

Abstract

Multiagent Cyber-Physical-Human (CPH) systems in realistic environments operate under uncertain conditions. Task inaccuracies, both in terms of exact location and exact priority, are to be expected. Furthermore, real-world deployment can encounter communication range limitations, leading to disconnected swarm components over short and medium periods. The APIS algorithm, first presented in [1], addresses this issue through a bee-foraging heuristic approach to task completion, balancing direct task completion (harvesting), mapping (dancing), and informational interchange (dancing). We propose to implement the Autonomous Persistent Intelligent Swarm (APIS) system in a real-world heterogeneous swarm setting, evaluating its efficacy in maintaining lines of communication, reducing performance uncertainty, and maintaining swarm cohesion.

We will undertake two parallel efforts. First, to improve the fidelity of the APIS simulation and evaluate its mission efficacy in a variety of system configurations. Second, to create a physical APIS-compatible system capable of completing a variety of tasks and mapping the environment to validate the simulation results and as a proof-of-concept technology demonstrator.

System Overview

The APIS (Autonomous Persistent Intelligent Swarm) system supports arbitrary classes of drones, with heterogeneous capabilities, in an uncertain environment. It is decentralized and robust to agent non-responsiveness, by leveraging the message routing features of the BATMAN (Better Approach to Mesh Networking) mesh networking algorithm.

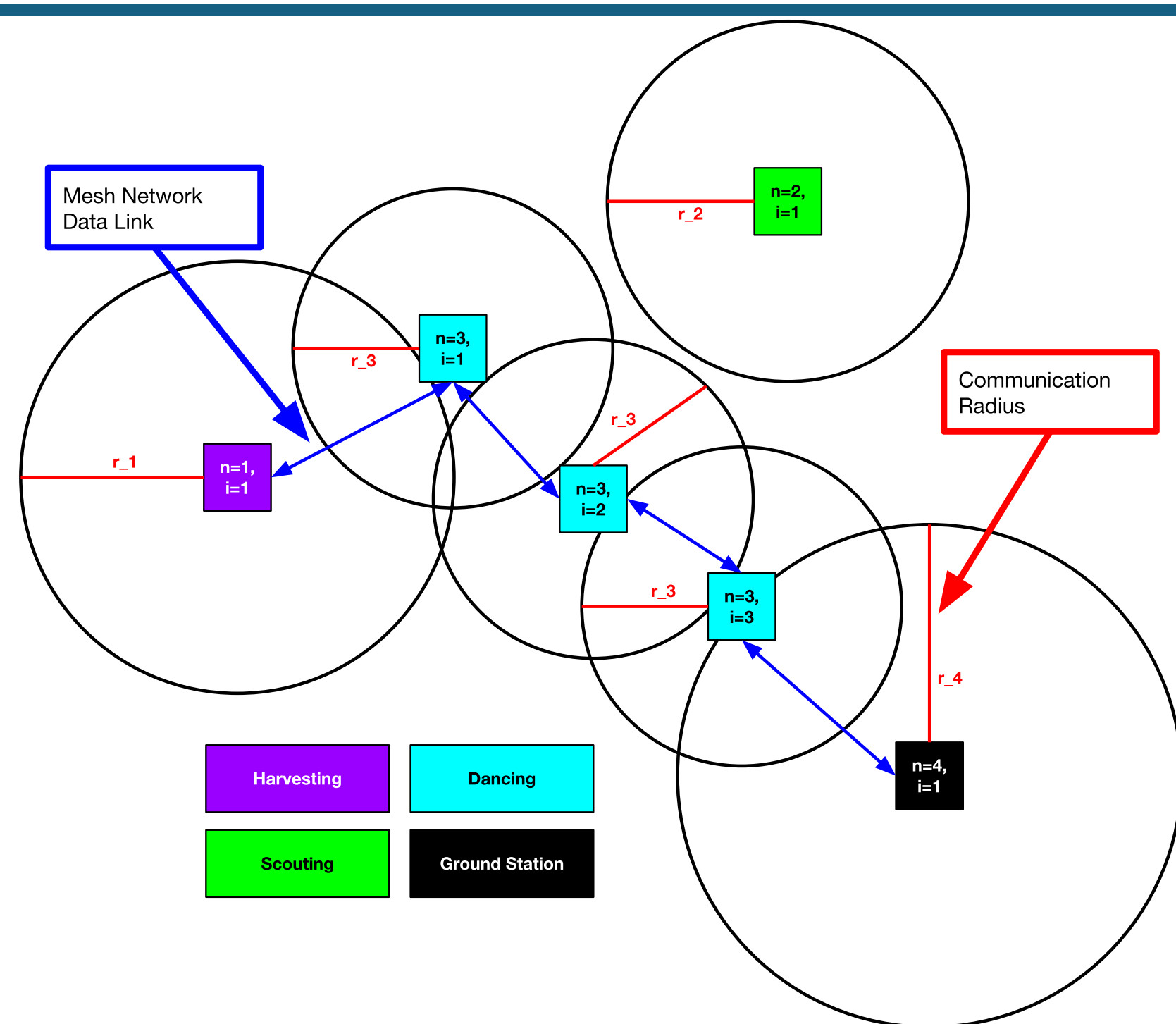


Figure 1: Spatial swarm architecture, with three jobs (harvest, scout, dance), three classes (heavy $n=1$, medium $n=2$, small $n=3$), and a ground station.

APIS employs a heuristic approach to task assignment, in which agents stochastically self-assign into one of three jobs: harvesting, where agents will choose the best next task; scouting, where agents will map the environment and reduce uncertainty; and dancing, where agents will form a mesh networking backbone, to encourage model exchange. Agents exchange models of tasks, other agents, and of the environment, over the network.

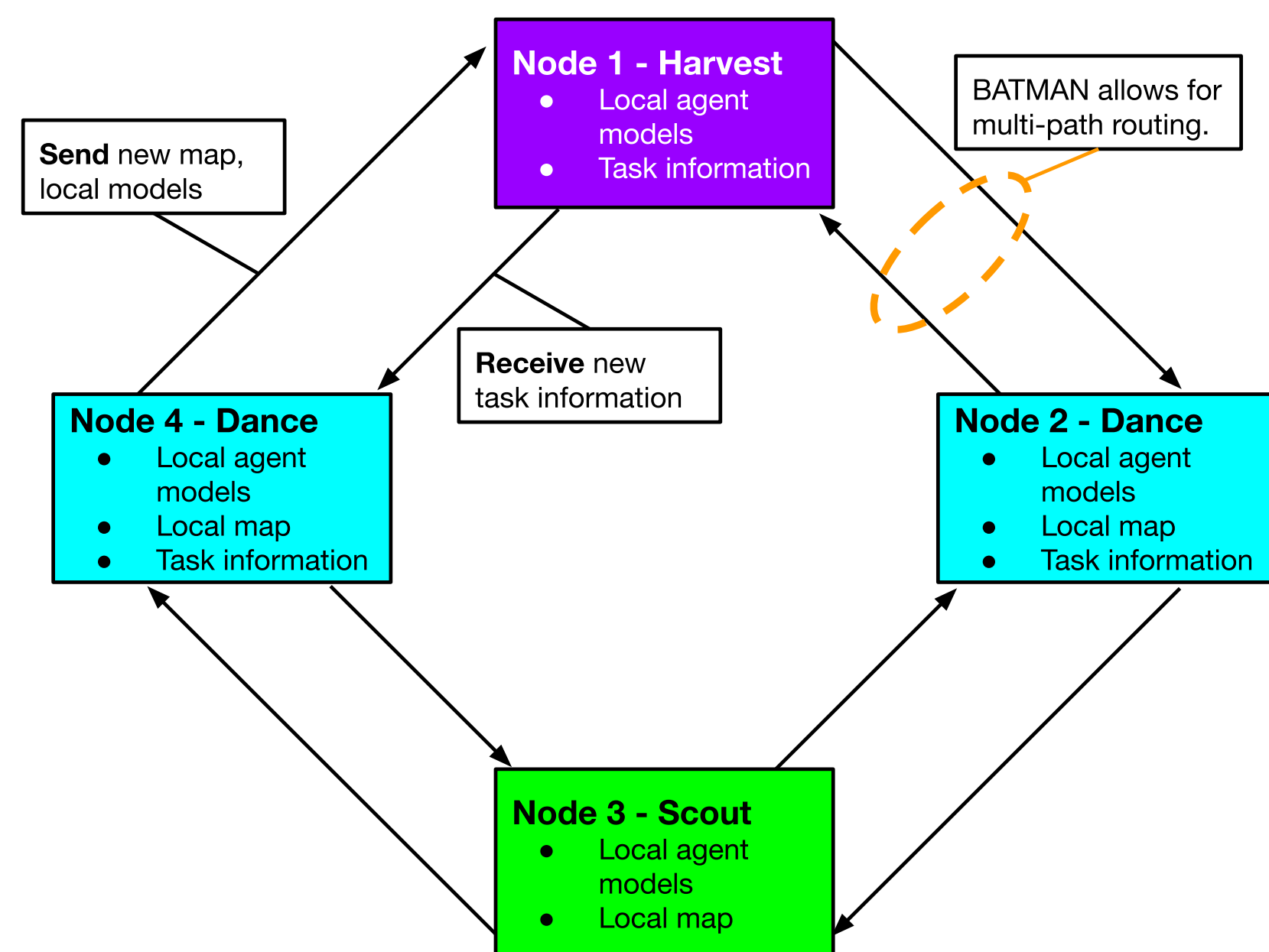


Figure 2: Mesh network swarm architecture, with three jobs (harvest, scout, dance).

This research is based on *APIS: Honey Bee Foraging Task Assignment for Use in Uncertain and Unreliable Environments* (J. Pye, N. Alexandrov), presented at the AIAA SciTech 2024 Forum.

Thank you to the x88 Course Series and Professor Halow for sponsoring the project, Professor Tzoumas for technical advising and feedback, and Dr. Natalia Alexandrov at the NASA Langley Research Center for research advising. Thank you also to the University of Michigan Engineering Honors Program. This work constitutes the culmination of the principal investigator's Engineering Honors Capstone.

Simulation

We simulated the APIS algorithm in a three-dimensional simulation, with three types of tasks and three classes of agents. Each agent could complete either one, two, or all three types of tasks (“harvesting”). Two classes of agents could map the area (“scouting”), and all agents could serve as mesh nodes (“dancing”). Once all tasks are completed, the agents return to the takeoff area.

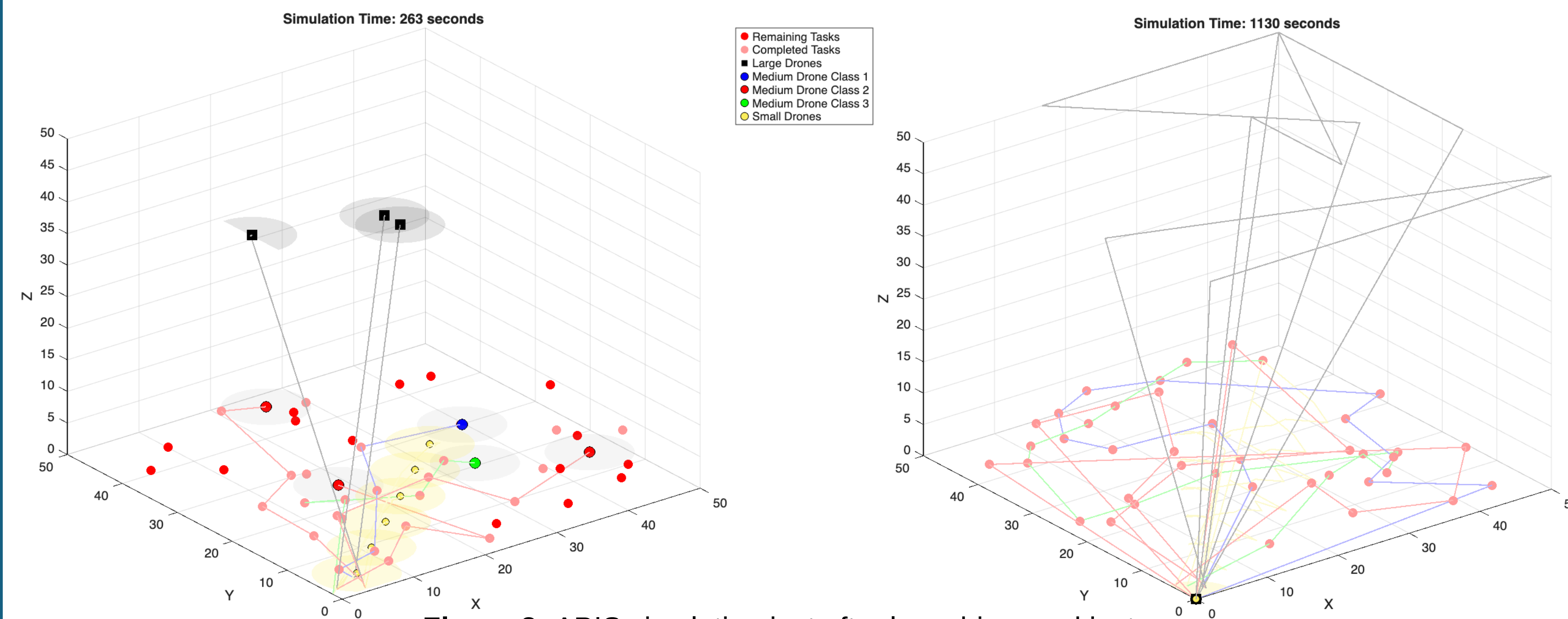


Figure 3: APIS simulation just after launching, and just after all drones return to the takeoff point.

38x26x25, [1, 1, 1], [2, 0, 0], [0, 0, 3], 40 tasks

Scores	[0, 1, 0] [1, 0, 0] [0, 0, 1]	[0.2, 0.8, 0] [1, 0, 0] [0, 0, 1]	[0.2, 0.8, 0] [0.9, 0.1, 0] [0, 0, 1]	[0.2, 0.8, 0] [0.9, 0.1, 0] [0.2, 0, 0.8]
Scouting	0.994	0.996	0.999	0.996
Harvesting	0.889	0.927	0.654	0.648
Dancing	0.812	0.804	0.837	0.779

38x26x25, [1, 1, 1], [2, 0, 0], [0, 0, 3], 100 tasks

	[0, 1, 0] [1, 0, 0] [0, 0, 1]	[0.2, 0.8, 0] [1, 0, 0] [0, 0, 1]	[0.2, 0.8, 0] [0.9, 0.1, 0] [0, 0, 1]	[0.2, 0.8, 0] [0.9, 0.1, 0] [0.2, 0, 0.8]
Scouting	0.999	0.999	1.000	1.000
Harvesting	0.326	0.920	0.609	0.601
Dancing	0.980	0.824	0.927	0.923

38x26x25, [1, 3, 1], [3, 0, 0], [0, 0, 6], 40 tasks

	[0, 1, 0] [1, 0, 0] [0, 0, 1]	[0.2, 0.8, 0] [1, 0, 0] [0, 0, 1]	[0.2, 0.8, 0] [0.9, 0.1, 0] [0, 0, 1]	[0.2, 0.8, 0] [0.9, 0.1, 0] [0.2, 0, 0.8]
Scouting	0.997	0.997	1.000	1.000
Harvesting	0.667	0.674	0.544	0.698
Dancing	0.753	0.800	0.864	0.825

76x52x50, [1, 1, 1], [2, 0, 0], [0, 0, 3], 40 tasks

	$[0, 1, 0]$ $[1, 0, 0]$ $[0, 0, 1]$	$[0.2, 0.8, 0]$ $[1, 0, 0]$ $[0, 0, 1]$	$[0.2, 0.8, 0]$ $[0.9, 0.1, 0]$ $[0, 0, 1]$	$[0.2, 0.8, 0]$ $[0.9, 0.1, 0]$ $[0.2, 0, 0.8]$
Scouting	0.988	0.966	0.984	0.974
Harvesting	0.846	0.868	0.702	0.705
Dancing	0.815	0.812	0.894	0.849

We evaluated the swarm's performance using three criteria:

1. **Scouting:** The percentage of the operation area surveyed.

1. **Scouting:** The percentage of the operation area surveyed.
2. **Harvesting:** The ratio of the time the swarm took to complete all tasks compared to the ideal time with no communication limitations.
3. **Dancing:** Average connectivity, as measured by the average difference between each agent's local models of other agents and those agents' true states.

We varied the number of tasks, agents, and area sizes to evaluate how these performance indicators changed as the operation environment changed. We also varied the APIS role weightings for each scenario to adjust the frequency of agents taking on each role.

Results and Future Work

We have successfully demonstrated the capability of the APIS method of cooperative task assignment and heuristic behavior to reduce uncertainty, explore new environments, and maintain lines of communication between system agents. This has been demonstrated in simulation and is nearing completion in flight testing. However, the key demonstrator elements – that tasks can be delegated over an ad-hoc mesh network, that even large data structures such as LiDAR maps can be down-sampled and likewise exchanged, and that agents are able to serve as mesh network nodes – have already been validated. These markers demonstrate that the technological readiness (TRL) of APIS has increased and is nearing readiness for more large-scale field testing. We have validated that the optimal role weighting, especially in light of our large number of tasks, is to keep medium

Our next steps are to continue validating the performance of APIS in real-world flight tests. In order to further increase the TRL, we need to characterize the worst-case delays in the mesh network and the network reliability and continue to fine-tune the heuristic behavioral weightings of the swarm. Further attention should also be given to the best employment of sensor payloads, as the basic functionality of an APIS swarm now opens the door to more complex inter-agent cooperative tasks.

Flight Testing



Figure 4: From left to right: the Heavy Drone Class, able to map the area and complete visual tasks; the Medium Drone Class, able to complete visual, thermal, and radio tasks; and the Light Drone Class, able to complete visual tasks. All drones are able to serve as mesh nodes.

In order to validate the capability of APIS to coordinate drones in the real world, we created three different classes of drones to demonstrate heterogenous task assignment and coordination. For our implementation, we deploy one Heavy Drone,

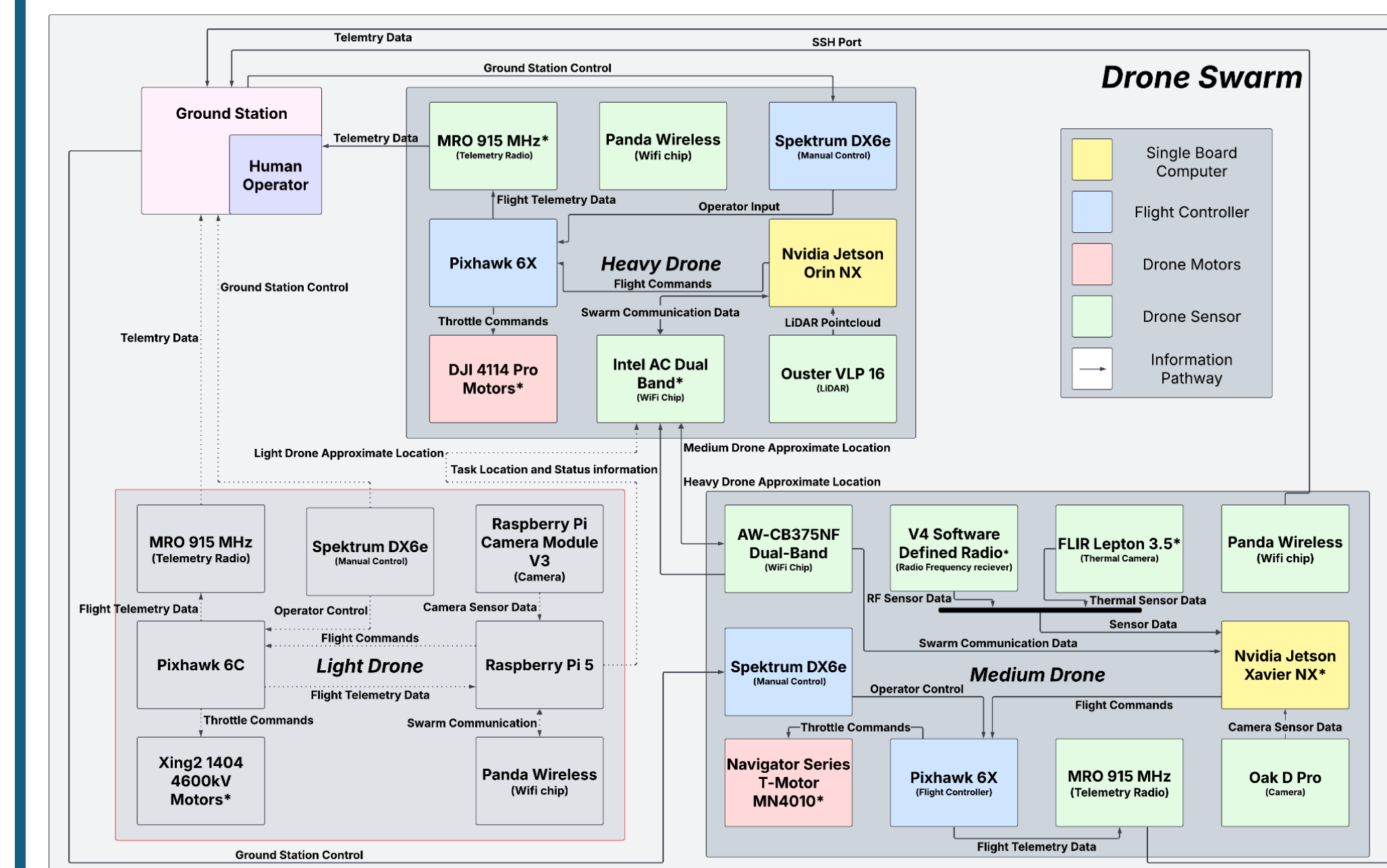


Figure 5: Drone swarm physical and logical architecture, with currently-descoped light drone.

search task to create realistic tasks with different required sensor payloads. For our initial implementation, however, we will focus on the radio and visual tasks and Heavy and Medium drones. All drone classes are currently operational, and all task completion methods have been simulated. Our next step is to move from simulation to reality and deploy the drones in an all-up flight test.

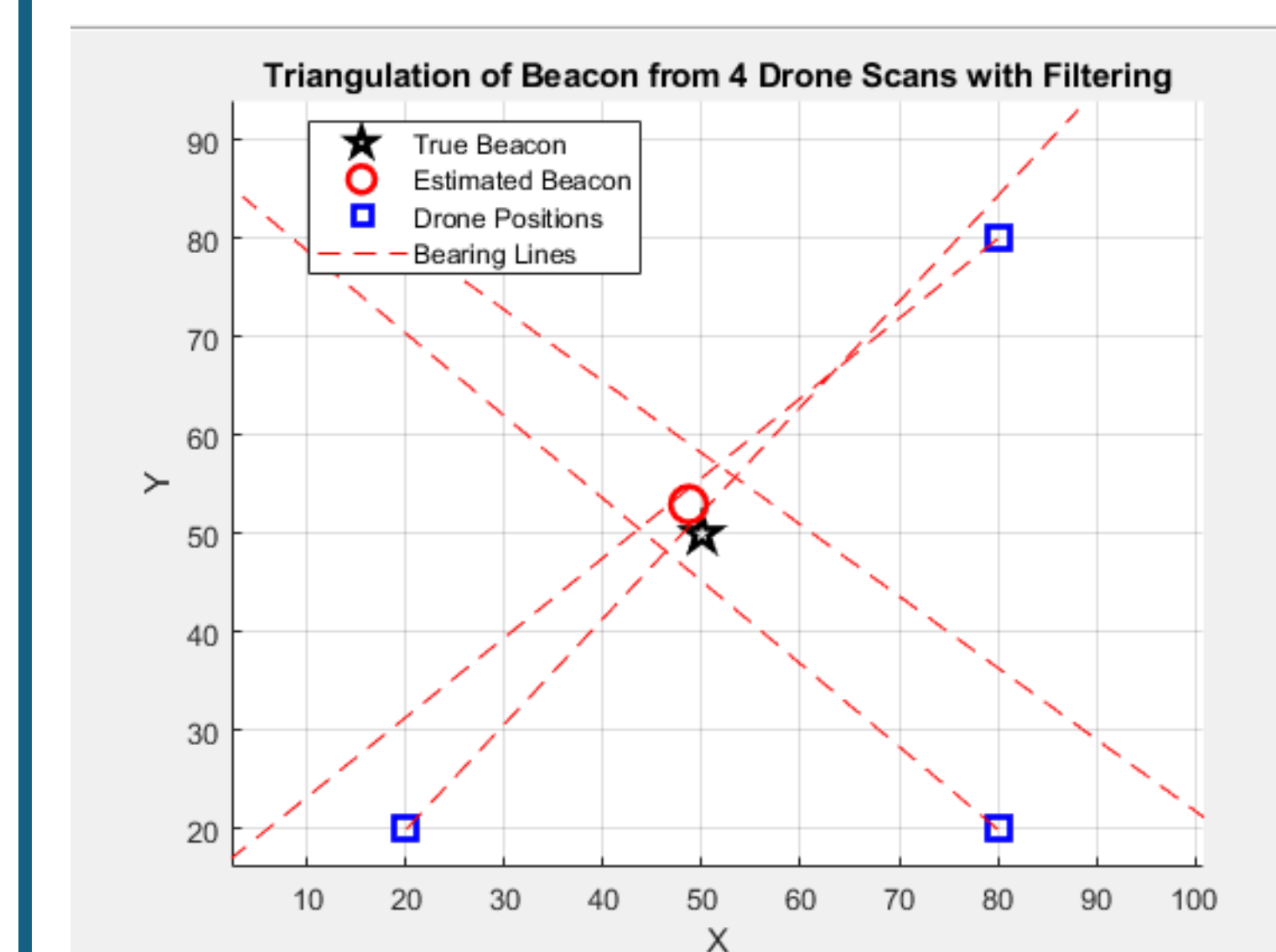


Figure 6: Simulated radio beacon direction-finding, using a directional antenna and a single drone.

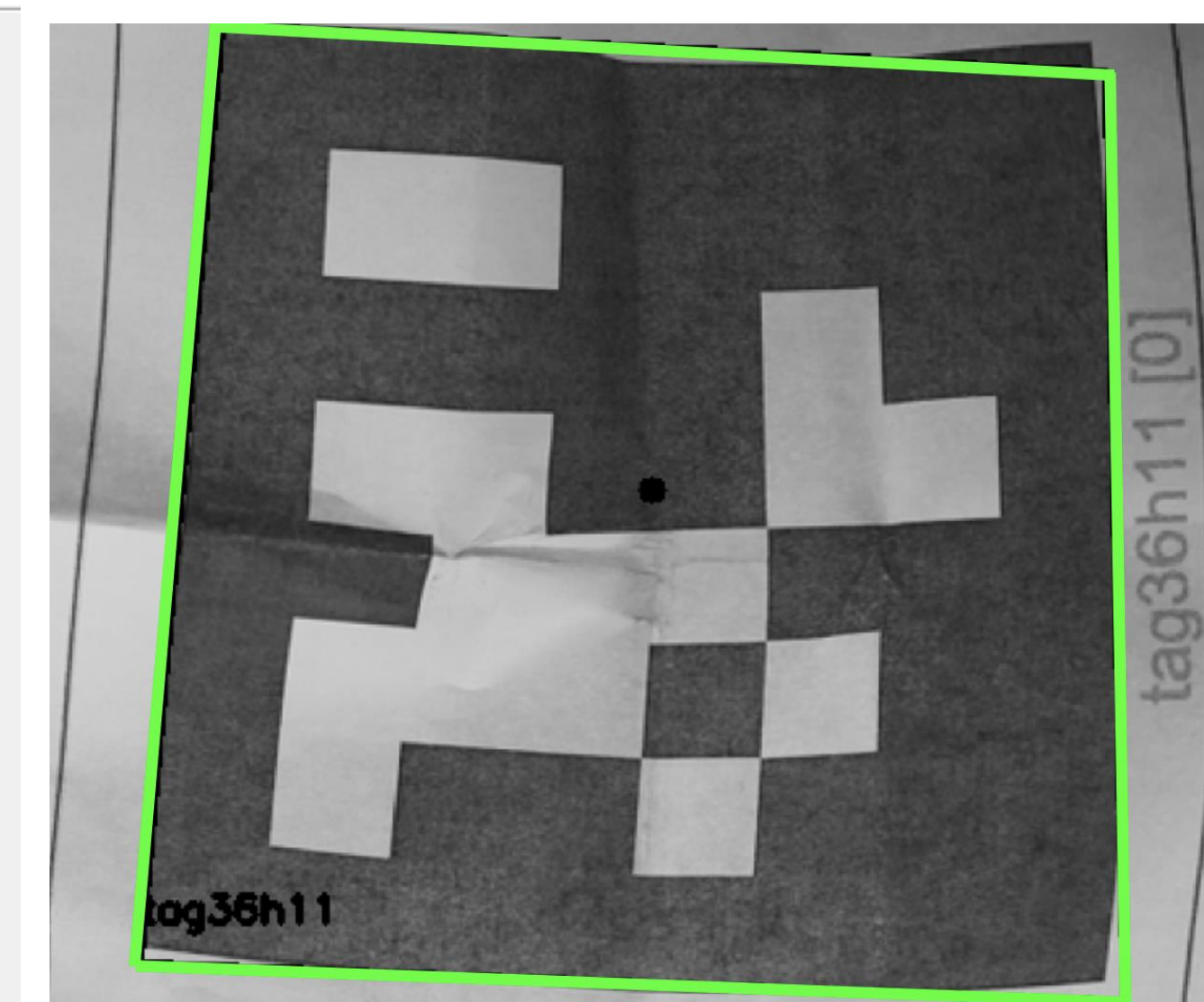


Figure 7: Visual fiducial detection, using an AprilTag.

[1] J. E. Pye and N. M. Alexandrov, "APIS: Honey Bee Foraging Task Assignment for Use in Uncertain and Unreliable Environments," *AIAA SCITECH 2024 Forum*, 2024, doi: 10.2514/6.2024-0333.

[2] A. Neumann, C. Aichele, M. Lindner, and S. Wunderlich, "Better approach to mobile ad-hoc networking (BATMAN)," *IETF draft*, pp. 1–24, Jan. 2008.