Autonomous Coupling of a UAV and UGV

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Introduction: Motivation

- In disaster situations, victims may become trapped by fallen debris or immobilized by their injuries.
- First responders risk their own lives by entering buildings without fully understanding the dangers at play.

- Teams of robots can enter a compromised structure before, alongside, or in place of human workers.
- Every task that a robot can do reduces the time that a human worker spends in harm’s way.

Introduction: Motivation

- Search and rescue teams encounter many types of obstacles and must perform many types of tasks.
- Increasingly complex robots can address more of these tasks but become more expensive and less expendable.
- Increasing the complexity of a robot to address its weaknesses can detract from its strengths.

- A heterogeneous team of robots can maximize their strengths while complementing each other's weaknesses.
- These simple robots can achieve more working together than they could on their own but cost less than a single robot with the same combination of capabilities.

Introduction: Previous Work

- A team from the University of Zagreb recognized that a UAV can lift a UGV over an obstacle, and the UGV can carry the UAV to conserve battery life.
- The team focused on developing high level task scheduling and mission planning algorithms and used a simulation to demonstrate their results.

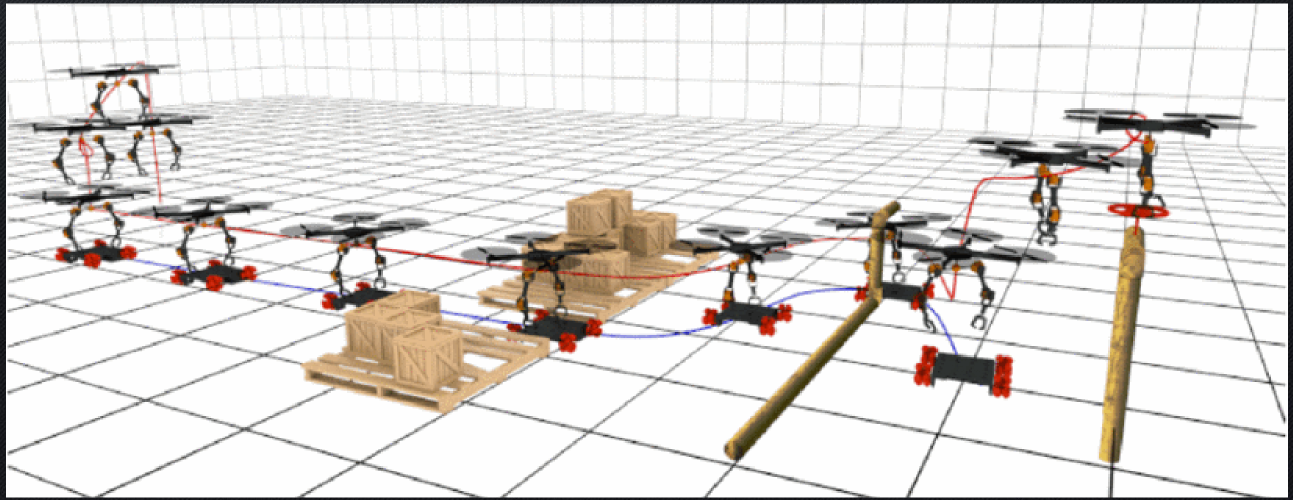

Figure 1: Simulation of a Symbiotic UAV and UGV Relationship

Introduction: Problem Statement

- This project aims to validate the symbiotic UAV and UGV relationship with a physical implementation of a heterogenous team of robots and a demonstration of their capabilities.
- This paper details the selection of robots, the design of the physical coupling mechanism, and the design of the autonomous controls.
- The team must be capable of the following:
  1. The UGV must navigate a space while the UAV follows.
  2. The UAV must couple with the UGV.
  3. The UAV must lift the UGV over an obstacle.
  4. The UGV must navigate the space while carrying the UAV.

II. Method

i. Robot Selection
ii. Coupling Mechanism Design Requirements
iii. Coupling Mechanism Design
iv. Hardware and Software Setup
v. Localization
vi. Offboard Position Control
vii. Final Assembly

Method: Robot Selection

- The selection of robots primarily depends on the weight of the UGV and the payload capacity of the UAV.
- The UGV must be lighter than the UAV’s payload capacity but large enough to serve as a stable platform upon which the UAV can land and ride.
- The UAV must be large enough to lift the UGV but small enough to maneuver through a hallway and land on the UGV.

Method: Robot Selection

Two-Wheel Drive UGV: light and stable

- Acrylic Chassis
- 140-millimeter diameter
- 330 grams
- Four points of contact with the ground

Figure 2: 2WD UGV Platform

Intel Aero Quadrotor UAV: small and powerful

- Open frame
- 360-millimeter diagonal hub-to-hub length
- 1-kilogram payload

Figure 3: Intel Aero UAV Platform

Method: Coupling Mechanism Design Requirements

Primary Design Requirements:

- The mechanism must allow the UAV to lift the UGV and remain coupled during flight.
- The mechanism must allow the UGV to carry the UAV and remain coupled while driving.

Secondary Design Requirements:

- The coupling mechanism must account for the robots’ resolution of control.
- The coupling maneuver must be simple.
- The coupling mechanism must not affect the control of the robots.

Method: Coupling Mechanism Design

- Ferromagnet interface attaches a steel plate to the UAV.
- Electromagnet interface attaches an electromagnet to the UGV.

- UGV powers the connection during flight and when the UAV is out of battery.
- 90-millimeter circular ring prevents opening mode separation to stabilize the connection.
- Slotted mounting point adjusts to the center of mass to preserve the dynamics of the system

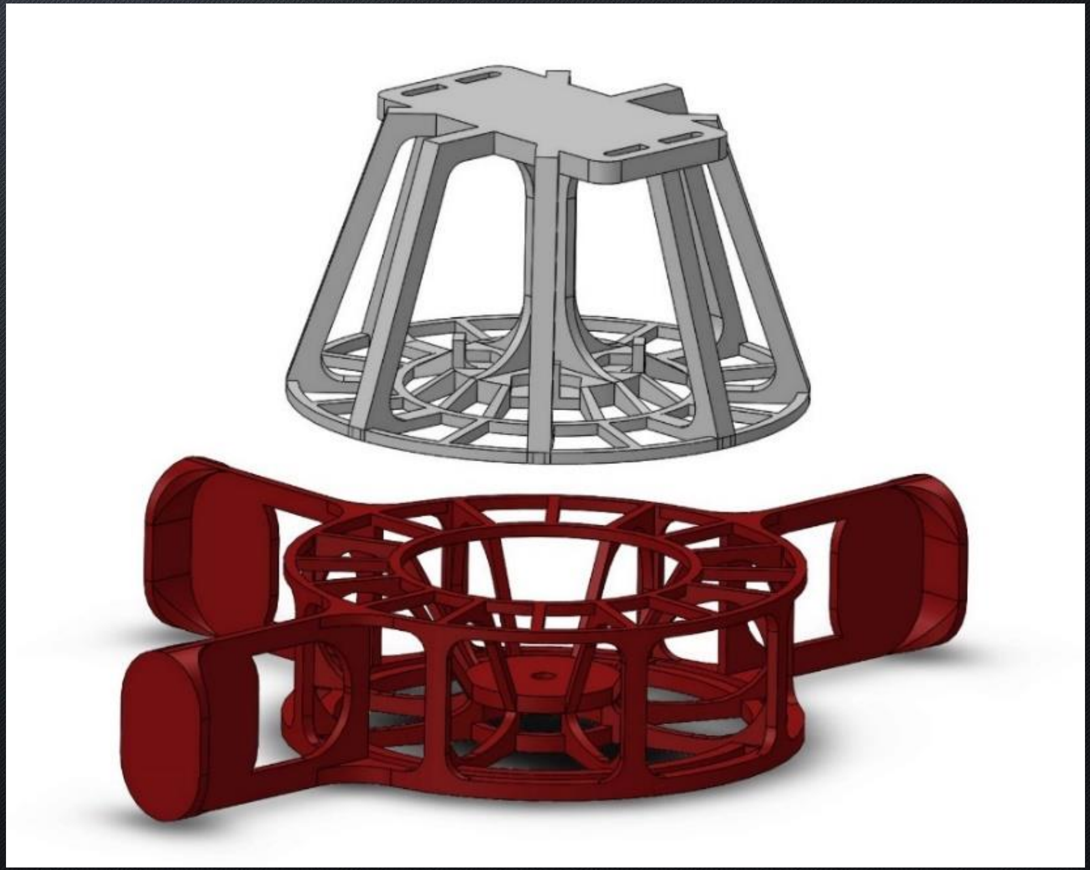

Figure 4: EM Interface (Red) and FM Interface (White)

Method: Coupling Mechanism Design

Electromagnet

- 5 kilogram holding force
- 0.3 amp draw at 5 volts
- 20 millimeters tall
- 25-millimeter diameter
- Compatible with Raspberry Pi

Steel Plate

- No residual pull
- 35-millimeter diameter

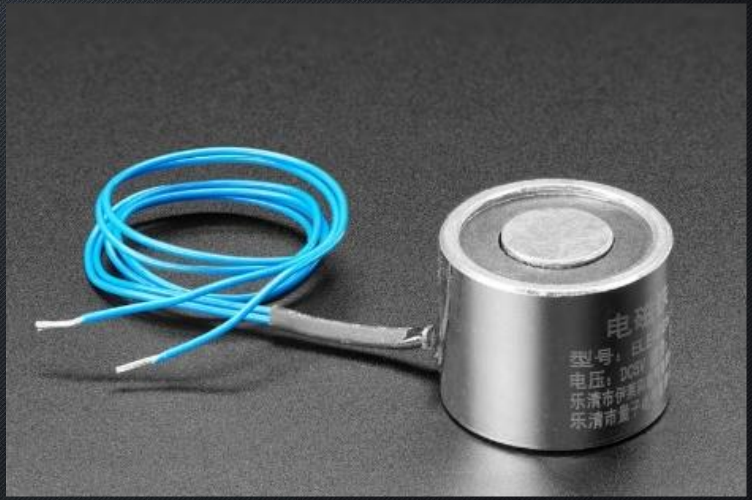

Figure 5: Electromagnet

Figure 6: Steel Plate

Method: Coupling Mechanism Design

Coupling Maneuver

1. UAV matches the UGV’s stationary ground position.
2. UGV engages the electromagnet.
3. UAV descends towards the UGV.
4. Electromagnetic forces guide the interfaces to the coupled position.

Decoupling Maneuver

1. UAV lands.
2. UGV disengages the electromagnet.

- The vertical descent preserves the other control outputs of the UAV.
- Guiding forces account for control errors.
- The process to engage and disengage the coupling mechanism occurs instantaneously.

Method: Hardware and Software Setup

UGV

- Raspberry Pi
  - Motor HAT
- Ubuntu MATE 16.04 operating system
  - ROS Kinetic
  - Adafruit_MotorHAT library

Laptop

- Ubuntu 16.04 operating system
  - QGroundControl

UAV

- Intel Aero Compute Board
  - Intel Aero Flight Controller
- Ubuntu 16.04 operating system
  - ROS Kinetic
    - vrpn_client_ros package
    - mavros package
  - PX4 Autopilot
    - LPE position estimator

Method: Localization

- This project was performed in ASU’s motion capture space.
- This space tracks objects with an accuracy of < 1 millimeter in position and < 1° in orientation.

- The desktop hosts a VRPN server that publishes the real-time pose data of the robots to the Wi-Fi network.
- The UAV launches roscore and the vrpn_client_node which subscribes to the tracked objects published by the desktop.
- The UGV communicates with the ROS master running on the UAV to receive the pose topics.

Figure 7: Motion Capture Space

Method: Localization

ROS Output:

- Forward-Left-Up local frame
- East-North-Up world frame
- The UGV uses this frame of reference for its controls.

PX4 Input:

- Forward-Right-Down local frame
- North-East-Down world frame
- The UAV uses this frame of reference for its controls.
- VRPN client remaps the pose topic to /mavros/mocap/pose.
- A mavros performs the transformation and relays it to the PX4.

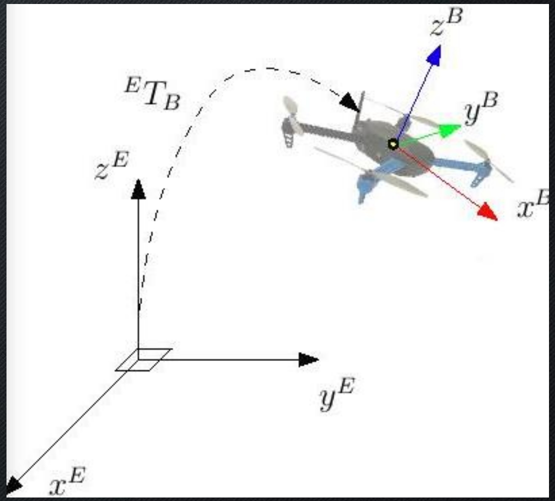

Figure 8: ROS frame: FLU/ENU

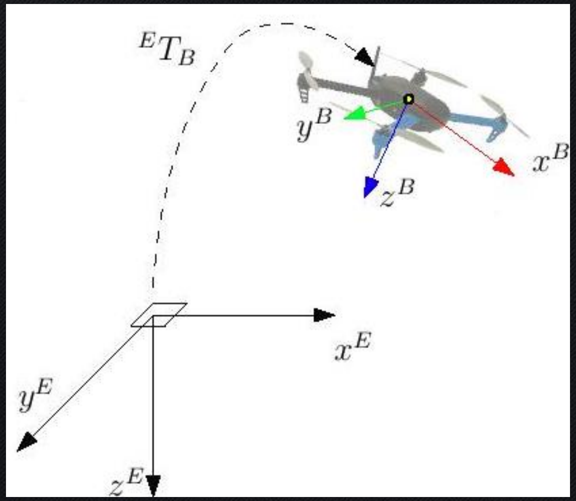

Figure 9: PX4 frame: FRD/NED

Method: Offboard Position Control

- The UGV's Python script subscribes to its pose topic and drives the vehicle through a list of predefined waypoints.

- The UGV simulates a differential in the motors to steer itself to the waypoints.
- A proportional-derivative controller calculates the steering differential required to drive the measured angle to the desired steering angle.
- When the UGV reaches an acceptable distance to the waypoint, the UGV will target the next waypoint on its list or stop if it is at the end of its path.

- The UGV engages the electromagnet with the same commands that drive the motors.

Method: Offboard Position Control

- The UAV’s Python script subscribes to its pose topic and drives the vehicle through a list of predefined waypoints.

- Offboard position control of the UAV is performed using the setpoint package in mavros.
- The setpoint commands are accompanied by an acceptable distance and a delay.
- The UAV flies within the acceptable distance to the waypoint and maintains that position for the duration of the delay.
- After the delay, the UAV performs the next setpoint command.

Method: Final Assembly

- The EM interface was 3D printed.
- The EM interface is mounted over the UGV's center of mass.
- Tracking markers are mounted to the wings.
- The final assembly of the UGV weighs 639 grams.

Figure 10: UGV Final Assembly

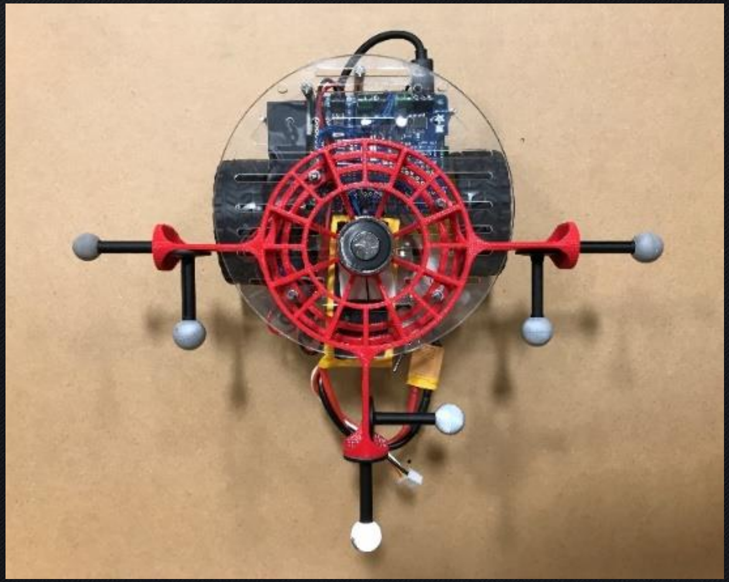

Figure 11: UGV Top View

Method: Final Assembly

- The FM interface was 3D printed.
- The FM interface is mounted below the UAV's center of mass.
- Tracking markers are mounted to the upper deck.
- The final assembly of the UAV weighs 1015 grams.

Figure 12: UAV Final Assembly

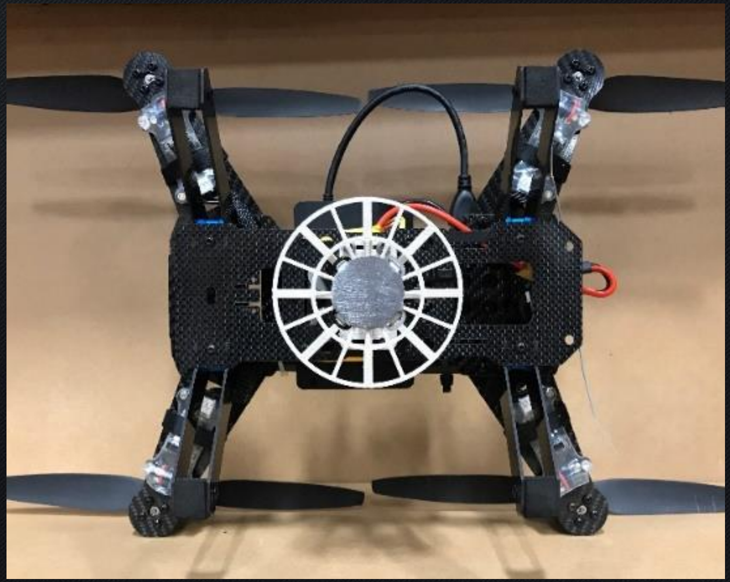

Figure 13: UAV Bottom View

Method: Final Assembly

- The height of the mechanism is 8 centimeters.
- The final assembly weighs 1654 grams.
  - 246 grams below the maximum takeoff weight.
  - 87% of the maximum takeoff weight.
- 159% increase in driving load.
- 63% increase in flying load.

- UGV’s tracking markers extend beyond the landing gear of the UAV.
- The landing gear of the UAV does not interfere with the coupling mechanism.

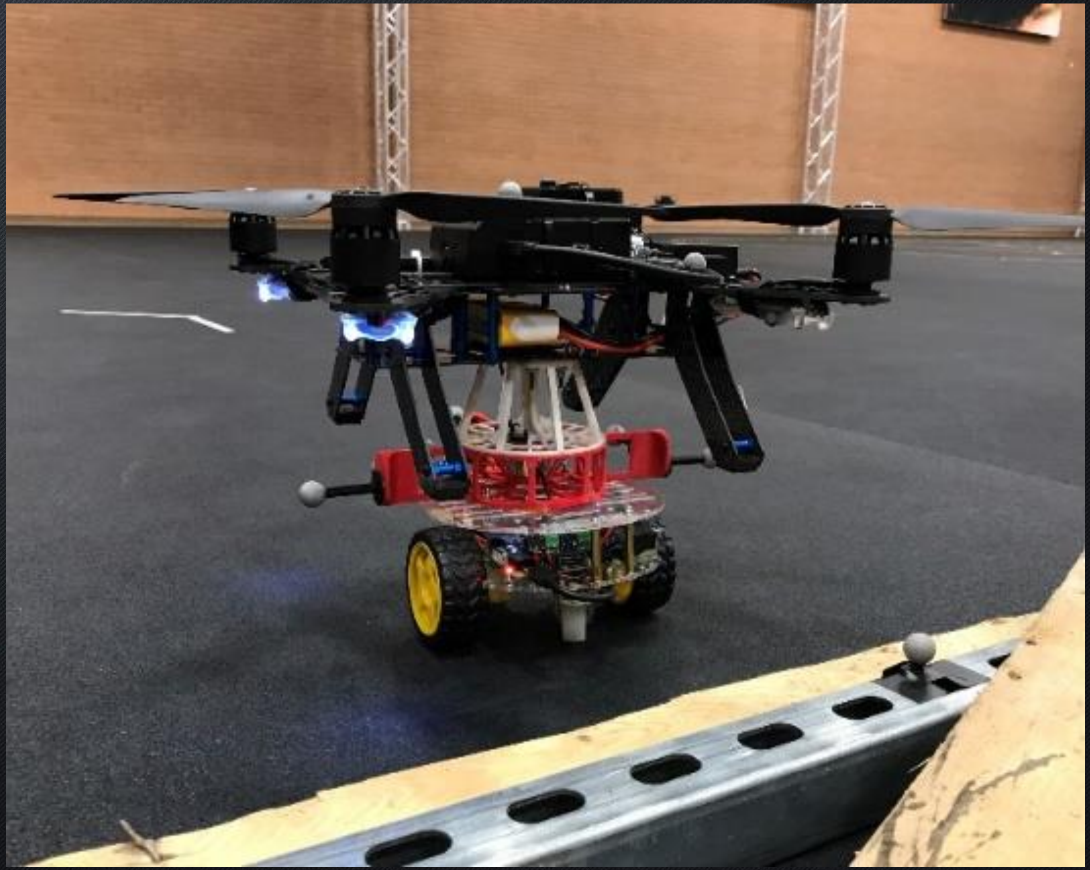

Figure 14: Coupled System Final Assembly

III. Experiment

i. Objective
ii. Autonomous Controller Design

Experiment: Objective

Objective: Assess the capabilities of the robots according to the performance requirements described in the problem statement.

1. The UGV must navigate a space while the UAV follows.
2. The UAV must couple with the UGV.
3. The UAV must lift the UGV over an obstacle.
4. The UGV must navigate the space while carrying the UAV.

- The motion capture space isolates the performance of the hardware.
  - The controlled environment limits disturbances to the system.
  - The tracking capabilities provide accurate localization.
- The motion capture space can also store the tracking data for analysis.

Experiment: Objective

- Course is defined by six waypoints interrupted by an obstacle.

- Uncoupled driving and flying through two 45-degree turns.
- UAV performs coupling maneuver at the obstacle.
- UAV lifts the UGV over the obstacle.
  - The team decouples briefly and couples again.
- The UGV carries the UAV through two more 45-degree turns.

Figure 15: Experimental Test Bed

Experiment: Autonomous Controller Design

- The UGV subscribes to: UGV pose, UAV pose, obstacle pose, fly mode

- The UGV begins in “standby” mode and continually evaluates the distance to the UAV, to the waypoint, and to the obstacle.
- When the UAV is within 10 centimeters of the UGV, the UGV switches to “drive” mode.
- When the UGV is within 7 centimeters of a waypoint, it targets the next waypoint.
- When the UGV is within 30 centimeters of the obstacle, it switches to “engage” mode.
- During engage mode, the UGV receives instructions from the UAV via fly mode updates.
- The UGV activates the electromagnet.

Experiment: Autonomous Controller Design

- The UAV subscribes to: UGV pose, UAV pose, obstacle pose
- The UAV takes off and continually evaluates the UGV's distance to the obstacle.
- While the UGV drives, the UAV matches the UGV's ground position with 10-centimeter accuracy.
- When the UGV reaches the obstacle, the UAV saves the UGV's stationary ground position and updates its fly mode to begin the coupling procedure.

- The UAV targets waypoints over the coupling position with decreasing altitude and increasing accuracy until it reaches the coupling position.
- The UAV targets a waypoint 0.6 meters above the coupling position with 20-centimeter accuracy to take off.
- The UAV targets a waypoint on the far side of the obstacle, and one more waypoint in the landed position.

- When the UAV lands, it waits 1 second to settle, updates the fly mode to decouple, waits 1 second for the electromagnet to disengage, then takes off again.
- Once in the air, the UAV updates the fly mode, and continues following the UGV. At the third waypoint, the robots couple again.
- Instead of lifting, the UAV updates the fly mode indicating a "resting" state and disarms its motors while the UGV carries it through the last two turns and stops at the final position.

IV. Results and Discussion

i. Following
ii. Coupling
iii. Lifting
iv. Resting

Results and Discussion: Video

Video

Results and Discussion: Following

- Objective: Decoupled driving and flying through two 45-degree turns
- Start: UAV takes off
- End: UGV reaches the obstacle
- Top view projected onto x-y plane

- UGV targeted waypoints with minimal overshoot and settling time
- UAV followed UGV through both 45-degree turns
- UAV trailed ~1s and ~0.5 behind the UGV

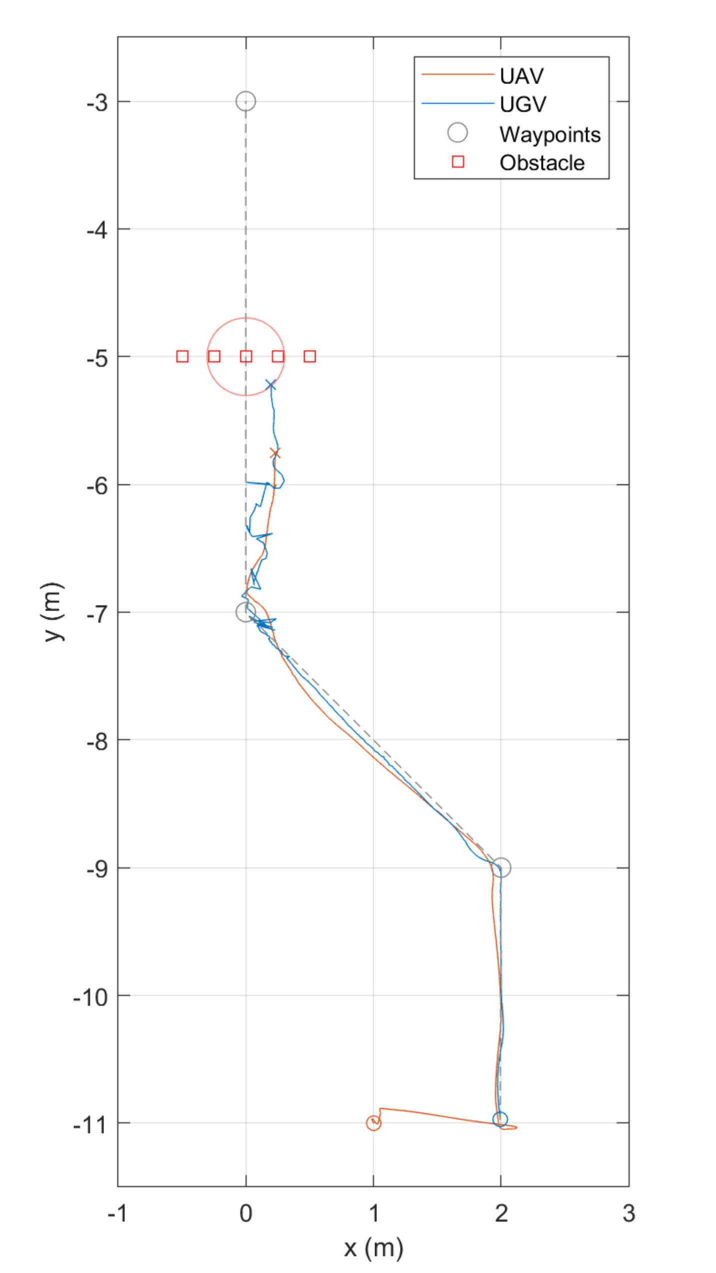

Figure 16: Following Phase Tracking Map

Figure 17: Start Position

Figure 18: UAV Following UGV

Results and Discussion: Coupling

- Objective: UAV performs coupling maneuver with stationary UGV
- Start: UGV reaches obstacle
- End: Robots are coupled
- Side view projected onto y-z plane

- UAV targeted waypoints with minimal overshoot
- Overshoot and error decreased as the accuracy increased
- UAV met UGV at the coupling position

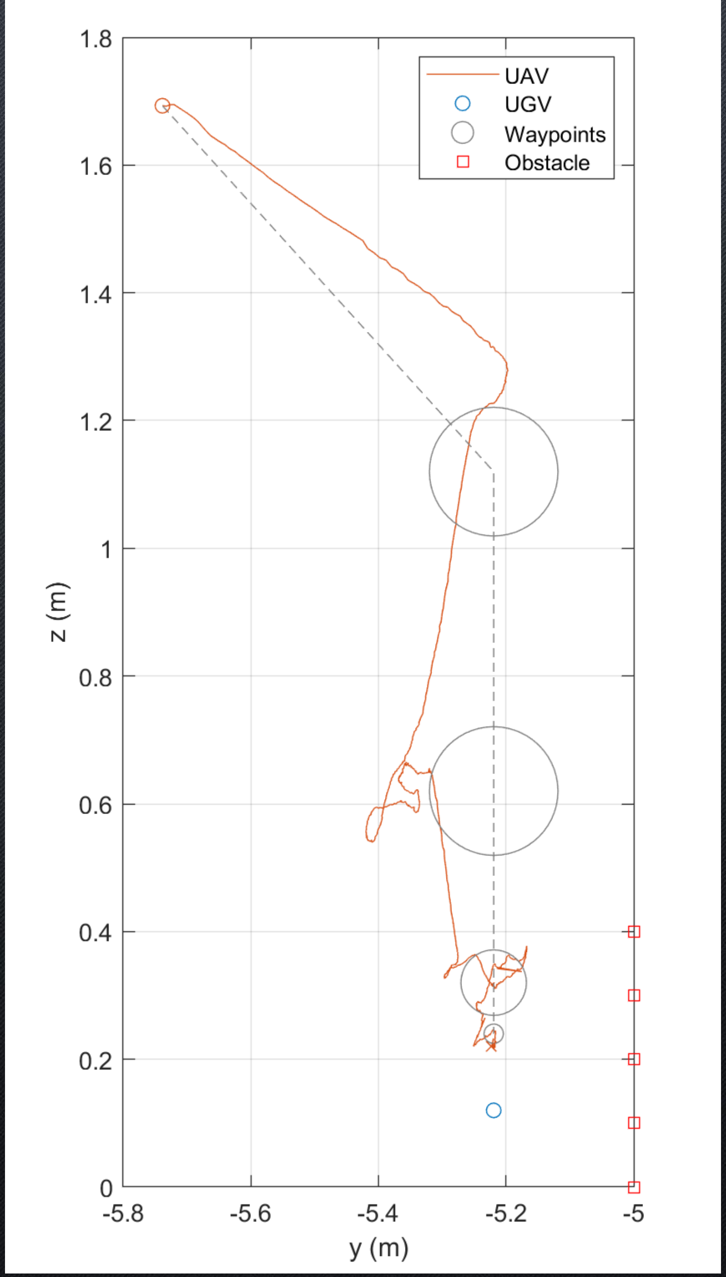

Figure 19: Coupling Phase Tracking Map

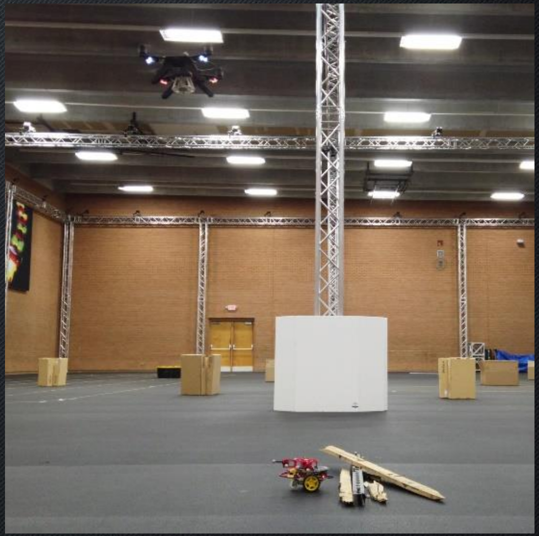

Figure 20: Initial Position

Figure 21: Coupled Position

Results and Discussion: Lifting

- Objective: UAV lifts UGV over obstacle
- Start: UAV takes off
- End: UAV lands
- Side view projected onto y-z plane

- UAV lifted UGV to first waypoint
- UAV rolled too much and lost elevation
- UAV still landed on the other side

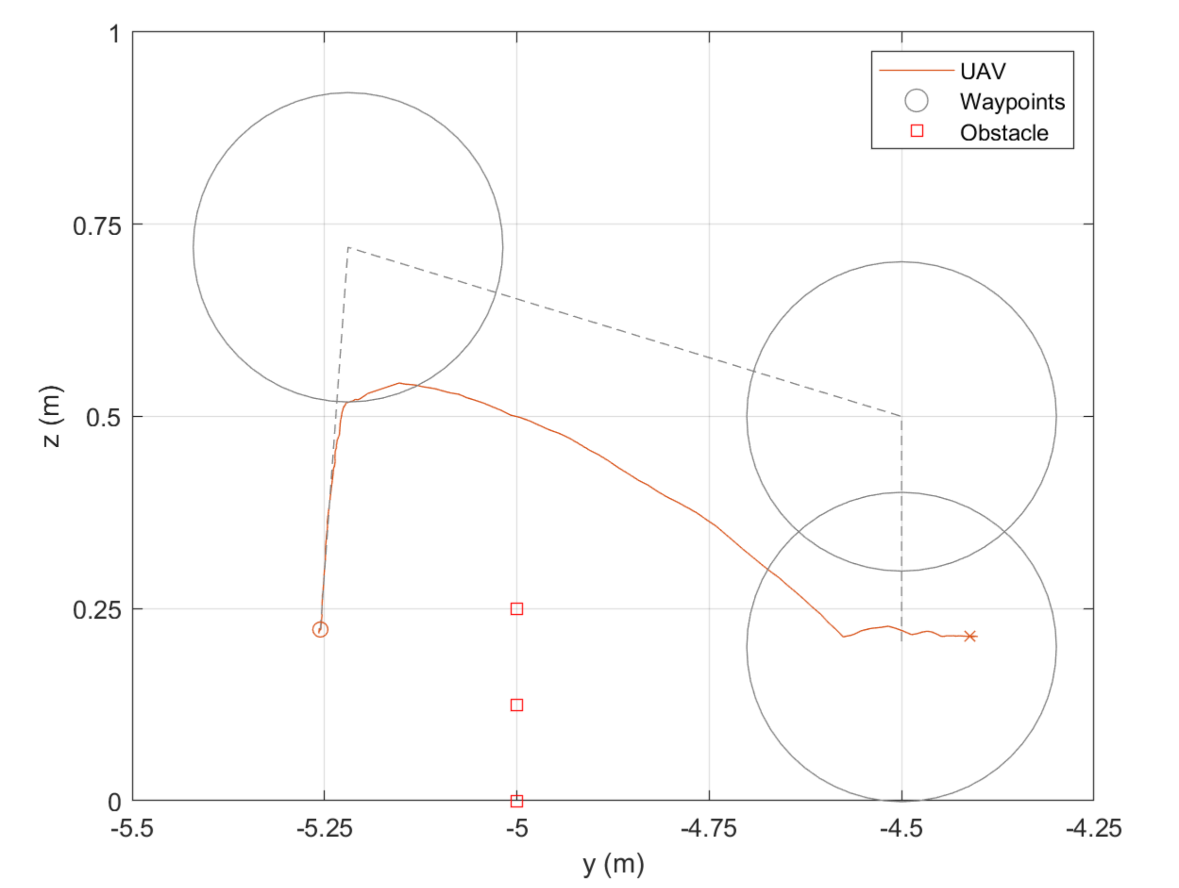

Figure 22: Lifting Phase Tracking Map

Figure 23: UAV Lifting UGV

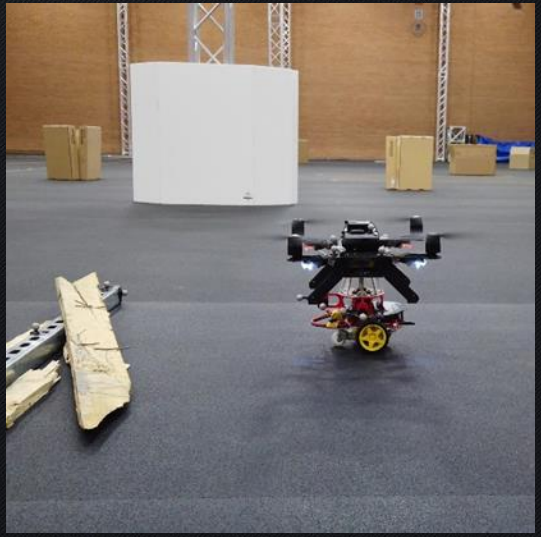

Figure 24: Landed Position

Results and Discussion: Resting

- Objective: Coupled driving through two 45-degree turns
- Start: UGV begins driving
- End: UGV reaches final waypoint
- Top view projected onto x-y plane

- UGV targeted waypoints with greater overshoot and settling time than uncoupled driving
- UGV drove at approximately the same speed
- UGV carried UAV through both 45-degree turns

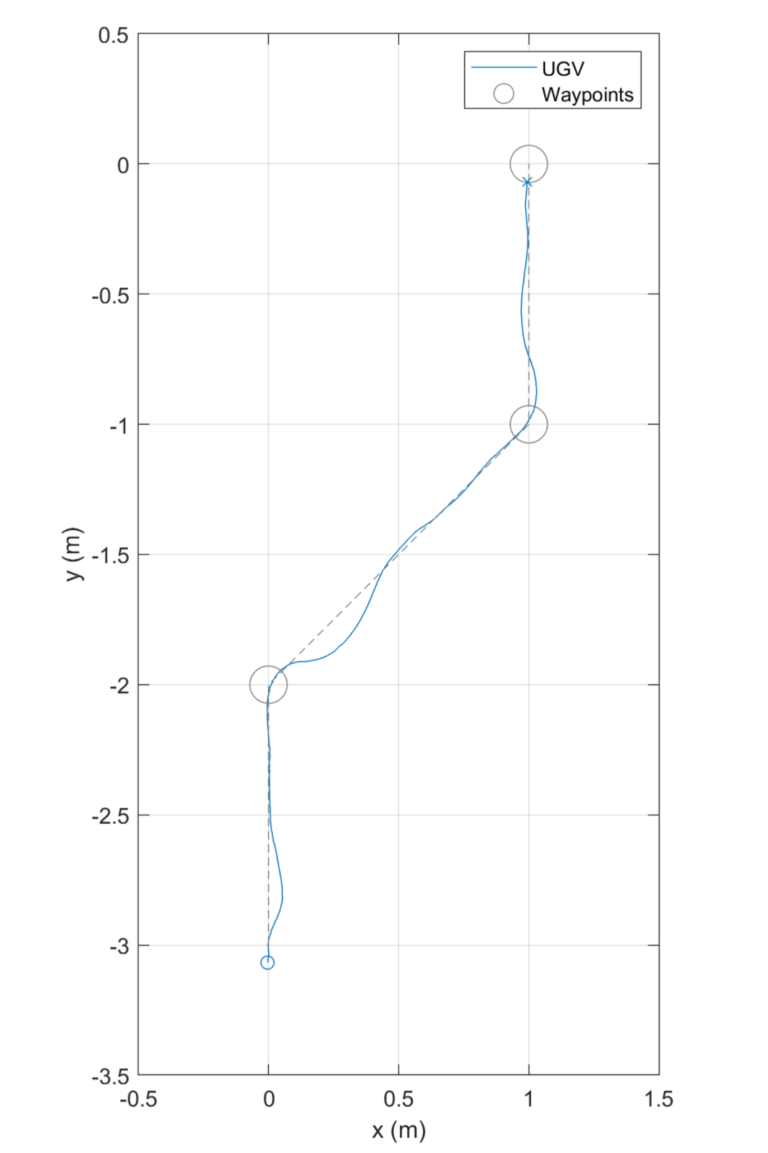

Figure 25: Resting Phase Tracking Map

Figure 26: UGV Carrying UAV

Figure 27: Final Position

V. Conclusion

i. Summary
ii. Future Work

Conclusion: Summary

- The selection of robots meets the design requirements of the heterogenous team of robots.
  - The UGV is light and stable. The UAV is small and powerful.

- The EM interface, the FM interface, and the coupling maneuver meet the design requirements of the coupling mechanism.
  - The coupling mechanism applies guiding forces, lifts the UGV, preserves the dynamics of the system, prevents opening mode separation, prevents interference with the rotors, prevents interference with the landing gear, prevents tracking interference, and causes no residual pull.
  - The coupling maneuver occurs in a single step and preserves the other control outputs of the UAV.
  - The process to engage and disengage the coupling mechanism occurs instantaneously.

Conclusion: Summary

- The offboard position control allows the robots to autonomously to waypoints.
  - The publishers and subscribers allow the robots to coordinate and perform complex procedures.
  - The motion capture space provides a controlled environment and accurate localization to isolate the performance of the hardware during the experiment.

- The results of the experiment conclude that the heterogeneous team of robots fulfills the performance requirements described in the problem statement.
  - The UAV successfully followed the UGV through two 45-degree turns.
  - The UAV successfully coupled with the UGV.
  - The UAV successfully lifted the UGV over the obstacle.
  - The UGV successfully carried the UAV through two 45-degree turns.

Conclusion: Summary

The fulfillment of the design requirements and the demonstration of the performance validate the symbiotic UAV and UGV relationship. The UAV and UGV shared their strengths to perform a complex task. The robots achieved more working together than they could on their own but cost less than a single robot with the same combination of capabilities. The robots’ capabilities can be applied to search and rescue missions in disaster situations to reduce the time that human workers spend in harm’s way.

Conclusion: Future Work

- Improvements could be made to this system to address the diminished control of the robots under load.
  - The robots could adjust their controllers for loaded driving and flying.
- The heterogenous team of robots could adapt to perform similar tasks.
  - UAV could lift the UGV up a flight of stairs.
- This coupling mechanism could be modified to enable power sharing between the robots.
  - Sharing battery capacity and power can increase flight time and thrust.
- The heterogeneous team of robots could be expanded to perform different tasks.
  - Distribute a suite of sensors, end effectors, and supplies across a larger team.
- The concept of using a heterogenous team to perform complex tasks could be applied to other systems.
  - A heterogeneous team of nanorobots could perform more complex tasks.

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