

ROUTING AND ACTION

MEMORANDUM

ROUTING

TO:(1) Network, Cyber, and Computational Sciences Branch (NC&CS) (Ulman, Robert)

Report is available for review

(2) Proposal Files Report No.: -RIP

Proposal Number: 70009-NC-RIP.1

DESCRIPTION OF MATERIAL

CONTRACT OR GRANT NUMBER: W911NF-17-1-0246

INSTITUTION: Virginia Polytechnic Institute and State University

PRINCIPAL INVESTIGATOR: Carl Dietrich

TYPE REPORT: Final Report

DATE RECEIVED: 3/1/23 4:23PM

PERIOD COVERED: 7/15/17 12:00AM through 7/14/19 12:00AM

TITLE: Final Report: Model city for unmanned aerial systems and wireless research

ACTION TAKEN BY DIVISION

(x) Report has been reviewed for technical sufficiency and IS [x] IS NOT [] satisfactory.

() Based on my technical review, I have identified no OPSEC or Technology Protection concerns that need to be addressed regarding this report.

(x) Performance of the research effort was accomplished in a satisfactory manner and all other technical requirements have been fulfilled.

(x) Based upon my knowledge of the research project, I agree with the patent information disclosed.

Approved by robert.j.ulman.civ@army.mil on 3/3/23 9:23AM

ARO FORM 36-E

REPORT DOCUMENTATION PAGE				Form Approved OMB NO. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 01-03-2023		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 15-Jul-2017 - 14-Jul-2019	
4. TITLE AND SUBTITLE Final Report: Model city for unmanned aerial systems and wireless research				5a. CONTRACT NUMBER W911NF-17-1-0246	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 611103	
6. AUTHORS				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Virginia Polytechnic Institute and State Univ North End Center, Suite 4200 300 Turner Street, NW Blacksburg, VA 24061 -0001				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211				10. SPONSOR/MONITOR'S ACRONYM(S) ARO	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) 70009-NC-RIP.1	
12. DISTRIBUTION AVAILABILITY STATEMENT 2 Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Carl Dietrich
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 540-231-2963

RPPR
as of 03-Mar-2023

Agency Code:

Proposal Number:

Agreement Number:

Organization:

Address: , ,

Country:

DUNS Number:

EIN:

Date Received:

Report Date:

for Period Beginning and Ending

Title:

Begin Performance Period:

End Performance Period:

Report Term: -

Submitted By:

Email:

Phone:

Distribution Statement: -

STEM Degrees:

STEM Participants:

Major Goals:

Accomplishments:

Training Opportunities:

Results Dissemination:

Plans Next Period:

Honors and Awards:

Protocol Activity Status:

Technology Transfer:

I certify that the information in the report is complete and accurate:

Signature:

Signature Date:

UAS Model City for RF Experimentation

Final Technical Report

Wireless @ Virginia Tech

Mid-Atlantic Aviation Partnership

Abstract

Wireless @ Virginia Tech and the Mid-Atlantic Aviation Partnership (MAAP) worked jointly to specify and purchase equipment that will serve as a new infrastructure for experimentation that involves unmanned aerial vehicles and systems (UAVs / UAS) and radio frequency (RF) application such as wireless communications and navigation enabled by software defined radio (SDR) and other radio equipment. Example topics that can be supported by the infrastructure include use of UAVs as airborne transceivers for characterization of air-to-air and air-to-ground radio channels including multi-input, multi-output channels, use of UAVs as airborne gateways between terrestrial ad-hoc networks, and many others. The grant was used to purchase UAV, software defined radio (SDR) and other components to enable these experiments, and initial tests were performed to confirm the feasibility of airborne RF experimentation with the purchased UAVs. The report also summarizes ongoing and planned projects that will use the new experimental capability and lists major purchased items.

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Introduction

UAS can enable many wireless communications applications, and operation of UAS is itself an application of wireless communications. Virginia Tech is developing a testbed to support experimentation in these areas.

Example Research Topics

The new testbed infrastructure is intended to support research on topics such as the following:

- **Employ UAVs as airborne transceivers.** Airborne transmitters and/or receivers for characterization of air-to-air and air-to-ground channels. This capability will enable measurement and modeling of air-to-air and air-to-ground radio channels. The resulting models will be used to design better wireless links and protocols for UAS (e.g., control, navigation, telemetry, and data) as well as for other aviation applications.
- **Airborne gateways between terrestrial ad-hoc networks.** The proposed infrastructure will enable investigations into effective interconnection of terrestrial networks, e.g., two or more ground-based tactical radio networks that do not have line-of-sight or other direct communication capability with one another.
- **GPS-denied and indoor navigation.** The vulnerability of UAS to GPS spoofing and dependence on GPS for mission accomplishment is an area of concern. Potential research topics here include the development of improved inertial and UWB radar based navigation capabilities (such as simultaneous location and mapping, or SLAM).
- **Cyber defense of UAS.** The threat of neutralizing or, possibly, gaining control of our UAS through cyber-attack must be addressed. Research remains to be done in attack vectors, defense methodologies and in defeat or mitigation of zero-day attacks.
- **UAS defeat.** DoD must also be able to defeat adversary UAS using kinetic and/or non-kinetic approaches. Research topics include the technologies to support UAS detection, classification and defeat mechanisms and into the tactics, techniques and procedures required to employ the developed technologies to achieve the mission while limiting collateral effects. The infrastructure will enable experiments to evaluate security concerns and to detect and mitigate violations of permitted UAV flight and radio spectrum use.
- **Use UAVs as rapidly deployable radios / network nodes.** The rapidly deployable and reconfigurable airborne nodes can serve as devices under test and interferers for spectrum-sharing / DSA experiments. This capability will enable rapid physical reconfiguration of spectrum-sharing networks under test and the signal environments in which they must operate. Radios may be operated in flight and / or relocated to temporary sites, e.g., rooftops, to enable longer-term operation of the radios without the need for the UAVs to expend fuel during the experiments or measurements.
- **Temporarily deployable base stations.** The airborne nodes can be used to investigate airborne “cells on wings” to boost capacity. UAV-borne radios can serve as rapidly deployable and mobile cellular base stations to supplement the fixed cellular infrastructure and boost capacity in selected locations when user density increases beyond levels considered in the cellular system design, e.g., during sporting events and traffic jams.
- **Distributed command and control architectures.** The FAA currently enables visual line-of-sight (VLOS) UAS operations but many key commercial and DoD applications of UAS require beyond line of sight operation (BLOS). A key challenge to BLOS operations is maintaining a robust control link over the horizon or beyond obstacles that prevent line-of-sight radio communications. Satellite communications are expensive, bulky, and suffer some latency. Fundamental research is needed to

establish communication strategies that enable communication relay or that leverage existing networks such as LTE.

- ***Sense-and-avoid capability.*** This capability will allow DoD aircraft the ability to safely transit the National Airspace System at home and to safely integrate into the overall air plan in overseas operations. Fundamental research is required to improve existing sensor technology, develop new sensor modalities and develop the required sense and avoid algorithms.
- ***Rapidly deployable geolocation receivers.*** This capability will enable investigation of search and rescue in which subjects of the search are equipped with wireless devices or beacons. If the UAVs' own positions are known, the UAVs can measure signal strength, time delay, and / or direction of arrival to find people in remote areas.
- ***Airborne ad-hoc networks.*** The UAVs can be used as nodes in to investigate networking approaches for use with UAVs / UAS and / or manned aircraft. This capability will enable cost-effective experimental investigation and evaluation of links and protocols that enable flexible communication among UAVs and / or conventional aircraft.
- ***Multi-vehicle operations (to include swarm).*** To fully exploit the capabilities and potential savings of unmanned systems, DoD must be able to fully exploit the capabilities of autonomy and seek to move well beyond the FAA's current requirement for one pilot to operate one UAS. To achieve this, additional research is required in the development of autonomy, multi-vehicle control algorithms such as swarm technology, and human systems integration.

Initial Use Cases

The Army Robotic and Autonomous Systems Strategy identifies, under Army Warfighting Challenges 7, the necessity to “assure uninterrupted access to critical communications and information links” as a major area of concern. Additionally, in order to lighten the cognitive load, the Army's short term goals include extending the Mission Command Network in dangerous situations. In civilian use, search and rescue missions are typically conducted in areas of low connectivity. Therefore, the ability to maintain strong networks for communication and information distribution can be integral to the effort. To fulfill these use cases, the ability for multiple nodes to reposition themselves in response to the movement of the end node and the RF environment can create networks that are more robust and can allow the node's software-defined radio to be more efficient. Our team created a test plan to assemble an infrastructure which would allow us to demonstrate a wireless network based on adaptive UAV nodes.

Under this test plan UAVs (unmanned aerial vehicles) were outfitted with companion computers and software defined radios in order to produce adaptive nodes in the real world. The primary objective was to demonstrate an optimization algorithm could re-position a UAV to maximize the RSSI (received signal strength indication) between it and another software defined radio on the ground. Work began with a hardware in the loop simulation environment that allowed for real world data sampling to be effectively used to create suitable control algorithms. The UAV was assembled to airworthy state, and manually carried around the environment to simulate changing RF conditions. These data sets were then used to run simulations with the same hardware and software to be used in flight, and how it would navigate to an optimal position. These simulations were used to refine the optimization algorithm to achieve its objective. Once the algorithm was refined in simulation, the entire system was flight tested to see if it could successfully optimize, as intended. These flights showed that the UAV was making navigation tendencies towards the highest RSSI value received, disregarding if the signal originated from the intended source node due to noise and other software parameters. Due to the fact

that the aircraft maneuvered in the direction of greater signal, it is believed that with further refinement and testing, the system may be a viable option for the use case.

Objectives

The research areas and use cases pursued by this work includes:

Primary Objective:

- a. Demonstrate the ability of a UAV outfitted with a software defined radio to optimize its position to maximize the RSSI (received signal strength indication) between it and another software defined radio on the ground.

Secondary Objectives:

- a. Demonstrate the ability of multiple UAVs outfitted with software defined radios to position themselves in a three-dimensional space to create an optimal wireless network between two nodes
- b. Demonstrate the ability of cognitive radios to adapt to a changing RF environment
- c. Explore the benefits of having redundant nodes in the air concurrently to provide reliability and increase the signal strength of the system

Technical Approach

The test plan took advantage of the newly constructed Drone Cage at Virginia Tech. As shown in Figure 1, nodes were installed around the perimeter of the cage, either on the interior or exterior, based on security. To satisfy the primary objective, one UAV was introduced into this environment with only one ground node. The secondary objective was to introduce multiple aircraft and multiple ground nodes.

The single UAV had no knowledge of the precise location of the end node. Instead, it was required to measure the RSSI and then modify its position to maximize RSSI. This repositioning would be occurring continuously while the UAV was in the air to constantly maintain the highest RSSI possible. The software-defined radio onboard the UAV provides information regarding RSSI as inputs to an optimization algorithm to generate updated position assignments for the UAV. The next section “optimization problem formulation” more precisely defines the design variables.

For the secondary objective and future work, the nodes not in use as start or end nodes could optionally be emitting interference, creating a more complex environment. To test adaptability, the locations of start or end node could be changed (such as by switching node roles) and the central processing system would be required to estimate new locations for the UAV.

In order to satisfy secondary objective (b), the software defined radios aboard the aircraft would use cognitive radio to adapt to a changing RF environment (such as interference) by dynamically altering their RF communication schemes, such as altering frequencies in use (via frequency hopping) or altering the modulation scheme used.

In order to satisfy secondary objective (c), the central control system would be designed to determine the distance between the current start and end nodes. Then, it would calculate the appropriate number of UAVs needed to complete the network and the number of redundant nodes that

should be incorporated into the network. Redundant nodes will ensure that any loss of UAV would not affect the network strength.

The placement of equipment in the Drone Cage, assuming pursuit of all secondary objectives, would be as shown in Figure 1:

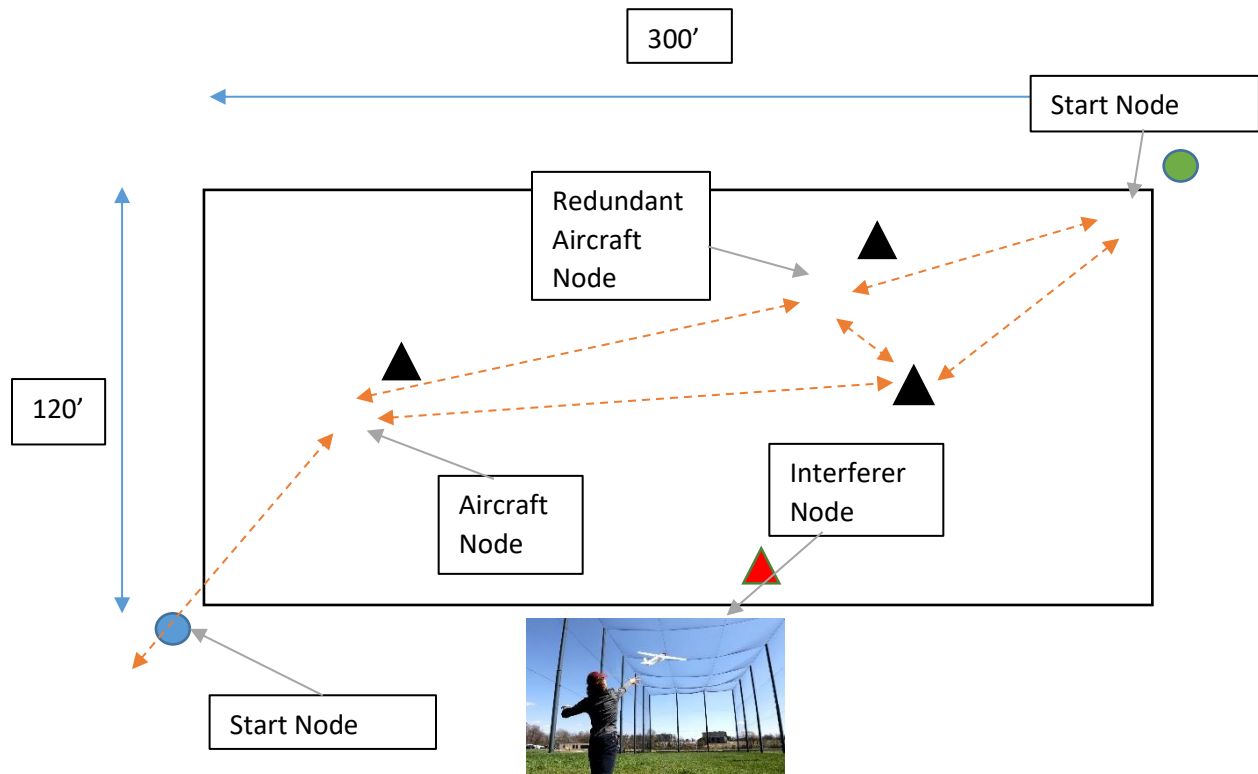


Figure 1 - Drone Park Cage, pictured at bottom of figure, with locations of mesh nodes (image from <https://vtnews.vt.edu/articles/2018/04/ictas-droneparkopens.html>).

Optimization Problem Formulation

With respect to the primary objective - demonstrate the ability of multiple UAVs outfitted with network nodes to position themselves in a three dimensional space to create an optimal wireless network between two nodes – the following optimization problem can be formulated:

Given:

- 1) A cuboid area of operations with geometry defined as: L, W, and H
- 2) Number of drone agents: N ($n_1, n_2, n_3, \dots, n_N$)
- 3) Drone positions in 3D space: $x_1, y_1, z_1, \dots, x_N, y_N, z_N$
- 4) Buffer distance between drones to prevent collision: d
- 5) Buffer distance(an offset from the boundaries of the operations area to account for GPS inaccuracy: b
- 6) The starting node and terminal node for the communications link: C_s, C_t
- 7) Communications network center frequency: f

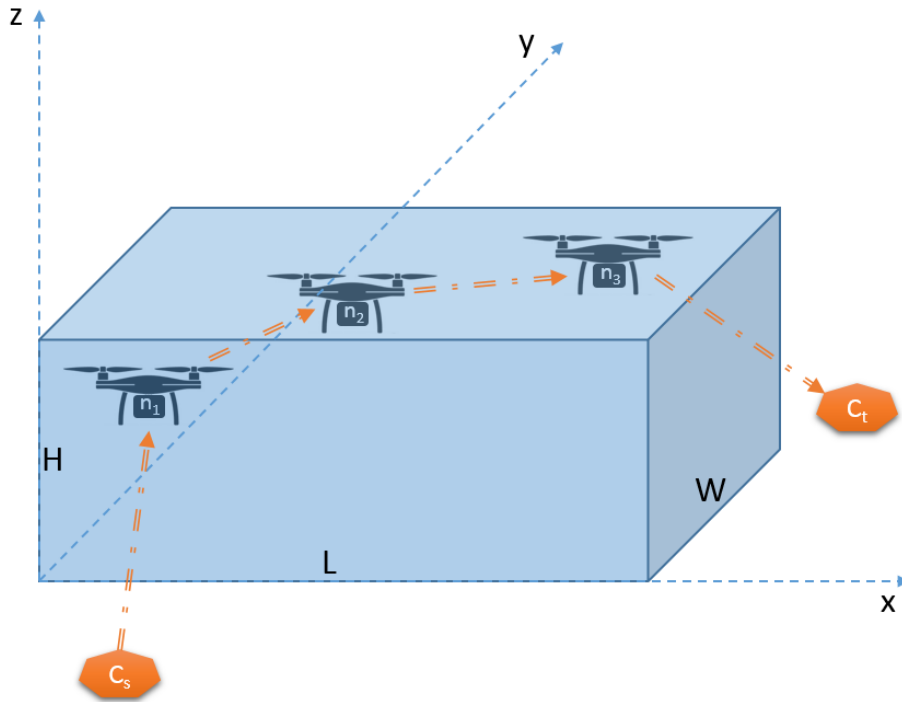


Figure 2 - Optimization design variable dimensions

Problem: For a given transmit power level find the drone agent positions and communications network center frequency that maximize RSSI or data rates.

Constraints:

Bounds on radio center frequency:

$$f_l \leq f \leq f_u$$

Bounds on agent positions (must be within cage):

$$b \leq x_i \leq L-b,$$

$$b \leq y_i \leq W-b,$$

$$b \leq z_i \leq H-b,$$

Anti-collision constraint (agents cannot occupy same location):

$$(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2 \geq d^2, i = 1, N, j = 1, N, i \neq j$$

Design Variables:

Network center frequency: f

Agent locations: $x_i, y_i, z_i, i = 1, N$

Aircraft Selection & Design

In order to carry the planned payload a multi-rotor configuration had to be designed and selected to maximize endurance, minimize size & weight, and achieve the primary objective. Endurance in such tests is important as considerable field time is spent readying the aircraft between flights. A 20min endurance was considered reasonable and a 30min endurance was very desirable.

For this project, a 640mm quadrotor with 15 inch props was estimated to have a flight time of 23.2min (Figure 3) carrying the E310 USRP and a companion computer (like a RPi3). Analysis on thrust to weight ratio (T/W) and endurance was performed with the eCalc utility for multi-rotor design. The per aircraft cost includes batteries sufficient for 3 flights per aircraft. A small quadrotor airframe, a Storm AntiGravity, was selected because its low weight and size while achieving adequate endurance. This was the initial aircraft selection based around the E310 USRP and RPi3 companion computer.

The Storm airframe was replaced by a Tarot 650 Iron Man airframe in favor of replacement part availability. Actual tests were performed with a B205mini and an Intel NUC which did not substantially alter the flying weight, so the same aircraft performance figures would approximate performance of the Tarot 650. The same propulsion system was used on the Tarot 650 as was intended for the Storm airframe.

Price Per AC	\$1,324.62
# Aircraft	3
Total Price	\$3,973.86

No Payload	T/W=2.6
Empty (g)	1563
Battery (g)	1271
Total Weight (g)	2834
Hover Time (min)	30

Equipped with E310 + RPi3	T/W=2.2
Empty (g)	1563
Battery (g)	1271
Companion Computer	127
E310 USRP	375
Total Weight (g)	3336
Hover Time (min)	23.2

Max Gross Takeoff Weight	T/W=1.7
Empty (g)	1563
Battery (g)	1271
Max Payload T/W=1.5 (g)	1607
Total Weight (g)	4441
Hover Time (min)	14.7



Figure 3 - Aircraft cost, weight, and endurance

System	Item	Weight (g)	QTY	Cost	Total Cost
AC	Frame - Storm Quad folding	650	1	\$160	\$160.00
AC	ESC - 20A+ KDE	80	4	\$41	\$163.80
AC	Motor - 4006 380kV Tmotor antigravity	272	2	\$150	\$300.00
AC	Props - APC 15x5.5 MR	72	4	\$7	\$26.00
AC	Props - APC 15x5.5 MRP	72	4	\$7	\$26.00
Avionics	Flight Controller - Pixhawk 2 Cube	340	1	\$198	\$198.00
Avionics	HERE GNSS GPS	40	1	\$48	\$48.00
Avionics	Holybro 100mW Telemetry Radio Set (915Mhz)	20	1	\$35	\$35.00
Avionics	RC Receiver - FrSky X8R 16ch	17	1	\$34	\$33.99
GCS	RC Transmitter - FrSky Taranis Q X7 2.4GHz 16CH	0	1	\$105	\$104.99
AC Battery	Tattu 5.2Ah 15~30C (2 X 635.5 g: 1271 g)	1271	6	\$38	\$228.84

Figure 4 - Aircraft bill of materials

Test Configuration Flown

The final test configuration was altered from the original test plan to achieve a minimum viable test. The same overall architecture discussed above was used except only one USRP on the ground was used. The goal was to locate the single USRP on the ground with the optimization algorithm maximizing RSSI by changing the aircraft's position laterally. This new configuration was tested in a simulation environment before proceeding to flight test.

Aircraft Description

The aircraft utilized for the test payload was the Tarot Iron Man 650 quadcopter. This airframe was selected for its cost, versatility, and modular component scheme. The carbon fibre construction allows for a study yet light airframe that can accept a variety of loads. This frame allows for the payload to be integrated easily and quickly using the factory mounting options on the lower body plate. Using aluminum standoffs and 3d-printer payload bays, the chosen electronics are stowed under the body, allowing for payload compactness as well as easy access to both communications ports and power. The airframe also folds for easy transport and portability.

These components, pictured below, include the intel N.U.C. (6) and software defined radio (7) with supporting hardware and wiring. The Auto pilot and supporting modules were mounted on top of the body to avoid radio interference. This included the Pixhawk2 (4), GPS module(3), R/C receiver(1),

telemetry radio(5), and battery monitors(2). The pixhawk2's serial input allows for easy access to flight control, which simplifies the process of receiving navigation commands from the payload.

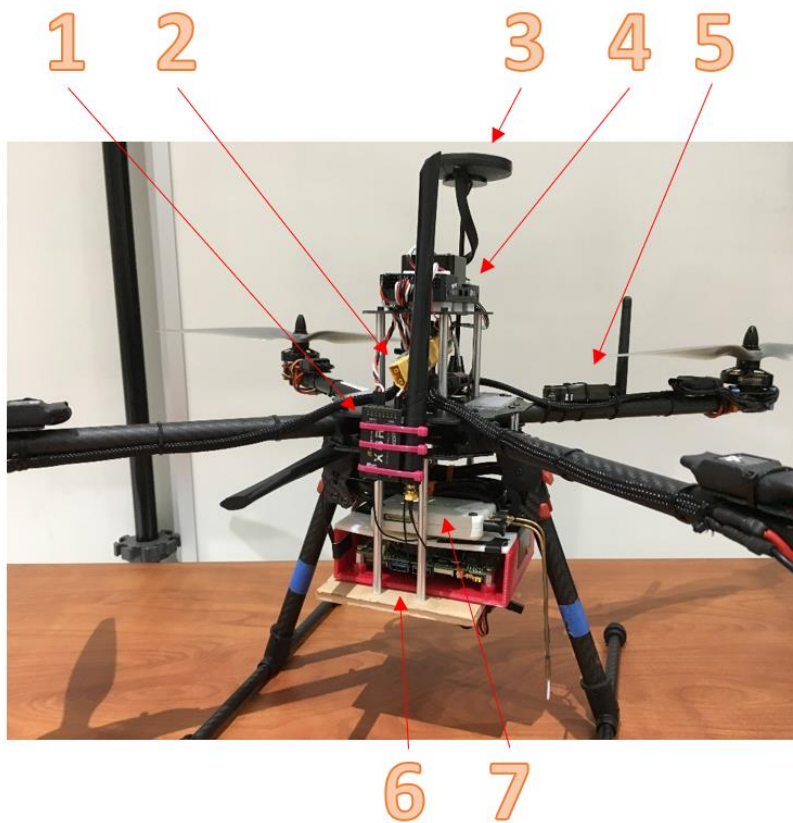


Figure 5 - Component locations on Tarot 650 quadrotor



Figure 6 - Tarot 650 Quad Airframe

The secondary airframe was the Tarot 680 Pro Hexacopter. The hexacopter layout incorporates many of the same features of the quadcopter frames, but with cleaner wiring to reduce EMI, added payload capacity, and added safety redundancy. The hex frames were set up with the same suite of flight control electronics to allow for seamless compatibility of payloads between the two airframes.



Figure 7 - Tarot 680 Hex airframe

System Description

In order to control the location of the UAV, the optimization program was used to calculate the optimum positions. For this to occur, radio performance data correlated with each aircraft's location is sent to the optimization program. The network and radio performance design variable inputs feed an optimization algorithm to determine the new aircraft location. The optimization program sends coordinates defining a new desired location to the aircraft's autopilot which will navigate the aircraft to the new location. The optimization program and software on the aircraft's companion computer (an Intel NUC) checked the new commanded locations against constraints from geofences. The overall architecture of the system is described in following sections that address different levels of hardware and software connectivity and software design.

The overall system architecture was altered from the original test plan but still used key components such as the Pixhawk, ROS, and a USRP. The primary change was using an Intel NUC and B205 mini USRP instead of a Raspberry Pi and E310 USRP. The Intel NUC with a Core i7 processor was favored to ensure adequate support for ROS, serial connections, and processing power. Originally, a E310 USRP was to be used with the SDR software and ROS software running internally on the ARM computer integrated in the E310. However, it was anticipated that ARM computer would not have sufficient processing power for future work. Also, the combination of the E310's Linux version and CPU type made implementing ROS difficult since ROS is mostly supported on Intel CPU types and Ubuntu Linux. Since the Intel NUC would handle processing of SDR waveforms the B205 mini was selected as it does not have an integrated computer like the E310. Typically, a computer integrated into the USRP is used for generating and receiving SDR waveforms but this functionality would be duplicative for this test because the Intel NUC would be handling the SDR waveforms. The [Ettus Research USRP b205 mini-i](#) radios were chosen by VT wireless for their broad frequency range and strong documentation/support in the radio research community. The B205 mini USRP offered the desired band coverage and bandwidth without an integrated computer.

Hardware / Network Architecture

The below Figure 8 shows the physical architecture of the system tested. The NUC on the aircraft ran all the optimization and control functions with ROS and a GNU Radio receiver. The NUC in the ground node ran GNU Radio as the transmitter for the USRP, broadcasting random data on a clear channel in the 5.8GHz band with a 10MHz bandwidth. The computers were all connected by a WiFi network provided by a router on the ground. The operators computer was used to remotely login via SSH to each NUC over Wi-Fi to start and stop the system. Each drone had a NUC which was connected to the USRP by USB2 and the Pixhawk by a USB to serial converter. A ground node could be any computer on the ground with a USRP acting as a transmitter. In the final use case the drones would be fully autonomous and would not require the separate WLAN where any data could be passed on the USRP communications mesh network. For these tests the mesh network was not implemented.

Since the mesh waveform was not available to implement, the test was run with a simplified waveform. The simplified waveform involved transmitting random data from the ground node where aircraft received the transmission and measured the raw magnitude of the radio signal (the RSSI) as the objective to maximize. In the results section this is shown to adversely affect system performance as it allows any interference on the channel to also appear as the desired radio signal to optimize toward.

Eventually, a completely developed waveform and networking capabilities will be added to the USRPs (or they will be replaced by something else).

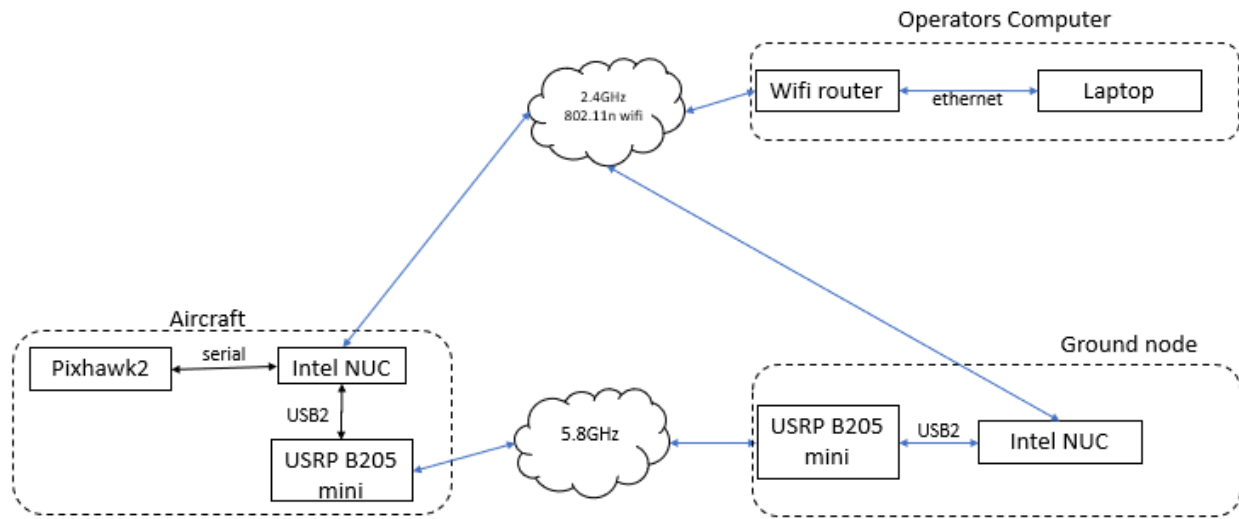


Figure 8 - Tested hardware architecture

Software Architecture

The Intel NUC was configured with Ubuntu 18.04, ROS Kinetic, and GNU Radio which have a series of packages and libraries to allow for rapid development of a test system. The Mavros ROS package was installed to allow controlling the Pixhawk2 with the MAVLINK protocol. ROS was used to facilitate command and control of the aircraft's Pixhawk autopilot and to collect position and RSSI information for the optimization routine. GNU Radio was used to construct one-way communication between the USRPs with one radio on the ground transmitting random data to the aircraft. The USRP on board the aircraft used GNU Radio to measure the received RSSI from the radio on the ground and pass the RSSI measurement into a ROS node for use in the optimization. ROS nodes were written in Python3 and contained in a single Catkin package which allowed automatically building components and easily starting all the necessary components to run the system, including GNU Radio.

The flight controller on each drone was a Pixhawk running ArduCopter v3.5. The serial telemetry port on the Pixhawk was connected by a USB/Serial adapter to the NUC. This connection carried MAVLINK messages between the Pixhawk and the NUC. Mavros was used as the software bridge between this interface and the ROS system. The system was configured so each drone hosted its own ROS master and had a separate namespace determined by the UAV ID. However, only one drone was flown for testing. All nodes were connected under the ROS system. Figure 9 shows the relationships between the nodes. Not every node was a true ROS node connected to the ROS message system, but they are initialized by the ROS launch file. The Optimization node had Geofence, UAV Control, and RSSI objects. UAV Control interfaces with Mavros through ROS messages. Mavros was connected to Ardupilot SITL when simulating and the Pixhawk when performing field tests. The RSSI node has an array of valueCubes (Blocks) that represent the RSSI within a localized cube location. The RSSI node was connected via ROS messages to the RSSI Dummy node when simulating and the ZMQ Client when performing field tests. The ZMQ Client connects to a ZMQ sink in gnuradio, which is connected to the USRP. Further details about the classes and methods that define the nodes are included in the appendix.

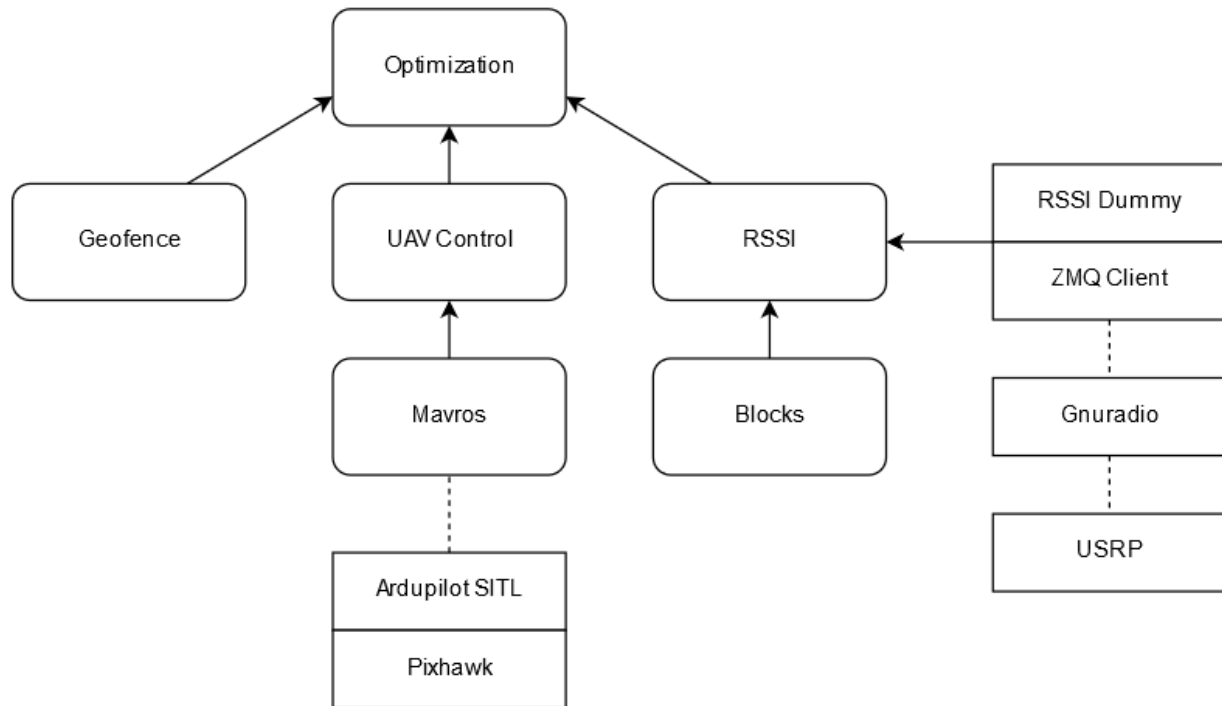


Figure 9 - ROS Node Hierarchy

Optimization Algorithm Description

The test configuration used a setup as follows: there was one ground node with a broadcasting radio transmitter and one aircraft with a radio receiver. The drone started at an arbitrary point in the space surrounding the transmitter and attempted to find the ground node by moving in the direction of the strongest RSSI gradient. The optimizer directed the drone by commanding the UAV to sample RSSI at three points (Figure 10). The optimizer calculated the gradient from the base point and then moved the drone in a set step distance in the direction of the calculated gradient. When the drone reached the next base point along the gradient it would repeat the process, sample the perpendicular point and proceed to the next base point. No stopping criteria were defined since the goal was to continuously optimize position as the RF environment changed. In the sim, when the optimal point was reached the aircraft would oscillate across the optimal point according to step distance between base points.

In addition to the running the optimization algorithm, the optimization node also scheduled position changes in the order they were generated. The flowchart (Figure 11) shows the algorithm's software logic and how it scheduled position changes. It used a position command queue to ensure the Pixhawk is commanded to positions in the order they were generated by the optimizer. The loop would wait until the aircraft reached the commanded location to ensure it was sampling data from the correct location and to slow down the control loop.

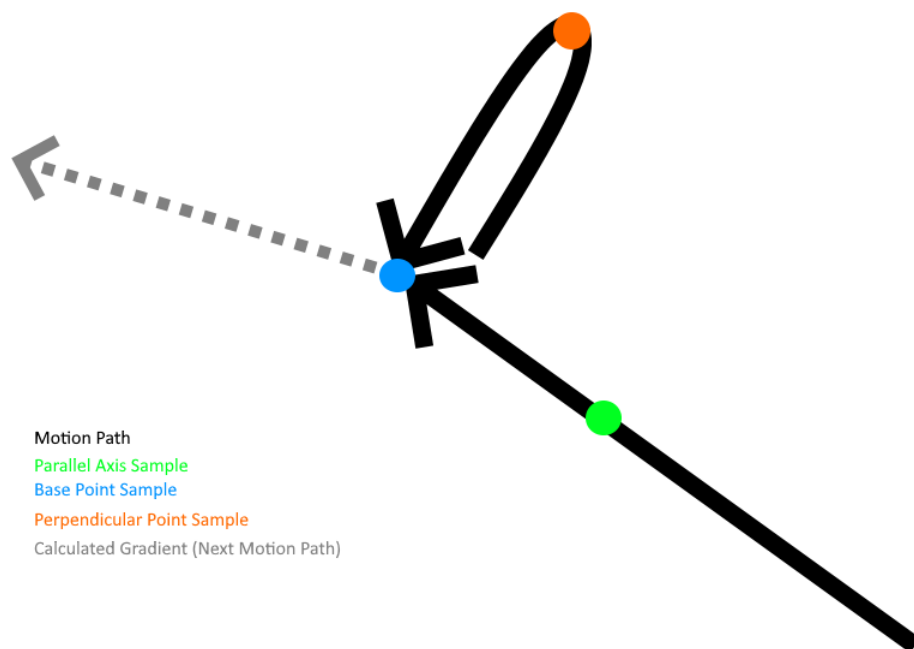


Figure 10 - Sampling the RSSI Gradient

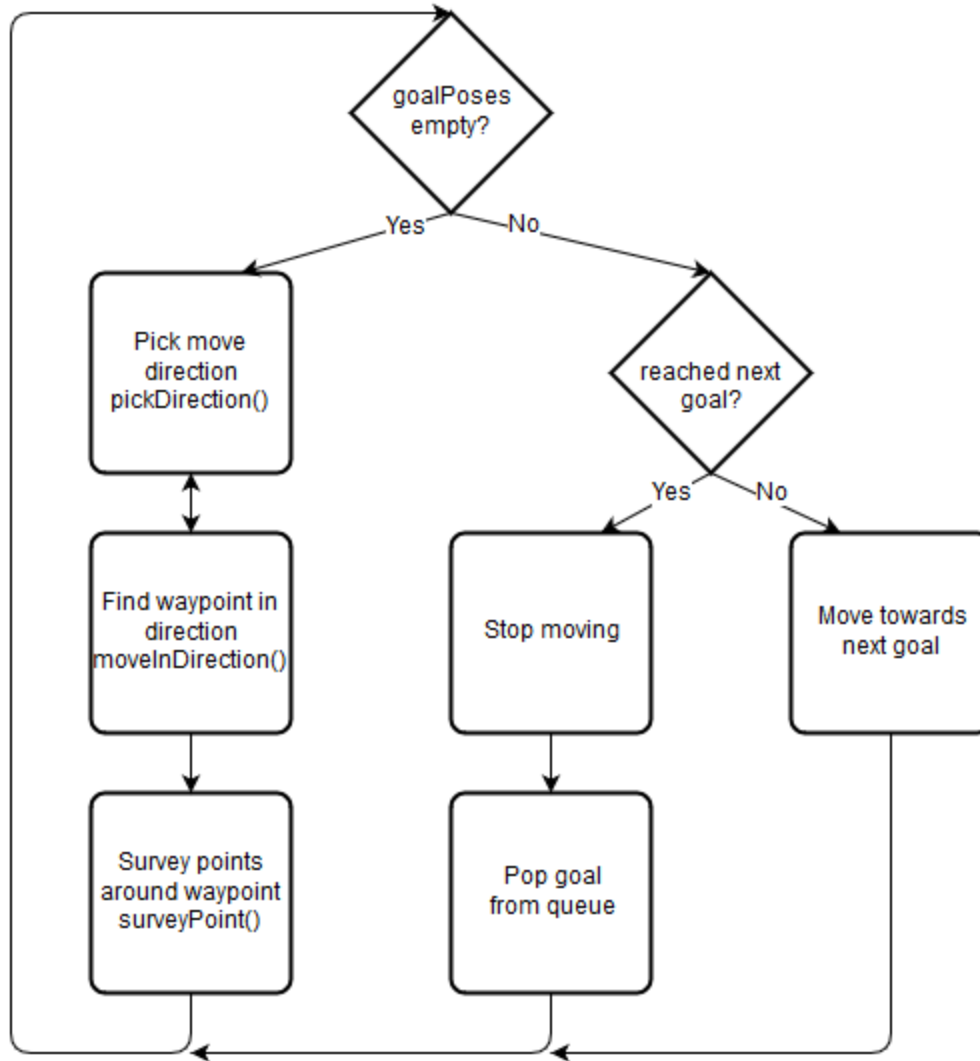


Figure 11 - Optimization Flowchart

To reduce the effects of noise the optimizer used a 3D grid of cubes, each of which stored a moving average of the RSSI at that point. Figure 12 shows an example of the cube grid in the visualization environment. The drone had to spend a certain amount of time in a cube to obtain an accurate RSSI value by averaging noise in the RSSI values. Since the aircraft was nearly always moving, the time it spent in the cube was dictated by cube size and aircraft velocity. The size of the cubes set the spatial resolution of the optimization. If larger cubes were used they would have been more successful in filtering noise, but would have reduced the accuracy of the drone's final position. The benefit of this approach allowed the system to store RSSI and position data for a future implementation of a global algorithm. Such an algorithm could calculate the gradient field of all the recorded values to better estimate the direction and range to the transmitting node.

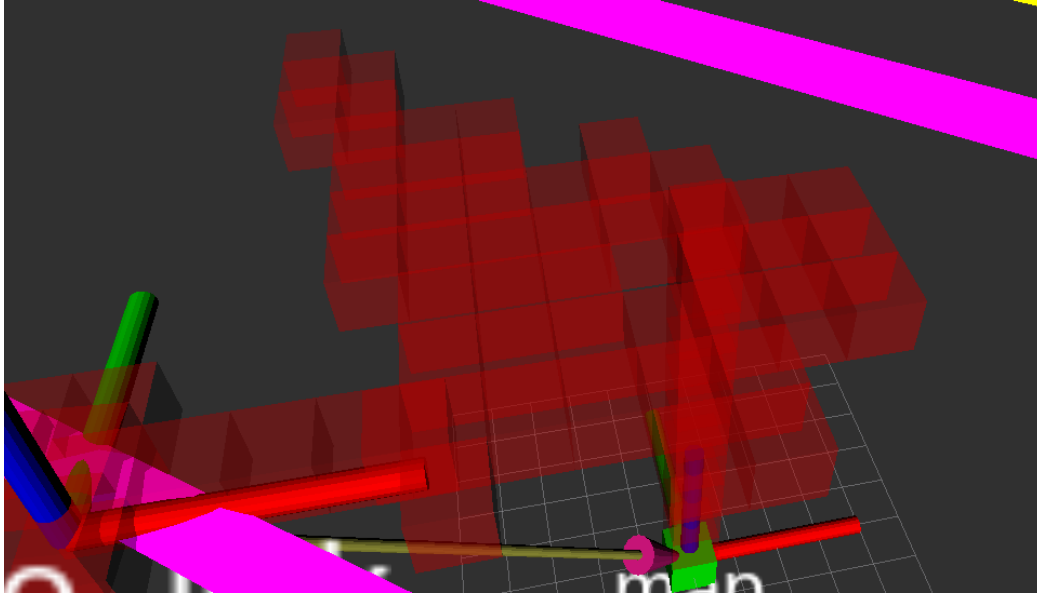


Figure 12 - 3D RSSI Value Cubes

For future development, the concept will be multiple UAVs in cells along the intended network path. Each drone will optimize within its cell, and eventually the swarm will settle into a path of least RF resistance (Figure 13). In this implementation, a base station will be used to upload initial points and geofences to each computer. Each drone will autonomously fly to its starting point and then enable the geofence on the Pixhawk. Then it will optimize its position within the geofence cell, as explained in the algorithm description below. For the tests flown, the drone was manually maneuvered to the starting point before putting the drone in Guided mode where the optimization would start.

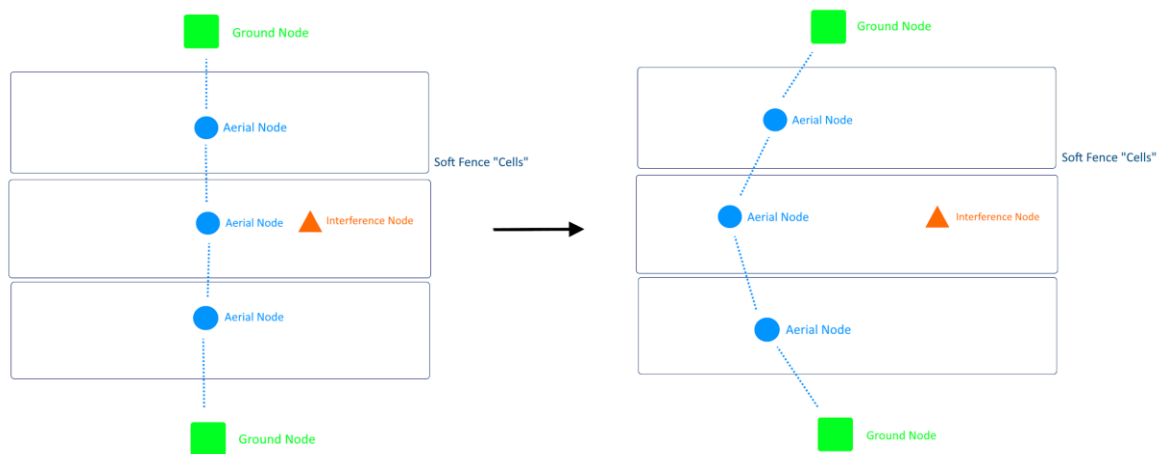


Figure 13 - Optimization Within Cells

Geofence Logic

For operational safety a geofence system was implemented. The geofence was critical in preventing the aircraft from colliding with the netted drone test facility it was tested inside of. Also, geofences would be used to prevent fly-aways when not operated in a net environment. Figures 14 & 15

show the “soft fence” logic where the system is still allowed to traverse the edge of the fence. This function was critical to allow the optimizer to still reach its goal. Figure 15 shows the effect of the soft fence in simulation where the system reached the fenced goal.

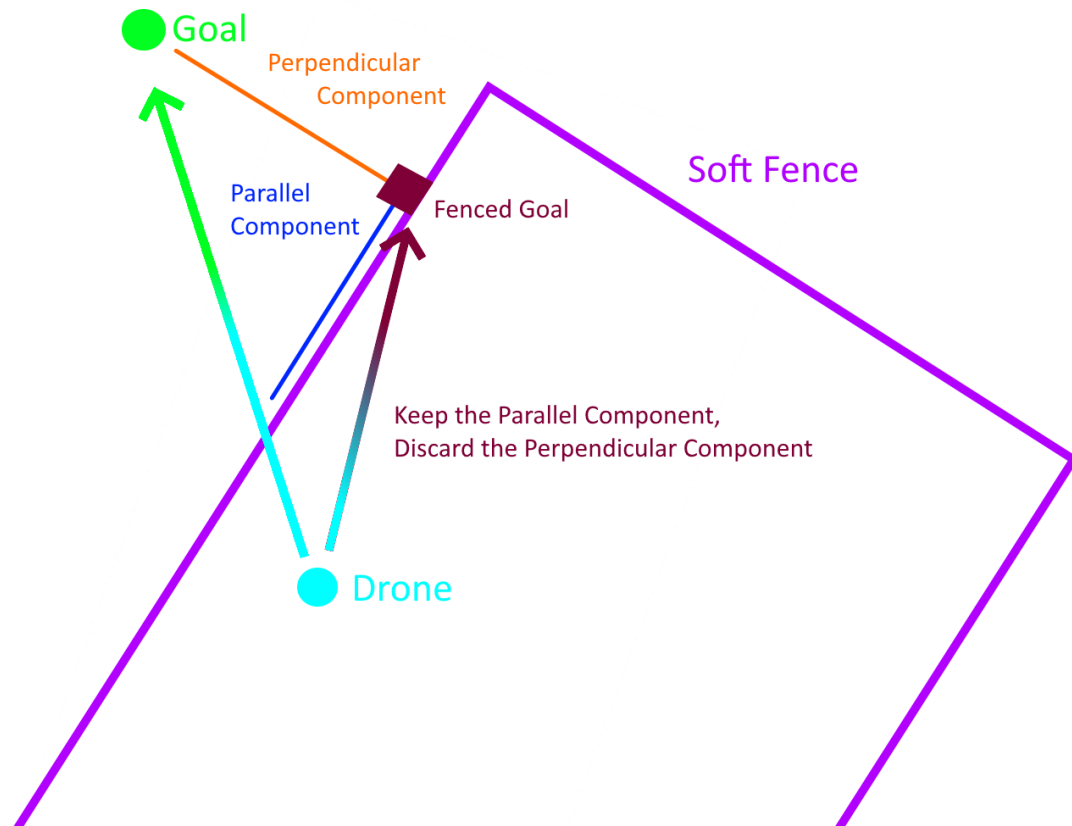


Figure 14 - Soft Fence

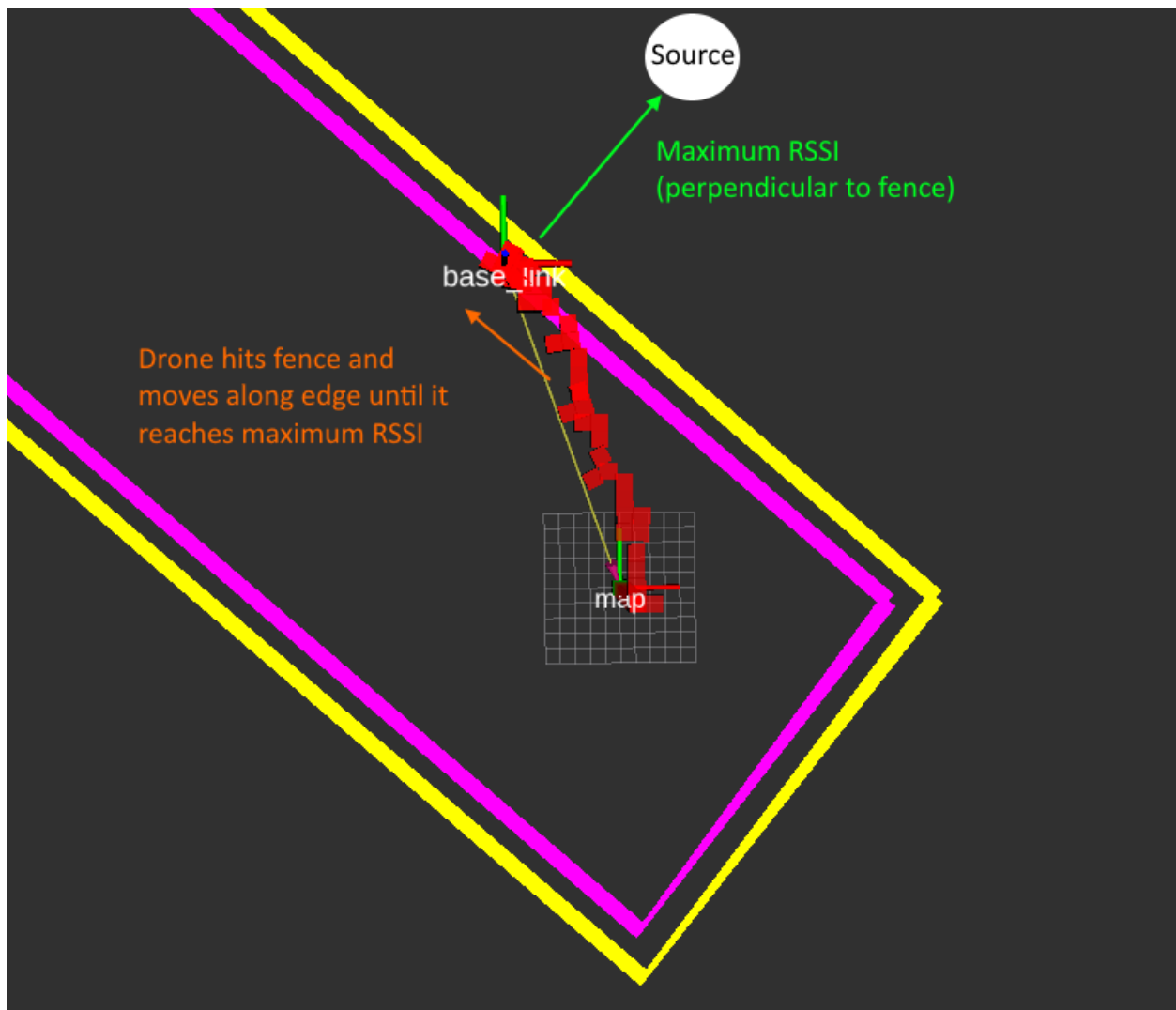


Figure 15 - Soft Fence in Simulation

Testing and Results

Summary

Initial results from ground and flight tests show the system is able to measure the change in RSSI as distance is increased from the transmitting node. However, due to random variations in RSSI measurements without a change in position adversely affected optimization performance and it did not optimize its position toward the transmitting ground node. Test runs in the simulator were tolerant of noise in RSSI measurements so it is suspected either RSSI noise was greater than anticipated or there is a un-discovered fault in the optimizer.

Before flight test the system was validated with collecting RSSI and position data in a parking lot. This data was used to characterize the rapid variations in RSSI measurements (most likely due to multipath fading caused by objects in the physical radio channel) which would be used to model noisy RSSI measurements in the simulator. The simulator environment was used to test and fine tune the optimizer and automation behavior where the simulation reliably optimized to the objective. Flight tests were performed in the Virginia Tech netted drone facility to validate the simulation and collect additional RSSI data for study. The flight tests resulted in the aircraft being commanded to the edge of the geofence, away from the objective. It was suspected a bug was responsible for that behavior and further testing is required to determine the root cause of the behavior. Flight tests showed the RSSI data to less reliably decrease as a function of distance. It was suspected other interfering radios were skewing RSSI measurements at the flight test location. For future development this will be mitigated by only measuring the RSSI of an established link between the two radios.

Parking Lot Test

The first test was a walking test in the parking lot to test radio performance and basic system functionality. This was done to evaluate the connectivity and data capture of the real-time system (not the simulator). The data from this test was used to improve the simulator by measuring actual noise in RSSI measurements and reproducing them in the simulator. The results shown in the visualization plot shows the change in RSSI walking forward and back in the optimal path (Figure 16), and RSSI was appropriately correlated with distance. The higher RSSI values are represented by brighter red color shading of the cubes. The difference between the first and second tests can be seen in Figures 17 and 18. After observing considerable noise in the first test's results, the moving average length parameter was modified to smooth the data in subsequent tests. The moving average changed the overall range of the RSSI data in terms of minimum and maximum values observed. This would not adversely affect optimizer performance since the optimizer relies on the gradient in the data.

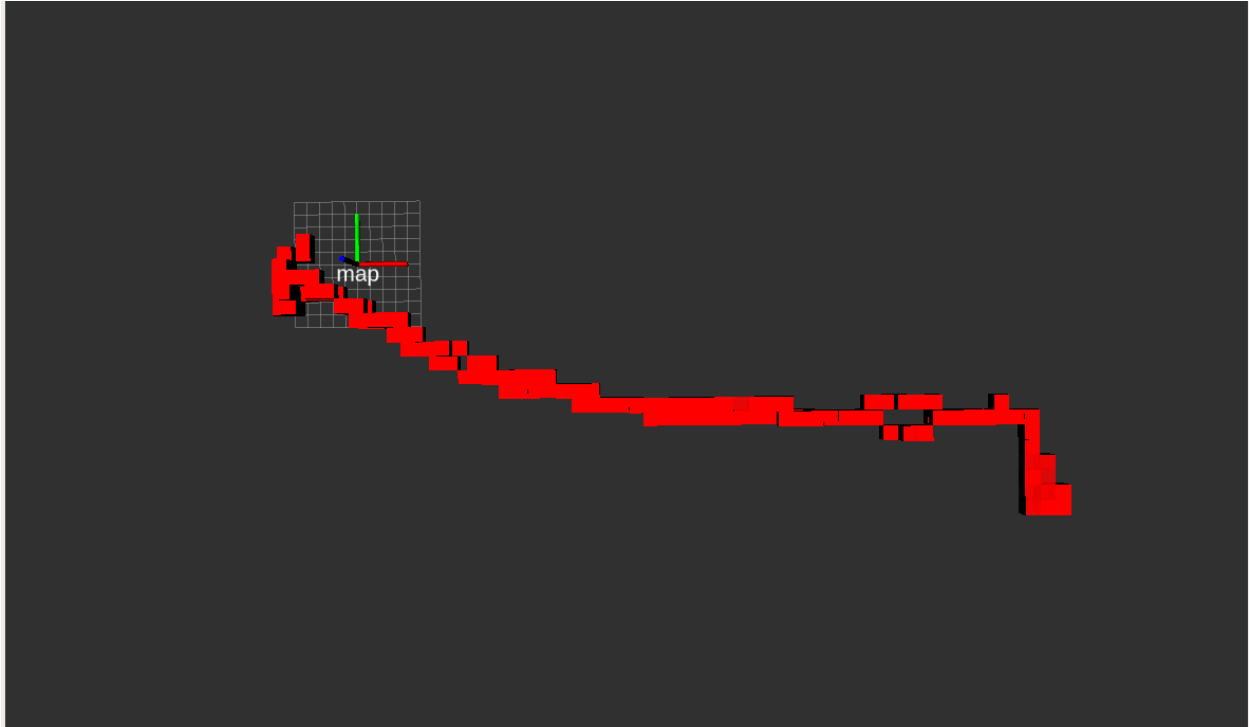


Figure 16 - Parking Lot Visualization

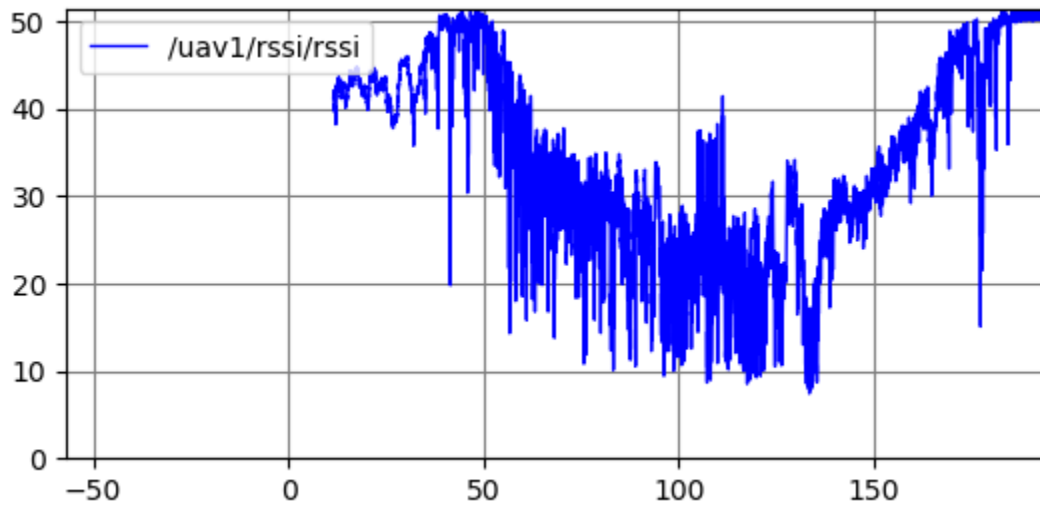


Figure 17 - Parking Lot RSSI Plot (Test 1)

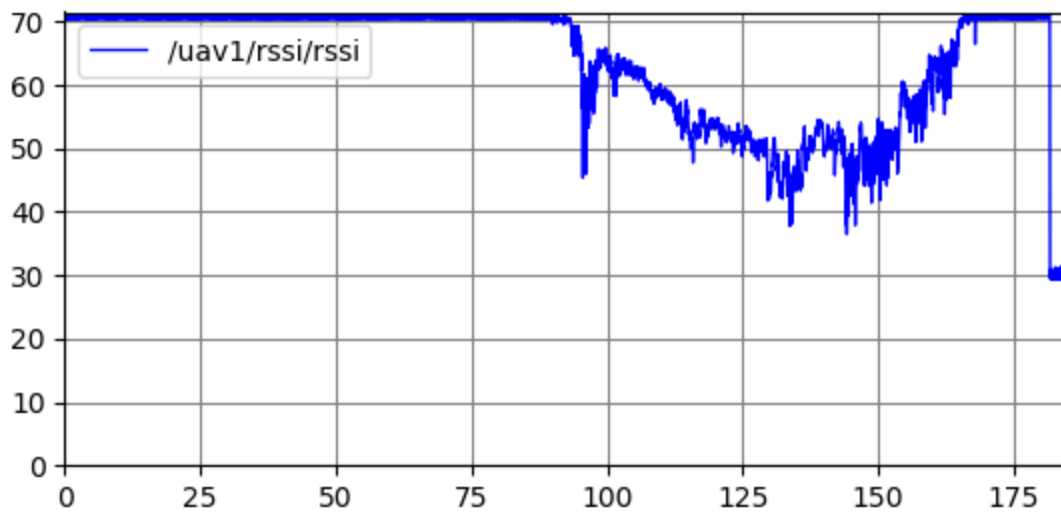


Figure 18 - Parking Lot RSSI Plot (Test 2)

Drone Cage Test

Three flights were accomplished inside the Virginia Tech drone test net facility, the Drone Park cage. Before flying a walking test was performed to verify the functionality of the Pixhawk geofence and check the RSSI gradient by walking the perimeter of the cage. The data from this ground test is seen in Figure 19 where the gradient of RSSI values were present but weak at distances far from the ground node and noisy as indicated by variations in the shading of the red cubes.

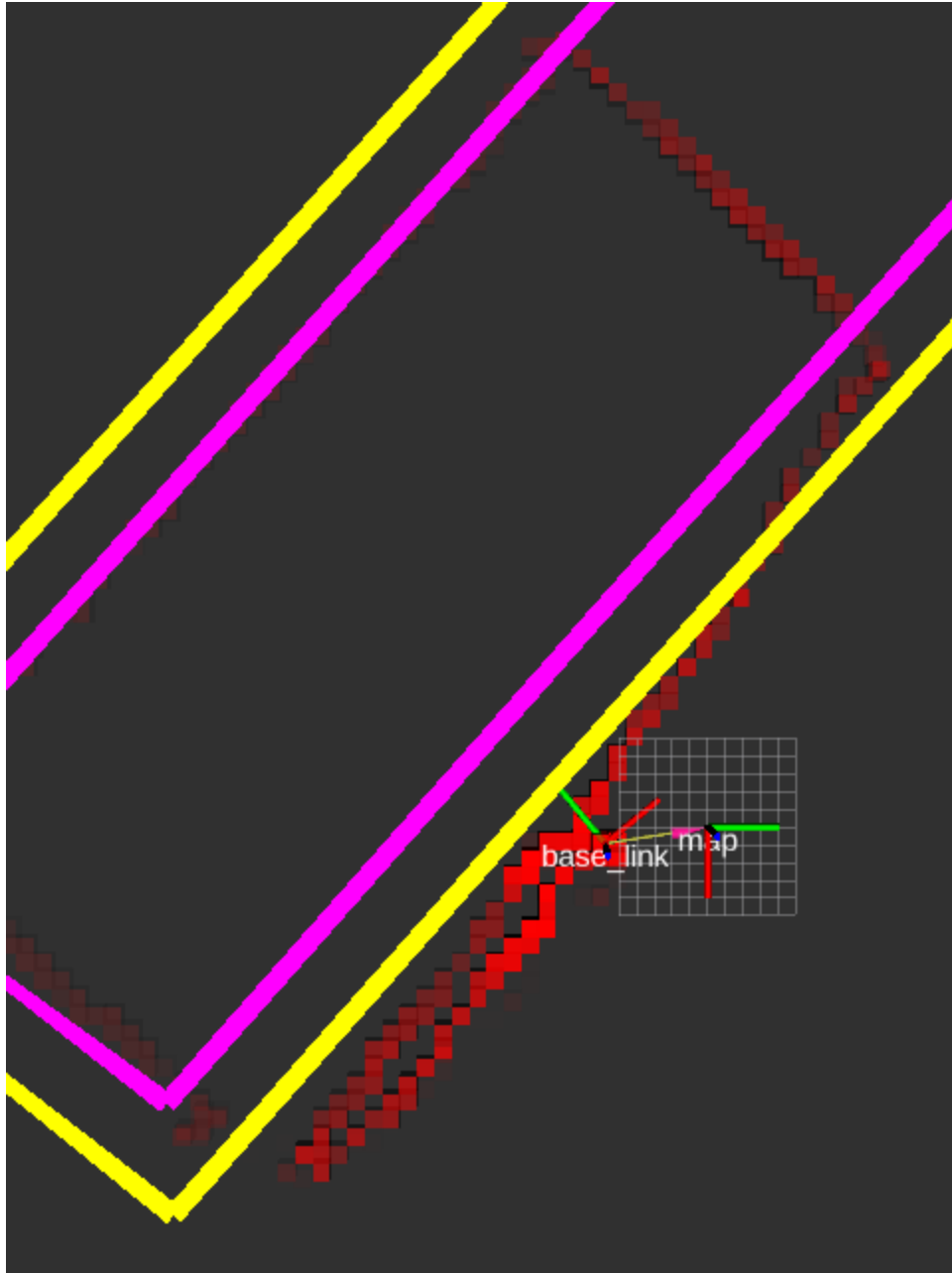


Figure 19 - Drone Cage Ground Test

After the ground test, the aircraft was flown and the optimization was tested. It was initially outside the soft fence, so when the optimization was engaged the drone made a rapid movement to return to the inside of the fence. Since the crew had difficulty determining this was normal behavior the pilot took control of the aircraft and recovered it. This flight did not produce enough data so no figure is shown. This flight showed that the system moved towards the highest RSSI value received, disregarding if the signal originated from the intended ground node. It is suspected this behavior was due to RF noise from other sources that prevented successful optimization. However, the source of the other potential

RF sources was not known so they could not be eliminated. Future work plans to address this issue by measuring only the RSSI of the link between the two nodes rather than the total RSSI from signals in the channel used in this test.

In the next test, to better the RSSI relationship to position, an aerial survey of the entire cage environment. Figure 20 is the visualization produced by the survey where “base_link” indicates the ground node transmitter location. Multiple rows were flown with the aircraft in an automated flight mode to survey the cage.

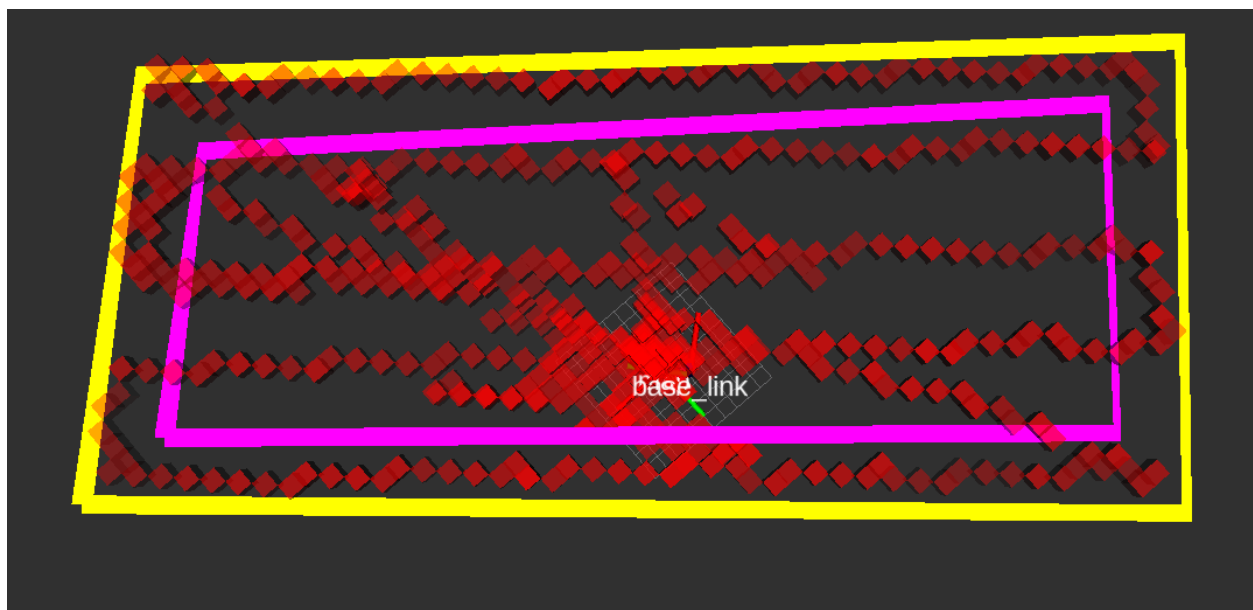


Figure 20 - RSSI Grid Survey

After the survey one more flight was performed where the optimization was enabled. This test uncovered a bug where the soft fence will force the drone to move all the way to one edge of the fence before beginning the normal optimization routine. After the sudden movement across the cage, the Pixhawk geofence was engaged. At this point the pilot was worried that the drone was too close to the fence so he switched to position hold to take over the aircraft. Data from this flight this flight is shown in Figure 21.

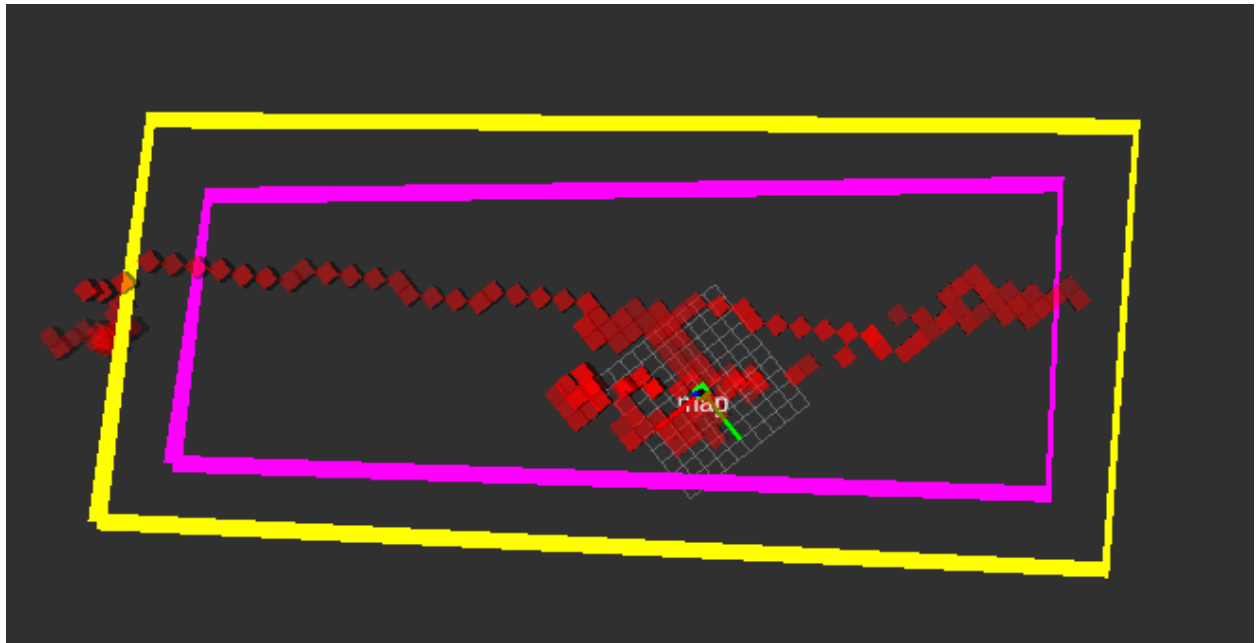


Figure 21 - Soft fence bug flight

Infrastructure and Example Scenarios for SDR-based Multi-UAV, Multiple Ground Station MIMO and SISO Experiments

UAV and Ground Station software defined radio (SDR) Nodes

Components have been purchased for six UAV and three ground station SDR nodes. Examples of each of the key components in these nodes are shown in Fig. 22. The UAVs will carry lightweight SDRs such as the self-contained USRP E312 with embedded processor, with optional NUC single board computer for additional processing capability, and the lightweight USRP B205-mini, which requires a computer such as the NUC to perform signal processing. NUC computers are also used for signal processing at the ground stations, with the USRP N310 multi-channel SDRs. Rugged laptops that have bright screens for outdoor use are used to control the NUC / USRP N310 base stations via Wi-Fi links. Directional antennas extend the ground stations' range of communication with UAVs, and a Thunderbolt 3 to 10 Gbit Ethernet interface allows efficient connection of the USRP N310 SDR to the NUC computer via 10 Gbps Ethernet.

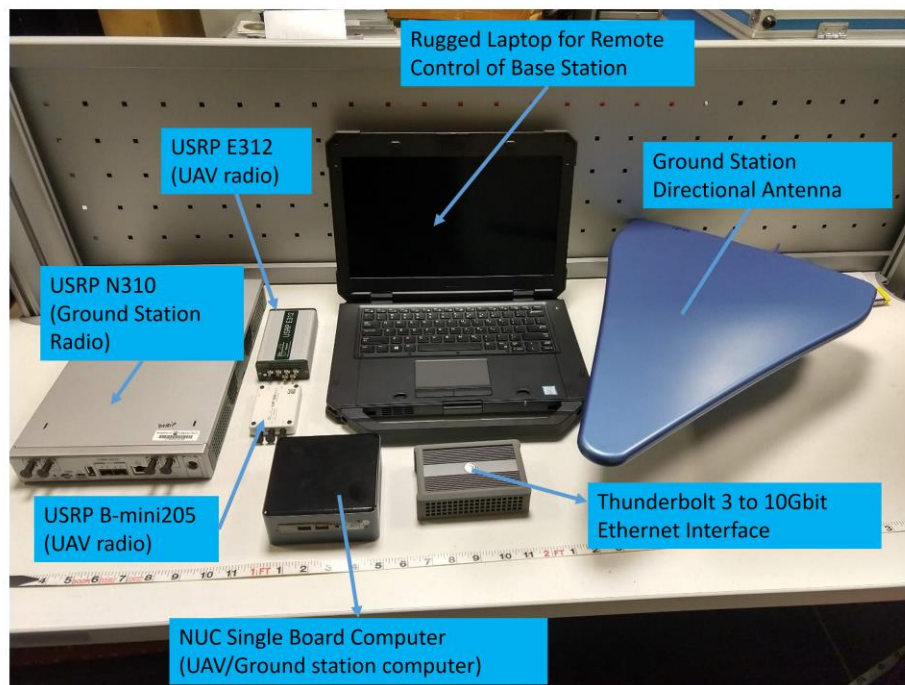


Figure 22. Components for UAS Software Defined Radio (SDR) Experiments

The UAV and ground station nodes will support many possible experimental scenarios. Figs. 23 and 24 below depict some general types of experiments that they will enable. Experiments can include air-to-air and air-to-ground 2x2 MIMO communication as shown in Fig. 23, as well as SISO communication as shown in Fig. 24.

Selected component specifications for the UAV and ground station SDR nodes are as follows:

- Dell Laptop Rugged:
 - Intel i3 7th generation / 8 GB RAM / 128GB SSD / Dual band WiFi /
- NUC:
 - Intel i7 8th generation / Thunderbolt 3 / 16 G RAM / 128 GB SSD / dual band WiFi
- N310:
 - 4x4 MIMO / 100MHz BW / 10-6000MHz / 1 and 10 Gbit Ethernet Interface
- E312:
 - 2x2 MIMO / 56MHz BW / 70-6000MHz / Embedded dual ARM processor / 1 Gb Ethernet and USB interface / embedded rechargeable Lithium battery
- B-mini205:
 - 1x1 / 56MHz BW / 70-6000MHz / USB3 interface
- Base / ground station antenna:
 - Log periodic antenna / 380 – 8000Mhz / about 5dBi gain / with Radome for protection /

NUC is optional. E312
Has a dual core ARM
processor. If intensive
CPU applications are
required NUC may be
added at expense of
reduced flight time

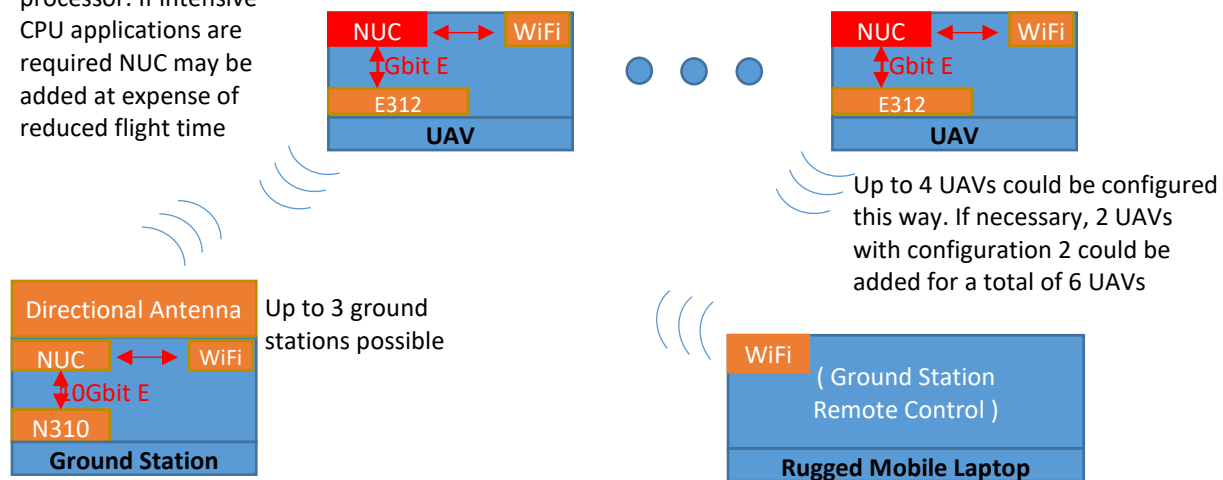


Figure 23. UAV experiment configuration 1: 2x2 MIMO with USRP E312 SDR (UAV nodes) and USRP N310 SDR (ground stations)

NUC is required to interface with radio B-mini205.

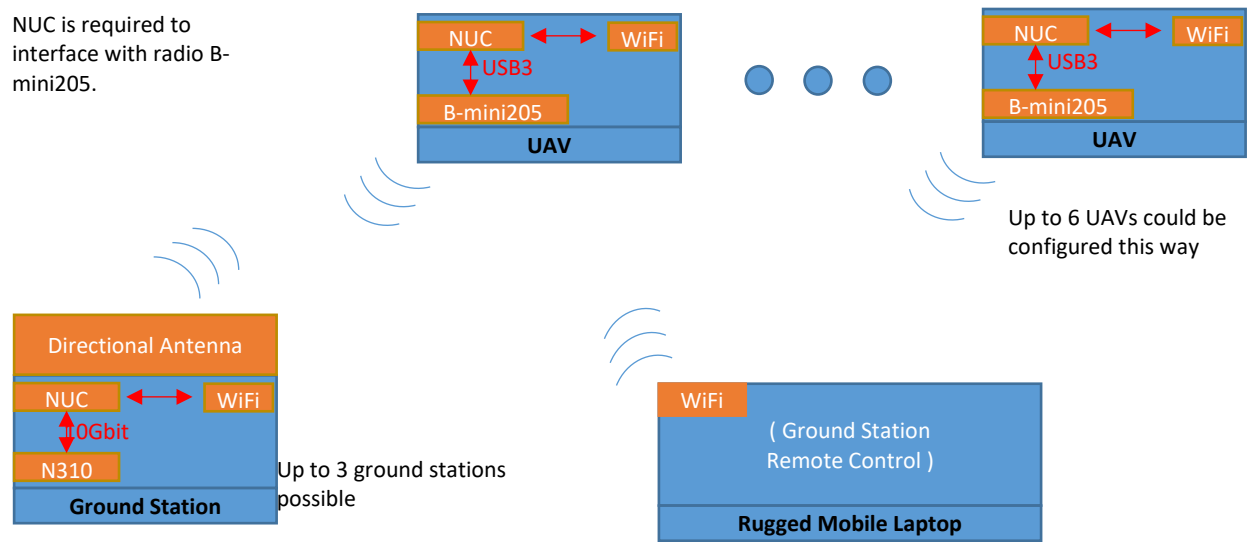


Figure 24. UAV configuration 2: Single Tx / Rx with USRP B205-mini SDR (UAV nodes) and USRP N310 SDR (ground stations)

Conclusion

A test system was constructed and flown that consisted of an Intel NUC and B205 mini USRP, and additional hardware was obtained to enable multi-UAV, multiple ground station SDR-based wireless experiments that involve both SISO and MIMO communication in air-to-air and air-to-ground channels.

In an initial test performed to demonstrate its operation, the initial test system was able to measure the change in RSSI as a function of position and perform gradient-based optimization on the data. The RSSI data was considerably noisy due to short-term variations in the channel which prevented the optimization routine from functioning properly. This was because the method of measurement involved measuring total power within the 10MHz bandwidth. This can be mitigated through establishment of a two-way link in which the radios measure only the power of each other's signal. Secondly, a moving average or low pass filter combined with appropriate sampling rate for the RSSI measurements as well as averaging time or bandwidth could remove short-term variations so that control can be based on longer-term trends in RSSI.

A low-cost solution to measuring RSSI of an established link can use existing radios such as Wi-Fi cards. Some of the remaining budget was used to purchase Raspberry Pi 3 kits and GL-iNet routers with built-in Wi-Fi chips which provide RSSI measurements of their link and can used off the shelf wireless protocols that are already developed. The Raspberry Pi's and GL-iNet routers can be configured with the BATMAN-ADV mesh protocol for testing a multi-node system as originally planned. These are intended to be used to test different optimization strategies while another waveform is developed for the USRP.

An area of improvement for the optimization algorithm that is being considered is using all the data collected to decide the next destination to test for RSSI. Currently, the algorithm as tested, sampled the gradient only at its current location to pick the next flight path direction. Calculating the gradient on all data collected would allow more precisely locating the radio source, the ground node. However, such an approach would make the system less tolerant to changes in the source location over time. As a result, future work should carefully balance these objectives of accuracy versus time variance tolerance.

The initial test has provided a proof-of-concept of system functionality and has provided examples of the types of problems that will be encountered in performing future experiments using the new infrastructure.

Wireless@VT and MAAP personnel including graduate and undergraduate researchers will continue integration and operation of the experimental infrastructure. The PIs will work jointly to recruit graduate and undergraduate researchers through a combination of paid, for-credit, and volunteer opportunities, including NSF REU supplements, independent study / undergraduate research credit, course projects, and will propose one or more Vertically Integrated Projects (VIP) to involve multiple cohorts of undergraduates in self-sustaining long-term research that uses the infrastructure. The PIs will continue to seek new sponsored projects that will use the infrastructure as well as use the infrastructure to enhance ongoing research.

Appendix A Description of Software Classes and Methods

The following describes the structure of the code and how classes and methods were assigned to objects that describe the UAS and optimizer. In this section only "public" methods are included and data members used outside of the class itself.

blocks

valueCube class - the basic unit of the 3d grid. A cube is used to store a finite list of values. Its position and average value are used to generate a marker message to display the block in RViz. We experimented with different ways to display and settled on a standard-size cube with opacity varying by average value.

Important members:

- pose: position and orientation
- values: list of values
- avgValue: average value
- markMsg: visualization marker

Important methods:

- addValue(int): add a value to the cube
- contains(geometry_msgs/Pose): check if the cube contains a point.

Utility (non-class) functions:

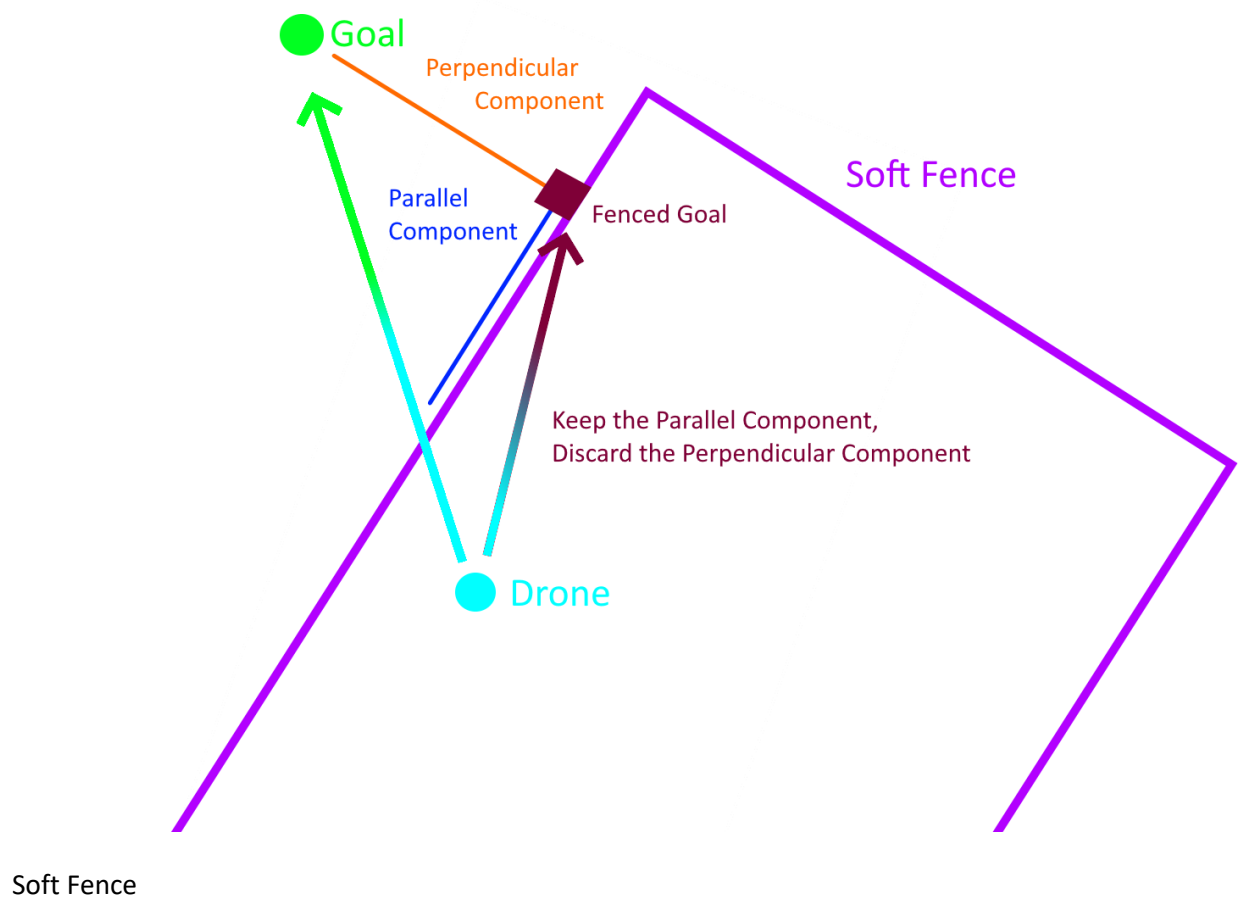
- getDistance(geometry_msgs/Point, geometry_msgs/Point): uses the distance formula to determine the distance between two Points
- getNearest(valueCube[], geometry_msgs/Pose): finds the nearest axis-aligned block in the array

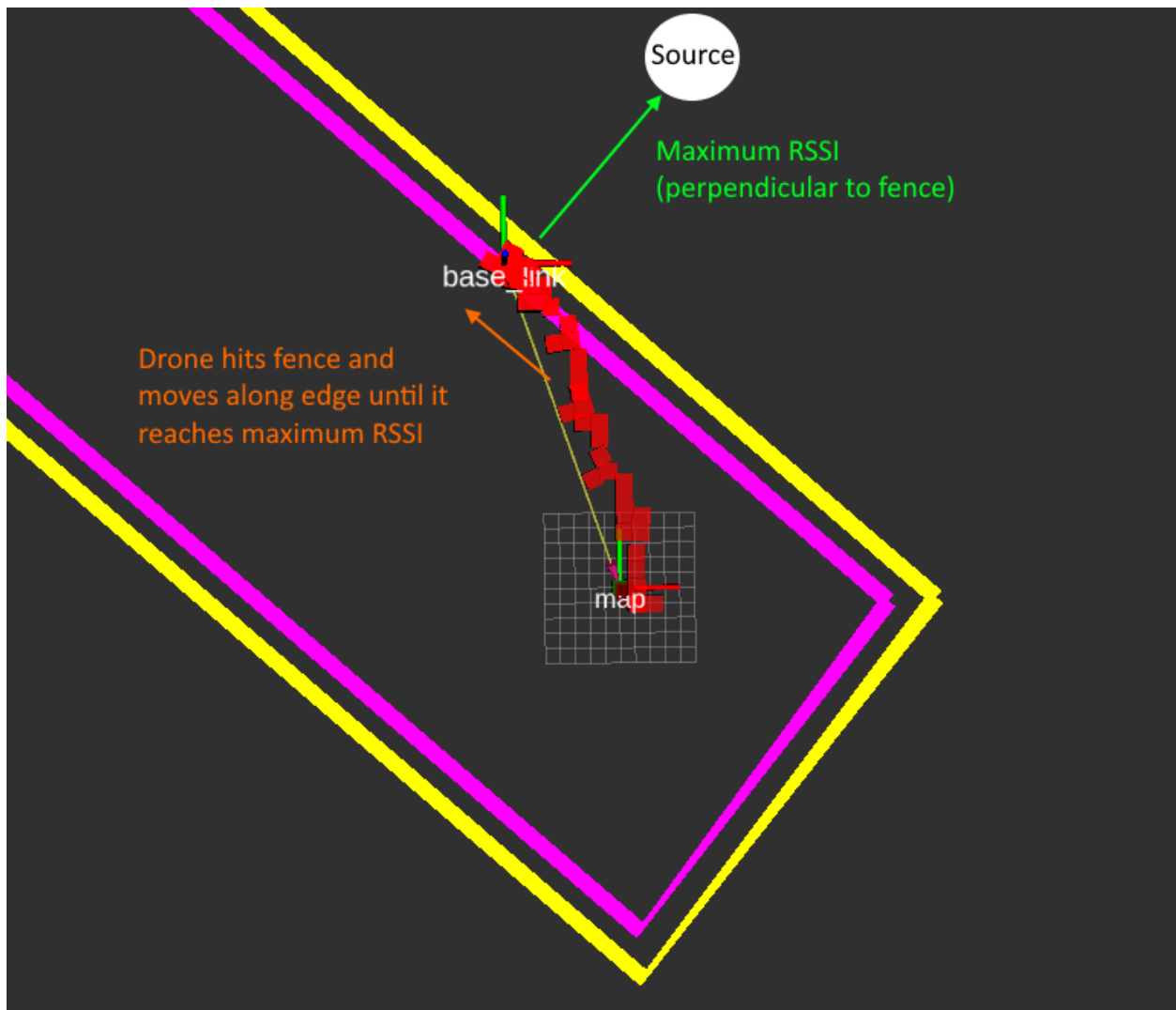
geofence

Fence class - this will read a geofence from a file and do all the necessary conversions for you to ensure that the drone stays within a padded boundary inside the actual "hard" Pixhawk geofence. The "soft fence" figure shows how the fence works. Whenever a point is being added to the waypoint queue, it is checked against the soft fence. The soft fence will clip any segment that causes the point to be outside the boundary. This way the drone ends up as close as possible to the actual goal. It can essentially "slide" up and down the boundary edge while hunting for the highest RSSI.

Important methods:

- check(geometry_msgs/Pose): makes sure a point is within the fence
- display(): displays the geofences in RViz

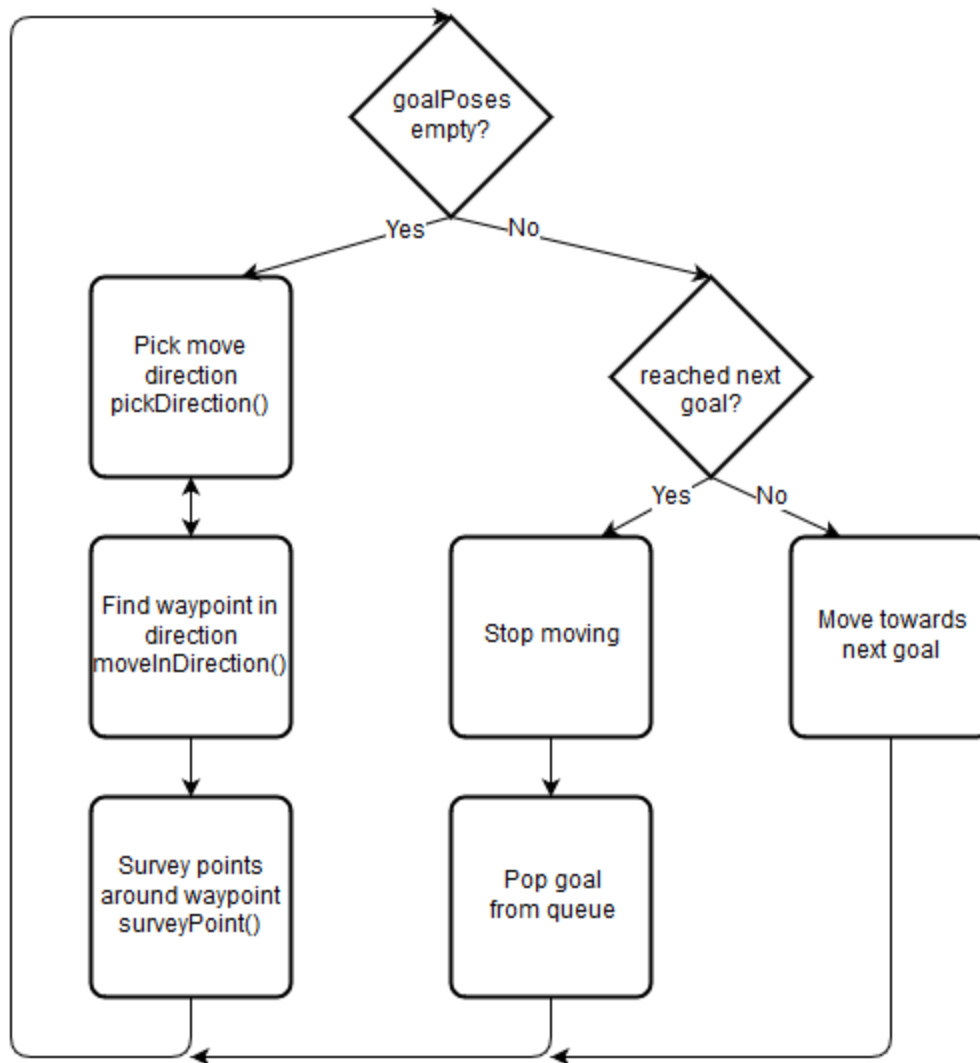




Soft Fence in Simulation

Optimization

This is the main control node. The flowchart shows the algorithm's logic. It uses a position command queue to ensure the Pixhawk is commanded to positions in the order they are generated by the optimizer. The loop waits until the aircraft reaches the commanded location to ensure it is sampling data from the correct location and to slow down the control loop.



Optimization Flowchart

rss

This keeps track of all the RSSI data in the 3D grid

Important members:

- blockArray: list of all valueCubes

rss_dummy_node

provides a model RSSI source for simulation

uav_control

UAV class - interface for mavros.

Members:

- uav_id: numerical ID
- uav_id_name: string UAV name
- base_path: the base path to mavros topics
- localPose: position and orientation of the UAV in local coordinates
- sub_local: subscriber to read local position messages
- ready: boolean - have any local position messages been received?
- localVel: UAV velocity
- sub_vel: subscriber to read velocity messages
- globalPos: position and orientation in global coordinates
- sub_global: subscriber to read global position messages
- pub_local: publisher to send guided waypoints
- seqId: sequence ID (Each waypoint must have unique ID)
- state information:
 - isConnected
 - isArmed
 - isGuided = False
 - mode
 - sysStatus
- sub_state: subscriber to read state messages

Methods:

- isReady(): returns true once we start receiving local position messages
- stateCallback(mavros_msgs/State): read all state information
- localCallback(geometry_msgs/PoseStamped): update the local pose
- globalCallback(sensor_msgs/NavSatFix): update the global position
- velCallback(geometry_msgs/TwistStamped): update the velocity
- setGuidedMode(): put the UAV in Guided mode
- setArm(): arm the UAV
- setDisarm(): disarm the UAV
- setTakeoffMode(): put the UAV in takeoff mode
- setLandMode(): put the UAV in landing mode
- setLocalPos(geometry_msgs/Pose): set the guided waypoint

Appendix B: Planned Research Using the Infrastructure

In addition to the initial tests described in this report, we anticipate that the infrastructure will be used in the following ongoing and planned research projects:

Project Title / Topic	Description	Sponsor (Program)	Status
EARS: Towards Harmonious Coexistence of Heterogeneous Wireless Services	Initial spectrum sharing / spectrum management experiments that involve UAS	National Science Foundation (Enhancing Access to the Radio Spectrum)	Ongoing (ends 09/30/2020)
Vertically Integrated Projects @ Virginia Tech	- Demonstration video for online tutorials on radio frequency spectrum agility and spectrum sharing - Possible multi-year undergraduate research project(s) related to UAS communications and/or security	Office of Naval Research (STEM Education and Workforce)	Ongoing (ends 04/09/2021)
Expeditions: Collaborative Research: An Integrated Framework for Communications and Computing in Extreme Environments	Use of UAS to support communications in challenging environments	National Science Foundation (Expeditions)	Proposed , pending sponsor decision
Remote UAV / UAS Laboratory Capability and University and High-School Level Competitions including Artificial Intelligence / Machine Learning and Communications-Intensive UAV Missions	Student challenge in which participants program UAVs to fly and communicate autonomously	Office of Naval Research (STEM Education and Workforce)	Submission planned for CY 2020
Multi-dimensional radio frequency resource management	Management of the radio spectrum for communications in three-dimensional space	National Science Foundation (CNS Core Programs)	Submission planned for CY 2020
Various software-defined radio related projects	To be determined	Virginia Tech (ECE 5674 Software Radios semester projects and undergraduate research projects)	Planned for CY 2020

Appendix C: Summary of Equipment Purchased

The following equipment items were purchased to support UAS / radio frequency experimentation. Items that cost less than \$2,000 are not considered equipment unless they are considered integral to systems that meet or exceed Virginia Tech's equipment cost threshold of \$2,000.

Item	Description	Intended Use	Supplier	Qty.	Unit Price	Total Cost
USRP E312	Battery-operated SDR (2x2 MIMO, 70MHz-6GHz)	Terrestrial or UAV mounted radios	National Instruments	4	\$3,541.32	\$14,165.28 + shipping
USRP N310	4 Channel SDR (4 ch. 10MHz-6GHz)	Terrestrial radios	National Instruments	3	\$10,800.00	\$32,400
USRP B205 mini-I with enclosure	(1x1, 70 MHz-6GHz)	UAV mounted radios	National Instruments	6	\$982.80	5,896.80
770-0031-000	HID, Wireless Keyboard and Mouse	Interface to NUC single-board computers	Simply Nuc, Inc.	8	\$46.06	\$368.48
421-0002-001	Antenna Kit (Dual Band)	Antennas for NUCs	Simply Nuc, Inc.	6	\$35.72	\$214.32
910-ZC10-041	Nuc 8s Single-board computer (i7, 16GB Mem, 128GB SATA SSD)	SDR processing (UAV mounted and / or terrestrial)	Simply Nuc, Inc.	8	\$878.85	\$7,030.82
802-0003-013	Warranty service, NUC extended 3-year	Warranty	Simply Nuc, Inc.	8	\$46.06	\$368.48
AKT3TGAA0008Y	AKITiO T3-10G Network Adapter Thunderbolt 3-10GbE	Interfacing Nuc computers with USRP X310s using 10 Gb Ethernet	Other World Computing	5	\$178.99	\$894.95
OWCCAT614BLU	4.2 m Ethernet Cat 6 patch cable	Interfacing Nuc computers with USRP X310s using 10 Gb Ethernet	Other World Computing	5	\$1.24	\$6.20
HX4-06058	Here+ V2 Rover	Enhanced GPS for UAVs	IR-LOCK, LLC	6	\$275.00	\$1,650.00
HX4-06019	Here+ base (M8P)	Enhanced GPS for ground stations	IR-LOCK, LLC	3	\$330.00	\$990.00
HX4-06001	Pixhawk2.1 Standard Set	Flight controller for UAVs	IR-LOCK, LLC	6	\$238.00	\$1,428.00

Item	Description	Intended Use	Supplier	Qty.	Unit Price	Total Cost
180A-X8	Airbot Power Distribution Board	Power distribution for peripherals / payloads on UAVs	IR-LOCK, LLC	6	\$25.00	\$150.00
TA-35C-6000-6S1P-XT60	22.2V 6S 6000mah Lipo Battery Pack with XT60 Plug	Power for UAV and payloads	Adorama	9	\$129.99	\$1,169.91
TA3566S1PXT6	6000mAh 22.2V 35C tS1P LiPo Battery Pack with XT60 Plug	Power for UAV and payloads	Adorama	9	\$129.99	\$1,169.91
TL3D01	Tarot T4-3D 3-Axis FPV Brushless Camera Gimbal	Mount for UAV Cameras and / or antennas	Amazon.com	6	\$169.98	\$1,019.88
B3R993959B	3 m straight "SMA" male to straight "SMA" male	Cable to connect radio hardware	Surplus Sales of Nebraska	12	\$15.00	\$180.00
LOG3080	Aaronia HyperLOG 3080	Ultra wideband log periodic antennas (up to 8 GHz) for use at ground station	www.tequipment.net	3	\$1,452.25	\$4,356.75
Cable	10-m SMA Cable	Cable for antennas	www.tequipment.net	3	\$161.33	\$483.99
1510	Protector Carry-On Case	Case for portable equipment	Amazon	5	\$189.95	\$949.75
XY3F1ASXUSK	XYZprinting da Vinci 1.0 Pro 3-in-1 3D Printer	For printing mounting brackets and replacement parts as needed	B&H Foto & Electronics Corp.	1	\$799.99	\$799.99
XYRFPLXS00C	XYZprinting 1.75mm PLA Filament Cartridge (600g, Clear Yellow)	Cartridge for 3D printer	B&H Foto & Electronics Corp.	1	\$22.95	\$22.95
XYRFPLBS01D	XYZprinting 1.75mm PLA Refill Filament	Filament refills for 3D printer	B&H Foto & Electronics Corp.	5	\$22.95	\$114.75

Item	Description	Intended Use	Supplier	Qty.	Unit Price	Total Cost
TAROT680PRO	Frame-Tarot 680 Pro hexacopter	UAV frame with rotor arms and landing gear	Helipal.com	6	\$180.00	\$1,080.00
1355	Props Carbon Fiber 13x5.5	Propellers / rotors	Helipal.com	18	\$24.00	\$432.00
Matek	Matek 4A 5V-12V and 4A 5V DC DC Converter	Power converter to power payloads	Helipal.com	6	\$17.00	\$102.00
KDEXF-UAS20LV	20A+ Electronic Speed Controller	Speed controller for UAV motors	KDE Direct	36	\$40.95	\$1,474.20
Motor-4006 380kV	UAV Motor – 4006 380kV	UAV motors	T-motor	9	\$150.00	\$1,350.00
4006 380kV	Motor – 4006 380kV	UAV motors	FOXTECH	9	\$150.00	\$1,350.00
YeecoSupply	150W 8A DC-DC Step Up Converter Board 8-32V 12V 24V to 9-46V 36V Voltage Regulator	to power some of the electronics mounted on the UAV	Amazon.com	6	\$11.69	\$70.14
FrSky 1356	FrSky X8R 16ch Receiver, SBUS, Smart Port – Amplified PCB Antenna	Remote control of UAVs	www.getfpv.com	6	Purchased using separate VT funds \$33.99	Purchased using separate VT funds \$203.94
FrSky 4139	FrSky 2000mAh 7.2v NiMH Battery for Taranis X9D	Remote control of UAVs	www.getfpv.com	6	\$24.99	\$149.94
FrSky	FrSky Taranis X9D Plus 2.4GHz ACCST Radio (Mode 2)	Remote control of UAVs	www.getfpv.com	6	\$194.99	\$1,169.94
9387000100-0	Holybro Telemetry Radio V3 (100mW) (915 MHz)	Remote control of UAVs	www.hobbyking.com	6	\$39.00	\$234.00
9466000004-0	Turnigy Raktor 250W 10A 1-6S	Power for UAVs / UAV electronics	www.hobbyking.com	3	\$50.00	\$150.00

Item	Description	Intended Use	Supplier	Qty.	Unit Price	Total Cost
	Balance Charger					
387000052-0	HKPilot Mega 10s Power Module With XT60 Connectors	Power for UAVs / UAV electronics	www.hobbyking.com	6	\$22.57	\$135.42
PCB004	HobbyKing Parallel charging Board for 6 packs 26S (XT-60)	Power for UAVs / UAV electronics	www.hobbyking.com	3	\$11.14	\$33.42
1923-1563-ND	Crystal Oscillator Atomic 10MHz Sine Wave	Rubidium oscillators to synchronize radios	Digi-Key	2	\$1,874.00	\$
	Crystal Oscillator Atomic 10MHz Sine Wave	Rubidium oscillators to synchronize radios	Mouser	2	\$	\$
Yotenko SMA	SMA Adapter SMA Male to RP SMA Female Jack Connector RF Coax Cable Couple Converter Pack of 2	Adaptors to connect cables to radios	Amazon.com	15	\$5.27	\$79.05
VBFZ-6260+	Connectorized Band Pass Filter, 5600-7000	Interference rejection / reduction	Mini Circuits	12	\$39.45	\$473.40
VBFZ-4000+	Connectorized Band Pass Filter, 3500-4500	Interference rejection / reduction	Mini Circuits	12	\$39.45	\$473.40
VBFZ-2575+	Connectorized Band Pass Filter, 2350-2800	Interference rejection / reduction	Mini Circuits	12	\$39.45	\$473.40
VBFZ-925-S+	Connectorized Band Pass Filter, 800-1050	Interference rejection / reduction	Mini Circuits	12	\$39.45	\$473.40