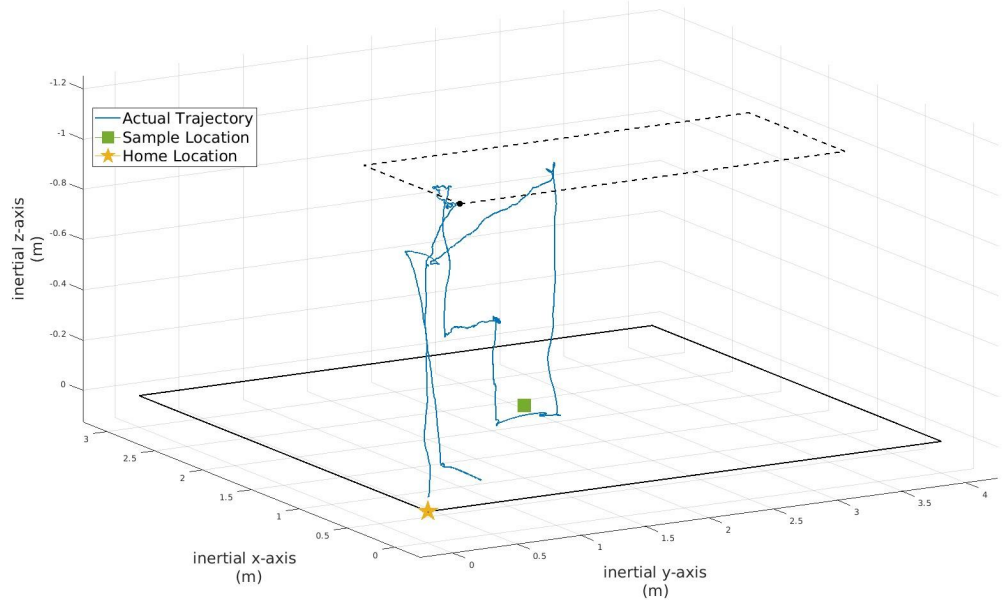
# End-to-End Demonstration: Trial 2

Time to complete: 106 seconds



Telemetry showing sample position w.r.t. vehicle

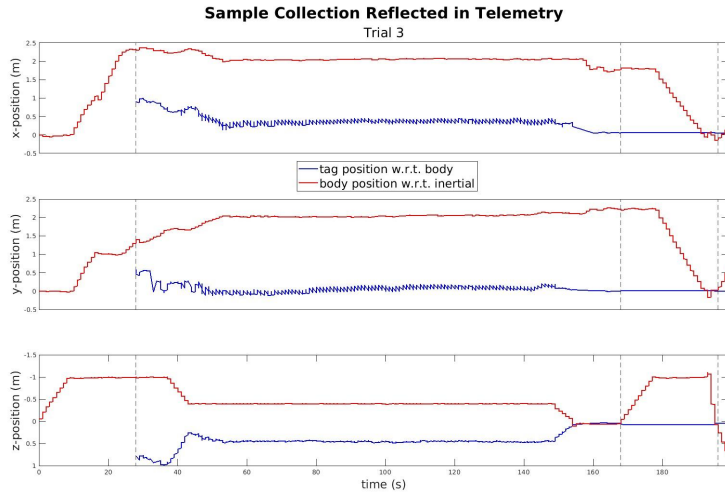
**Sample Collection from Aerial Search**  
Trial 2



3D inertial view of A-HAT-TRIC trajectory

# End-to-End Demonstration: Trial 3

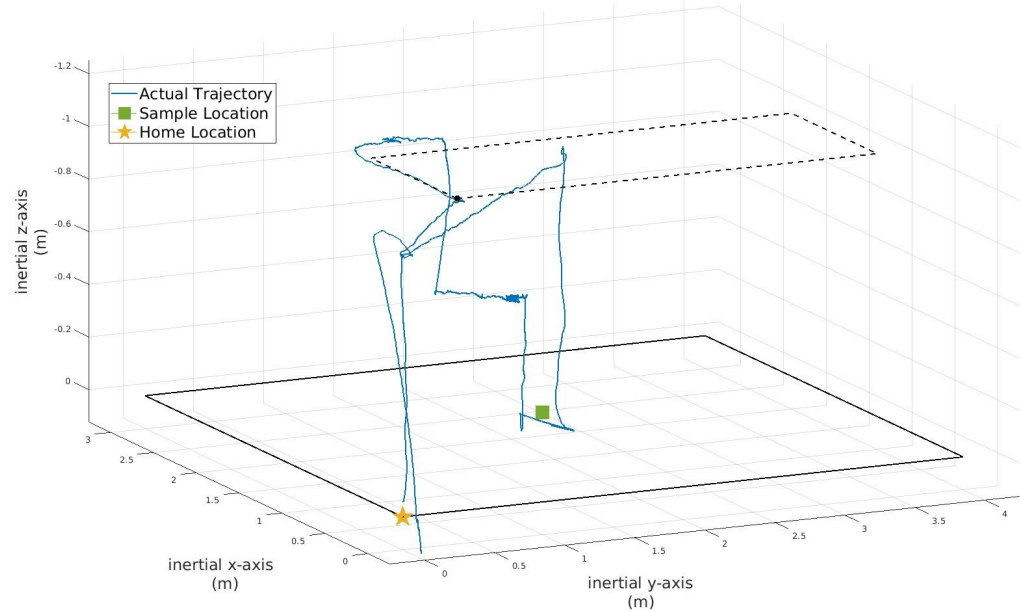
Time to complete: 196 seconds



Telemetry showing sample position w.r.t. vehicle

## Sample Collection from Aerial Search

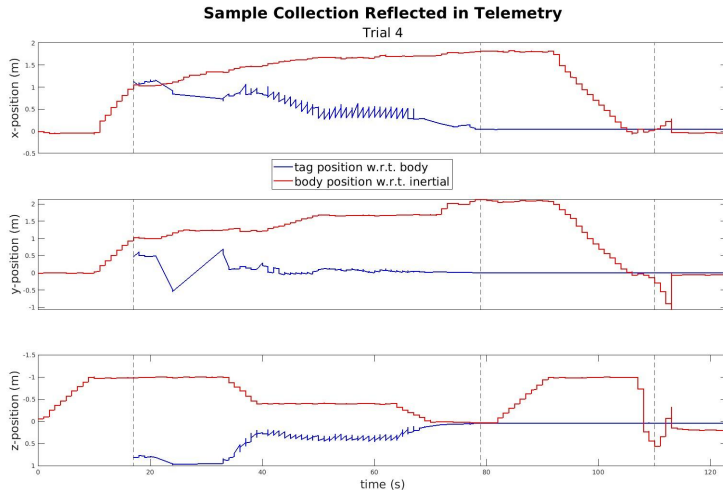
Trial 3



3D inertial view of A-HAT-TRIC trajectory

# End-to-End Demonstration: Trial 4

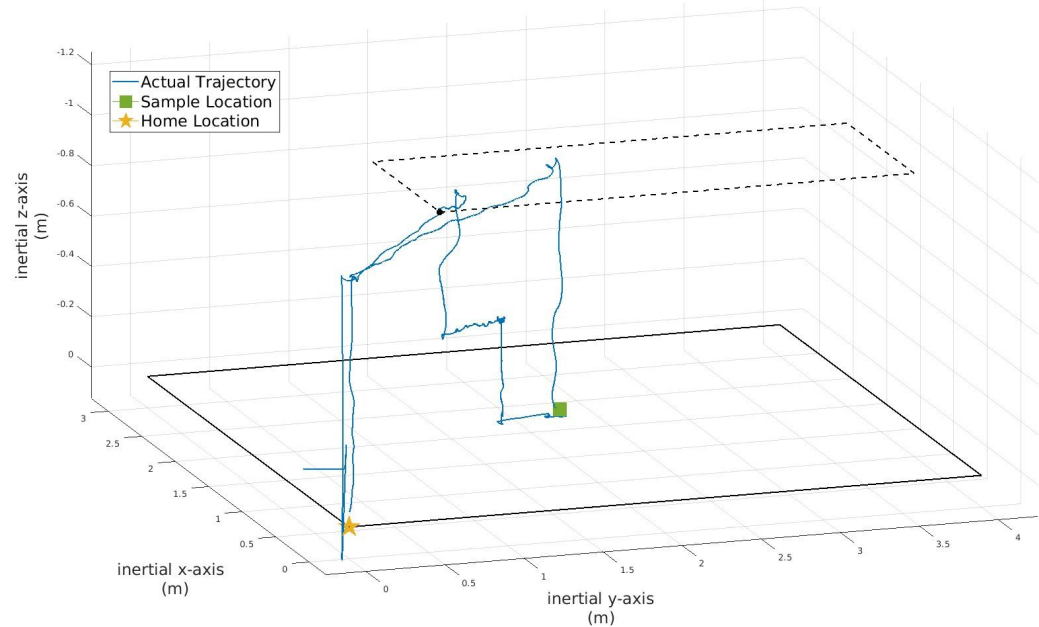
Time to complete: 123 seconds



Telemetry showing sample position w.r.t. vehicle

## Sample Collection from Aerial Search

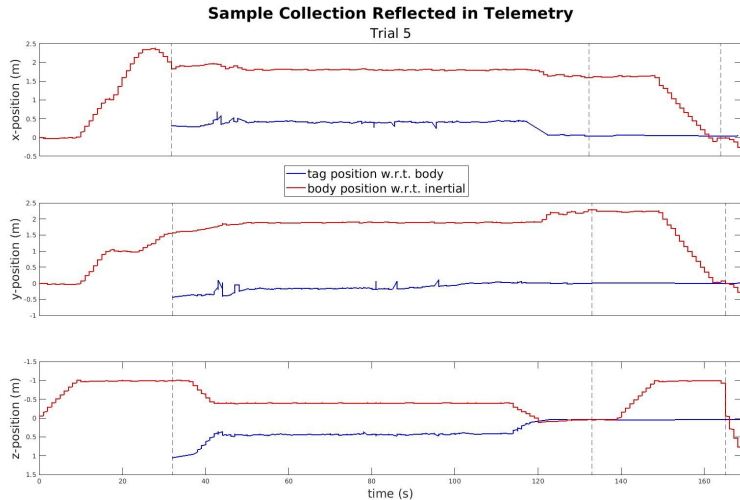
Trial 4



3D inertial view of A-HAT-TRIC trajectory

# End-to-End Demonstration: Trial 5

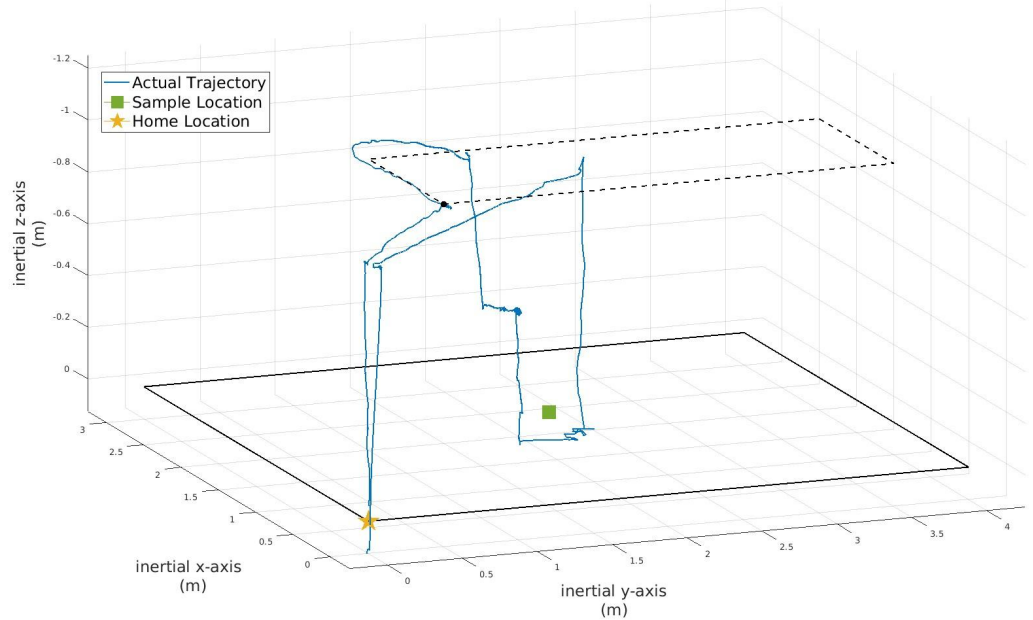
Time to complete: 170 seconds



Telemetry showing sample position w.r.t. vehicle

### Sample Collection from Aerial Search

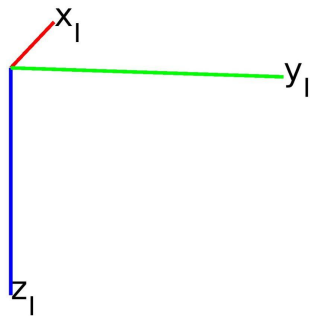
Trial 5



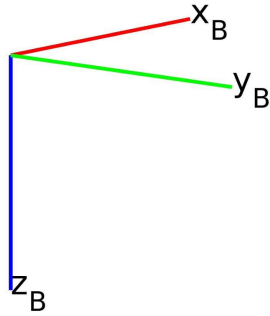
3D inertial view of A-HAT-TRIC trajectory

# AprilTag Detection and Localization

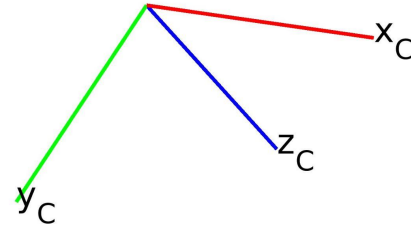
- Modified `voxel-tag-detector` and `voxel-mpa-to-ros2` packages used for receiving AprilTag information from camera streams
- Camera extrinsics and vehicle position data utilized to obtain AprilTag position in inertial frame



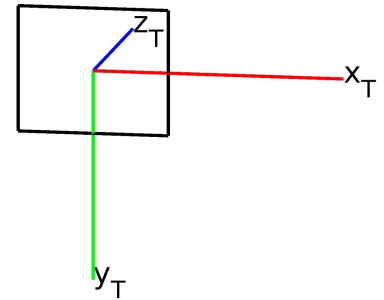
Inertial frame



Body frame



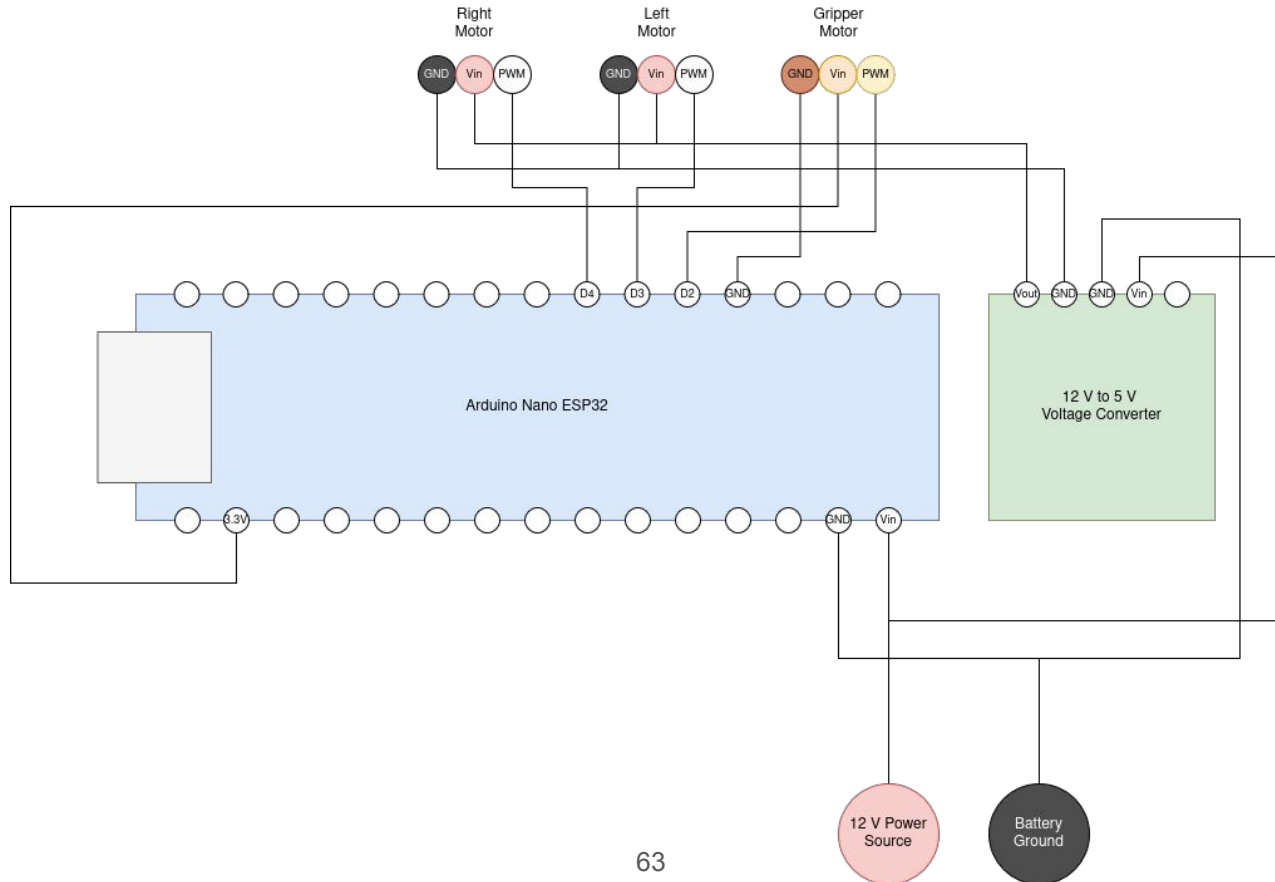
Camera frame



AprilTag frame

Reference frames utilized

# Terrestrial Platform Circuit

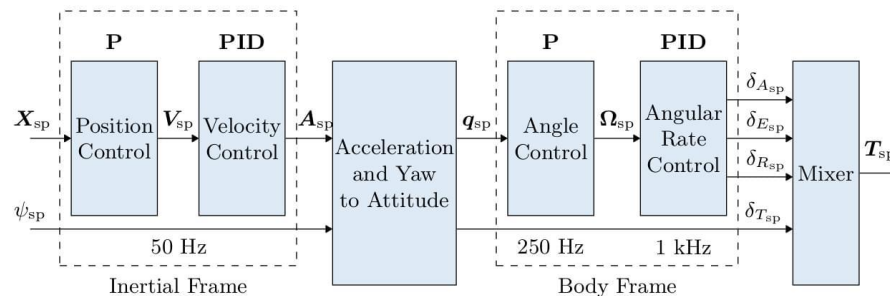


# Terrestrial Platform Design Constraints

- Maximum allowable payload: 1 kilogram
  - 3D-printed terrestrial platform to limit mass, using ABS material
  - Components designed in an attempt to create a balanced mass distribution about the airframe's center of mass
- Battery voltage output: 12 volts
  - Vehicle does not need to traverse complex terrain in the scope of this research
  - Powerful motors unnecessary, so available power was of minimal concern

# Quadcopter UAV Control Scheme Overview

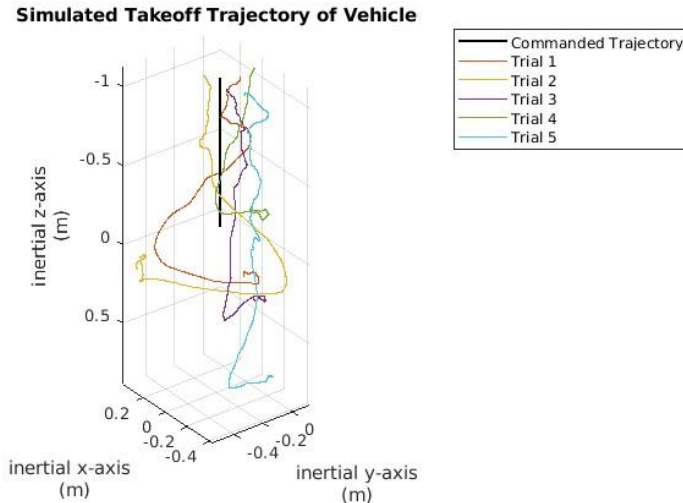
- Quadcopter control is affected through the torque imposed by each motor and the resultant thrust generated
- The PX4 flight controller utilized for this research due to its integration in the selected flight computer's architecture
- Flight controller is a mix of proportional and PID cascaded controllers [?]
- Accepts state estimates of position and yaw angle as inputs



PX4 control scheme [?]

# Vertical Takeoff

- Operator must arm vehicle for flight due to protections against auto-arming
- Inertial x- and y-coordinates held constant as vertical position integrated
- Once altitude within 5 centimeters of target, takeoff considered successful



Simulated takeoff trajectories

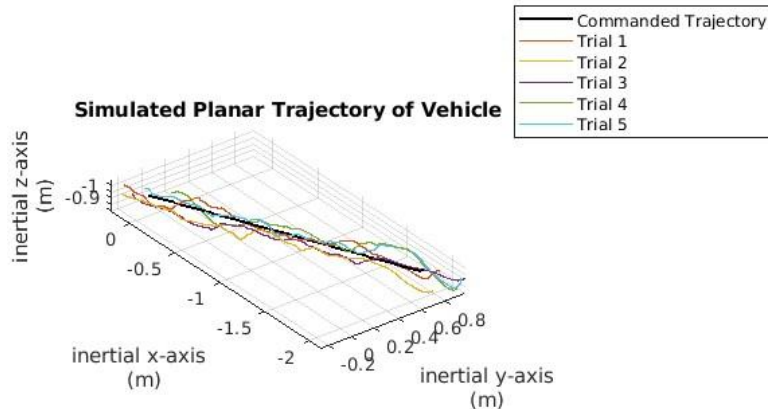
State transition if:

takeoff from home position →  
proceed to search area

takeoff from sample location →  
proceed to home location

# Navigation to and from Home Location

- All navigation planar between starting  $(x_1, y_1)$  and ending  $(x_2, y_2)$  coordinates
- Velocity calculated using total distance and prescribed linear velocity magnitude
- Commanded position integrated using computed velocities
- Once vehicle within 10 centimeters of goal, navigation is successful



Simulated planar navigation trajectories

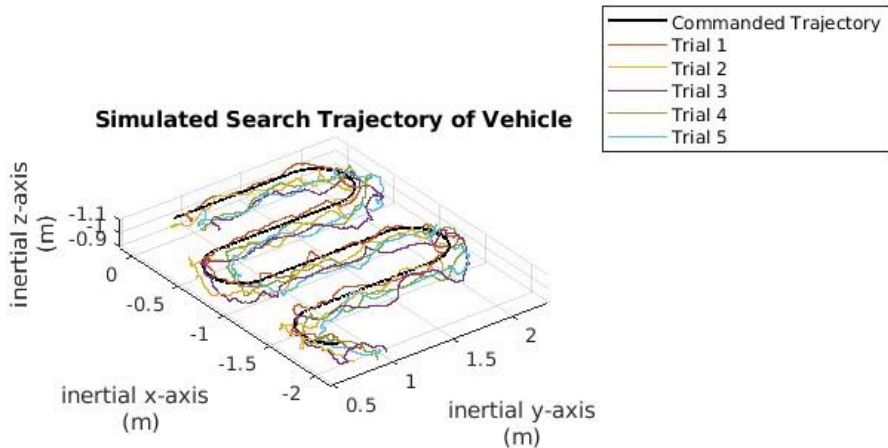
State transition if:

navigating to search area → begin search

navigating to home location → land

# Aerial Search Pattern

- Lawnmower search pattern implemented due to its simplicity and ability to provide adequate camera coverage of the search area
- Algorithm constantly checking for AprilTag detections in this state



Simulated search trajectories

State transition if:

no AprilTag detected, end of search area reached → navigate to home location

AprilTag detected → initiate landing for sample collection

# Precision Hover Above Sample Location

- Vehicle iterates its position in a planar navigation scheme using the inertial coordinates of the AprilTag to approach the landing site
- If the camera loses sight of the landing AprilTag, the vehicle proceeds along the most recently estimated trajectory for 1.5 seconds
- If no detection made after 1.5 seconds, the vehicle rotates about its z-axis until it regains sight of the AprilTag
- Once the vehicle is within 75 centimeters of the landing AprilTag, then this state is complete and algorithm proceeds to further reposition vehicle w.r.t. landing site

# Aerial Positioning and Landing Relative to Sample

- Vehicle reduces altitude to 40 centimeters before continuing to approach the landing AprilTag planarly
- Once the vehicle is within 35 centimeters of the landing AprilTag, it aligns its heading w.r.t. the sample itself (AprilTag ID 0)
- A vehicle heading within 1.5 degrees of the desired heading triggers a landing
- A consistent bias along the body frame y-axis was discovered, so prior to landing the vehicle is commanded to maneuver 5 centimeters along the negative body frame y-axis
- Landing is commanded by holding the x- and y-position of the vehicle constant and integrating in the vertical direction
- After landing, the state machine transitions to sample collection

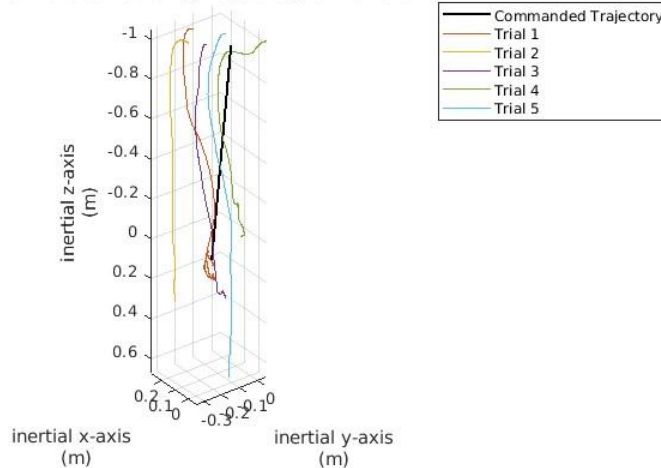
# Sample Grasping

- For sample collection:
  - Vehicle commanded to drive forwards for 3 seconds and gripper closed, AprilTag position estimate recorded
  - Vehicle commanded to drive backwards for 2 seconds, new AprilTag position estimate compared to previous
  - If new estimate has a magnitude 5 centimeters less than the initial, collection is considered successful
  - State machine proceeds to vertical takeoff and return home
- For sample deposit:
  - Vehicle commanded to open gripper and record current AprilTag position estimate
  - Vehicle commanded to drive backwards for 2 seconds, new AprilTag position estimate recorded to previous
  - If new estimate has a magnitude 5 centimeters greater than the initial, deposit is considered successful
  - State machine proceeds to vertical takeoff and resume search, if more samples indicated
- If sample collection or deposit fails, vehicle will try again 2 times before abandoning its attempts and marking the sample as failing to be collected

# Vertical Landing at Home Location

- Simple vertical landing commanded using `/fmu/in/vehicle_command`
- Desired vehicle heading passed as an argument, selected as the yaw which aligns the vehicle with the inertial frame

Simulated Landing Trajectory of Vehicle



Simulated landing trajectories

State transition if:

navigating from end of search area →  
takeoff and resume search

navigating from sample location →  
deposit sample