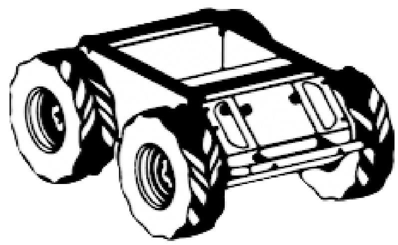
Heterogeneous Multi-Robot Sampling
Conceptual Design Review

Team G: SAMP



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Abstract

Current existing temperature modeling techniques usually meet the trade-off between poor accuracy and tremendous manual work with limited coverage. This project aims to deliver a heterogeneous multi-robot system (UAV-UGV) that performs online temperature sampling and modeling collaboratively given an outdoor area with different terrains. The cooperation of ground and aerial robots provide better mobility and coverage to improve the efficiency of sampling. The entire system consists of three major subsystems, a master computer, one UAV and one UGV. The master computer computes the temperature distribution model over the required region as well as commands UGV and UAV to collect temperature measurements at desired locations. The UGV and UVG autonomously navigate to target location per master computer's request and report the temperature measurements back to the master computer. In the spring semester, we have finished the major parts of all three subsystems. In SVD, our system has demonstrated good navigation accuracy for both the UAV and UGV, together with great convergence and generality of the informative sampling algorithm. SVD has also revealed a few limitations and aspects to be improved in the system. In the fall, we will start by solving the temperature sensor convergence problem, and then focus on integrating the three subsystems and implementing obstacle avoidance.

Contents

1. Project Descriptions

Current existing temperature modeling techniques usually meet the trade-off between poor accuracy and tremendous manual work with limited coverage [1]. Conventional modeling is conducted in a manual way with discretized and limited coverage, which may not provide enough information and require tremendous manpower, especially for large areas. However, sensing from a satellite can cover a wide range of area but with poor accuracy. Robotic automation could improve this situation by providing a more efficient and automated solution with an accurate and continuous map and comparable accuracy. The cooperation of ground and aerial robots could provide better mobility and coverage to improve the efficiency of sampling.

This project aims to deliver a heterogeneous multi-robot system (UAV-UGV) that performs online temperature sampling and modeling collaboratively given an outdoor area with different terrains. The cooperation of the two robots will enable them to overcome their physical constraints. For example, the UAV can cover unaccessible aerial areas for UGV. The UGV can produce precise detections in the informative area and can lengthen the working duration. The system will generate a distribution map of the temperature information across a self-defined region of interest to assist environmental scientists monitoring the environmental thermal activities.

2. Use case

Environmental Scientist at Yellowstone national park, Tom, wants to study Yellowstone's thermal activities. As part of his study, he needs to track the temperature across a region. It is not feasible for him to go out and collect data for modeling every day, and he cannot directly use satellite-based thermal infrared remote sensing data as the resolution is way below expectation. So he decides to use SAMP system, and start to work on SAMP master computer.

Tom first loads an existing map that includes all the geometry information indicating where the obstacles are. He then specifies the region he wants to track the temperatures on the map, as shown in Figure 1, the region of interest is bounded with a red bounding box. SAMP automatically deploys one UGV and one UAV to execute the temperature modeling task.

SAMP system divides the area of interest into UGV's area and UAV's area based on the geometry information and robots' capabilities. The modeling system then initializes a distribution map and generates two initial sampling locations for UGV and UAV to collect temperature samples respectively.

After receiving an initial target location, UGV and UAV start to automatically navigate to the target location without hitting obstacles. After reaching the target locations, robots take temperature measurements and send back to the master computer modeling system. modeling system reads the samples and uses them to update the temperature model. Based on the updated model, the system then selects the most informative positions as the new target locations and assign to UAV and UGV respectively. UAV and UGV then go to the next target locations to take samples and further update the model.

This online sampling process is conducted iteratively until the temperature model converges. During the sampling, if the UGV meets an unreachable area like hot spring or cliff, the system remarks that location as an interest point for the UAV. In addition, if a robot fails to navigate to the assigned target location within the time limit, a new target position will be sent to the robot. If the robot gets stuck during the navigation, a recovery behavior will first conduct, but if it does not help, then the new target location will be sent. If the robot fails to move to the new target location, then returning to starting point command will be executed. If the robot fails to move back to the starting point, Tom needs to retrieve the stuck robot manually based on the localization information.

After successfully finishing the sampling task, UAV and UGV will navigate back to the starting point, and the modeling system output the final distribution model that can be used for Tom's thermal activity study.

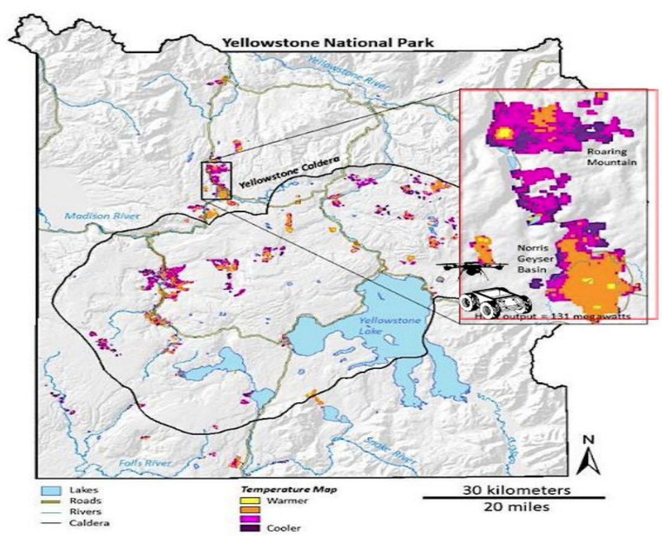


Figure 1. Yellowstone National park map with thermal information indicated in different colors. The selected interest region is shown in the red bounding box. A UAV and a UGV are deployed in the region of interest to take samples for generating the temperature distribution model.

3. System-level Requirements

3.1. Mandatory Requirements

3.1.1. Performance Requirements

Table 1. System-level Mandatory Performance Requirements

ID	Requirement	Description
M.P.1	The system will generate a temperature model for an area within the dimension of 20m×20m×5m.	A demo covering nontrivial scale is expected.
M.P.2	The **<u>RMS error</u>** of the temperature distribution model shall be within **<u>3 °C</u>**	The temperature distribution model is expected to be close to the ground truth temperature distribution. **This requirement has been changed to make the calculation of model accuracy more specific.**
M.P.3	Each selected interest point will reduce local uncertainty by at least 3%.	The selected interesting point is expected to be efficient and meaningful for the model update.
M.P.4	The system will collect temperature sample with an absolute error no larger than 2°C.	The temperature sensors are expected to provide accurate measurements for distribution modeling.
M.P.5	The system will update the model after receiving **<u>every 10 sample</u>**.	The system is expected to conduct an efficient model updating. **This requirement has been changed to make the model update step more efficient by using a small batch of data.**
M.P.6	Both UAV and UGV will reach and take temperature samples at the assigned locations with a success rate greater than 80%.	Many influences including navigation error, control error, etc. could cause sampling task to fail. Both UAV and UGV are expected a nontrivial chance to finish the sampling task.
M.P.7	Both UAV and UGV will achieve localization accuracy greater than 2m.	The UAV and UGV are expected to take measures close to the desired location.
M.P.8	Both UAV and UGV will plan the obstacle-free trajectory through randomly-deployed obstacles. The quantities and dimensions of obstacles are listed in Table 14.	The UAV and UGV are expected to avoid reasonably sized pieces of obstacles without human maneuver.
M.P.9	The system will last at least 15 minutes for each deployment.	The system is expected to avoid frequent recharging.

3.1.2. Non-Functional Requirements

Table 2. System-level Mandatory Non-Functional Requirements

ID	Requirement	Description
M.N.1	Both UAV and UGV will have no sharp edges.	Safety consideration 1.
M.N.2	UAV has drone blade guards.	Safety consideration 2.
M.N.3	Both UAV and UGV will have emergency stop mechanism.	Safety consideration 3.
M.N.4	Both UAV and UGV will maintain a low noise level.	Environmental consideration 1.
M.N.5	Both UAV and UGV will cause no damage to the operating environment.	Environmental consideration 2.
M.N.6	The system will be able to scale up to multiple heterogeneous robots.	Extensibility consideration for deployment in various environments.
M.N.7	The system will cost no more than 5000 dollars.	The sponsor can provide no more than 5000 dollars.

3.2. Desirable Requirements

3.2.1. Performance Requirements

Table 3. System-level Desirable Performance Requirements

ID	Requirement	Description
D.P.1	The system will generate a temperature model for an area with the dimension of 20m×20m×5m within 20 minutes.	The system is expected to operate efficiently, while there is no guarantee on the complexity of the environment.
D.P.2	The UGV will travel at an average speed of 3 mph.	The UGV is expected to move efficiently, while complex terrain could slow down its movement.
D.P.3	The UAV will travel at an average speed of 8 mph.	The UAV is expected to move efficiently, while weather condition could slow down its movement.

D.P.4	The UGV and UAV will have less than 2m×2m×1m overlapping in sampling coverage.	The UAV and UGV collaborative sampling is expected to have few overlapping, why it could be constrained by terrain’s geometry.

3.2.2. Non-functional Requirements

Table 4. System-level Desirable Non-functional Requirements

ID	Requirement	Description
D.N.1	The system will operate efficiently in different kinds of weather.	The system will operate robustly under different conditions for real scientific use.
D.N.2	The system will provide a user-friendly interface for interest area selection.	Users without coding experience will be able to operate the system easily.
D.N.3	The combined weight of UAV and UGV should be no more than 50kg.	The system will not be too heavy to be portable.

4. Functional Architecture

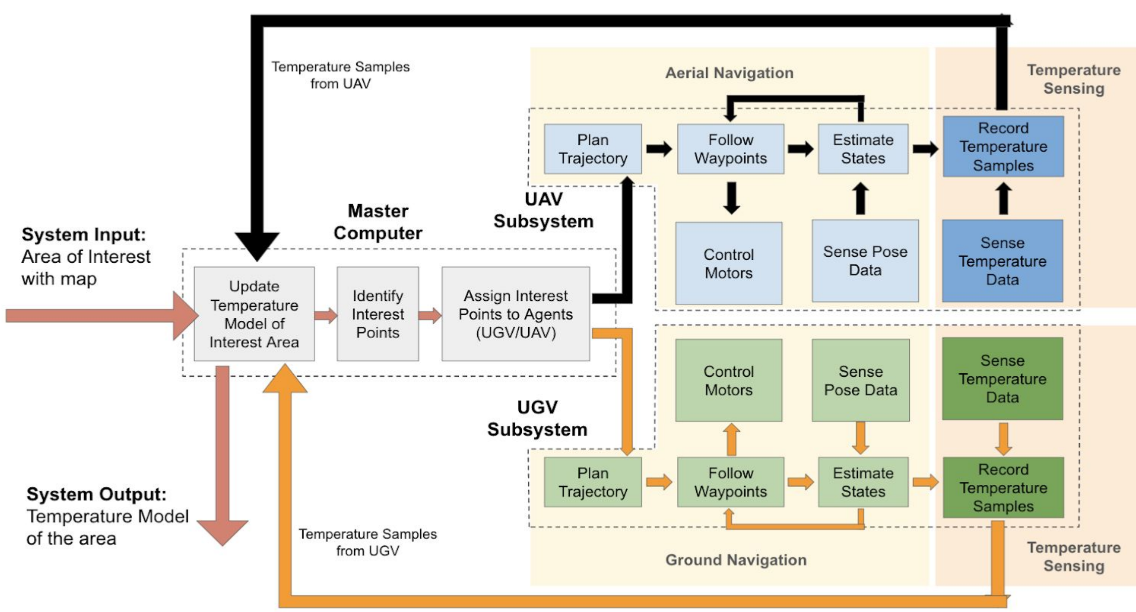


Figure 2. Functional architecture of the sampling project

Figure 2 shows the detailed functional architecture. The user should specify an area of interest and provide the corresponding geometric map for the system, and expect a temperature distribution model of this area from the system.

The entire system is composed of three subsystems: (i) a Master Computer that maintains and updates the temperature distribution model, as well as decides the next sample location for every individual agent based on their capabilities, (ii) an Unmanned Aerial Vehicle (UAV) subsystem consisting of one or multiple aerial robots, and (iii) an Unmanned Ground Vehicle(UGV) subsystem composed by one or multiple ground robots.

The master computer serves as a core mechanism for both receiving system input and generating system output. It reads in and stores the area of interest together with the geometric map. Given the geometric map, the master computer initializes a global temperature distribution model that is to be updated in realtime after receiving each sample from UAV/UGV subsystem. From the current distribution model, it identifies the next location to take samples from that would lead to the most improvement on the model, which we refer as an “interest point”. The master computer then allocates interest points to agents considering the different capabilities physical limitations of aerial and ground robots.

The UAV subsystem encompasses two major functional blocks: aerial navigation and temperature sensing. It receives the allocated interest point from the master computer and plans the trajectory on-board to navigate to the desired location. During navigation, the agent continuously estimates its state by comparing the current pose data with the desired pose. Once the agent believes it has arrived the allocated interest point, it measures the temperature at this location, and forward the temperature sample (temperature data together with the corresponding location on the geometric map) to the master computer.

The UGV subsystem has a similar functional structure as UAV with two main functional blocks, which are ground navigation and temperature sensing. The UGV subsystem contains the same functional sub-blocks as in UAV subsystem that receives and navigate to the allocated interest point, record temperature samples at the designated location and forwards to the master computer. Although these blocks are the same on the functional level, they differ cyber-physically (see Section 6).

One model update iteration finishes after the master computer receives desired samples from UAV/UGV subsystems and updates the current temperature distribution. When the temperature distribution model converges, the master computer outputs the model as the output of the entire system.

5. Cyberphysical Architecture

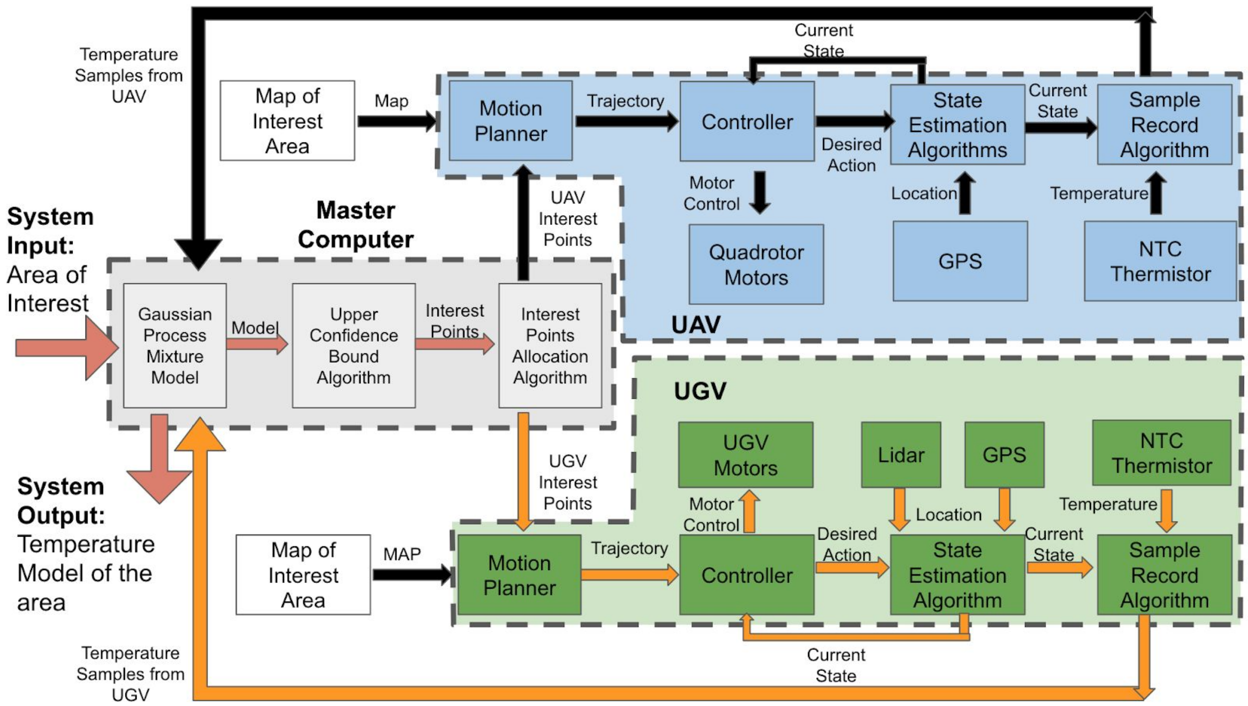


Figure 3. Cyberphysical Architecture and Information Flow

Figure 3 Shows the detailed hardware and software components of the system as well as the information flow between them. The system cyberphysical architecture can be divided into three major blocks: Master Computer, UAV Subsystem, and UGV subsystem.

5.1. Master Computer

The master computer plays roles as a central processor and commander of the system. The main function of the master computer is the following:

- **Generate a temperature distribution model.** The master computer applies Gaussian Process Mixture Model to generate the temperature model distribution based on samples since this model is widely used in modeling unknown utility distribution.

- **Identify interest points.** After the temperature model is updated, the master computer will use the upper confidence bound algorithm to identify the next interest point for the UAV and UGV to do sampling. The interest point located at the position whose temperature will provide maximal information to the system, which will improve the model accuracy at most.

- **Assign interest points to agents.** The master computer will use interest points allocation algorithm to assign the interest points. This algorithm considers the feature of UAV & UGV, which achieves the collaboration between them.

5.2. UAV and UGV Subsystems

The UAV and UGV subsystems include two major functions: aerial navigation and temperature sensing. The information of map and sampling spots is already stored in the UAV and UGV before the deployment. After receiving the interest point from the master computer, the UAV and UGV will use motion planner to do local path planning. Then, the UAV and UGV will process the navigation control loop including the motion controller, quadrotor motors, state estimation algorithms, and GPS sensors. The motion controller will use the state data as feedback and send commands to motors to control the movement. The state estimate algorithms will gather the location data from the GPS sensors (and LiDAR sensors for UGV). After the UAV and UGV arrive at the interest point, they will gather the temperature data from NTC Thermistor sensor and send the sample data back to the master computer.

6. Current system status

6.1. Spring-Semester Targeted System Requirements

Table 5. Spring-Semester Targeted System Requirements

ID	Requirement
M.P.1	Master Computer can generate a temperature distribution model for an area of interest within the dimension 20m x 20m x 5m.
M.P.2	The RMS error of the temperature distribution model shall be within 1 °C compared to the ground truth.
M.P.3	Master Computer shall self-select an informative point that reduces local variance by at least 3% at each time.
M.P.4	UAV/UGV shall collect temperature sample with error within +/- 2 °C.
M.P.5	Master Computer shall update the model after receiving every 10 samples.
M.P.6	UAV/UGV shall navigate autonomously in the area with a success rate greater than 80% (no obstacle, as we are not concern about obstacles in the spring semester).
M.P.7	UAV/UGV shall achieve navigation accuracy better than +/- 2 m.

6.2. Current System and Subsystem Descriptions

6.2.1. Overall System Depiction

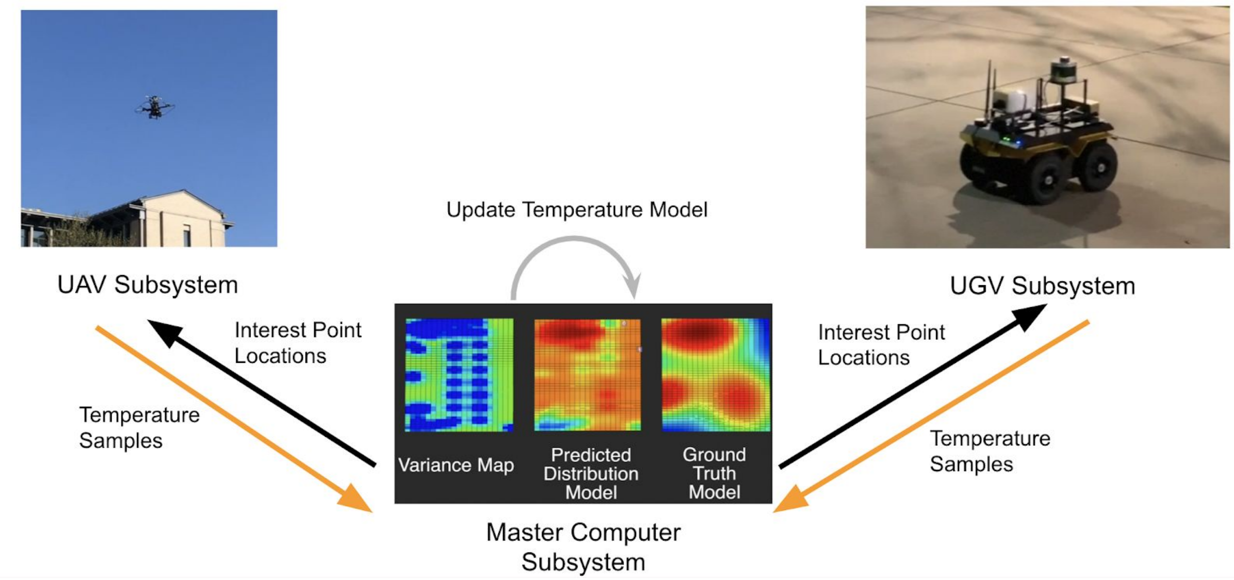


Figure 4. Heterogeneous Multi-Robot Sampling system depiction

The entire system consists of three major subsystems, a master computer, one UAV and one UGV. The master computer computes the temperature distribution model over the required region as well as commands UGV and UAV to collect temperature measurements at desired locations. The UGV and UVG autonomously navigate to target location per master computer's request and report the temperature measurements back to the master computer.

6.2.2. Master Computer

- **Temperature Model**

  Given multiple temperature samples at different discrete localizations, the master computer manages to provide a continuous distribution model for the temperature within the required area.

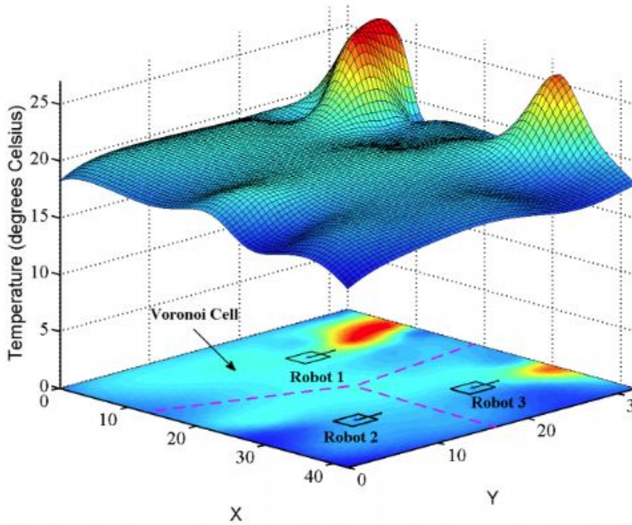


Figure 5. Example Temperature Gaussian Mixture Model [12]

Per the sponsor's requirement, the specific model is selected to be the Mixture of Gaussian Mixture Models [10]. A typical example is shown in Figure 5. It demonstrates a good generalization of environmental modeling, especially for temperature modeling. One assumption is made that every single robot is carrying one Gaussian Process, which means the Gaussian Process mixture model for our system consists of two single Gaussian Processes. We apply Expectation and Maximization algorithm to find the weights for every single Gaussian Process to give a most accurate Gaussian Process mixture model.

- **Interest Point Identification Algorithm**

  Current temperature model needs updating until converge. The next points at which the master computer wants the robots to take temperature are determined by interest point identification algorithm. The master computer selects the point with the highest variance/uncertainty as to the next interest point requiring temperature measurement. This interest point selection strategy will greedily improve the accuracy of the temperature model prediction.

- **Interest Point Allocation Algorithm**

  After the interest points are selected, the master computer would assign those points to specific robots by interest point allocation algorithm. The major considerations are under the robot's mobility. For example, the master computer would assign the interest point above a ground obstacle to UAV considering the limitation of UGV's mobility. The second consideration is the measurement efficiency. The master computer would assign the next interest point to the robot having a quicker arrival time.

- **Current Status**

  The master computer is able to simulate the execution of the entire system. The simulation is done by ROS and Gazebo. The simulation system consists of temperature model simulation and physical robot simulation. The master computer simulates the procedure of temperature Gaussian Process mixture model update and prediction, interest point allocation as well as the robot's movement to collect temperature measurements. For the simulation, once the robot reaches its target location, its temperature measurement would directly be fed with the ground truth reading from the dataset. When the average variance over the entire map is smaller than 1 ℃, the master computer would stop the simulation and then output the final temperature distribution model. As shown in Figure 6, the left plot indicates the overall temperature variance, the middle one is the temperature prediction and the right one is the ground truth temperature distribution.

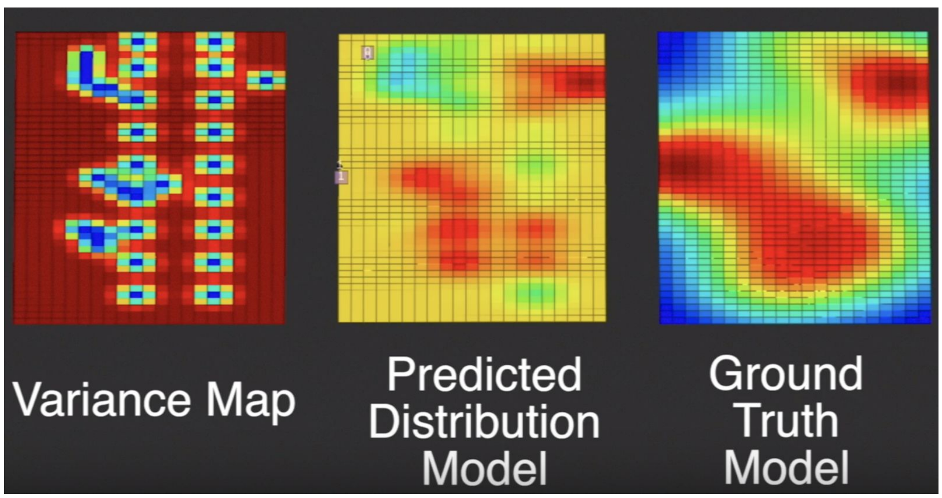


Figure 6. Master Computer Simulation

6.2.3. UGV Subsystem Description

- **Hardware**

  We are using Jackal UGV for the ground agent in the UGV subsystem throughout the project. Jackal is a fully integrated, lightweight and compact outdoor robot which provides a flexible platform for integrating sensors and utilizing its ROS API [1]. The machine is equipped with an Intel i5 onboard computer together with GPS and allows wireless connectivity via both Bluetooth and wifi [2]. It has an IP62 weatherproof casing and is rated to operate from -20 Celsius or +45 Celsius [2].

Additional to a Bumblebee stereo camera, a Velodyne VLP-16 LiDAR is also available onboard. According to the specification provided by Clearpath Robotics [2], the machine can handle a payload up to 20kg and with standard loads, the duration lasts for 4 hours.

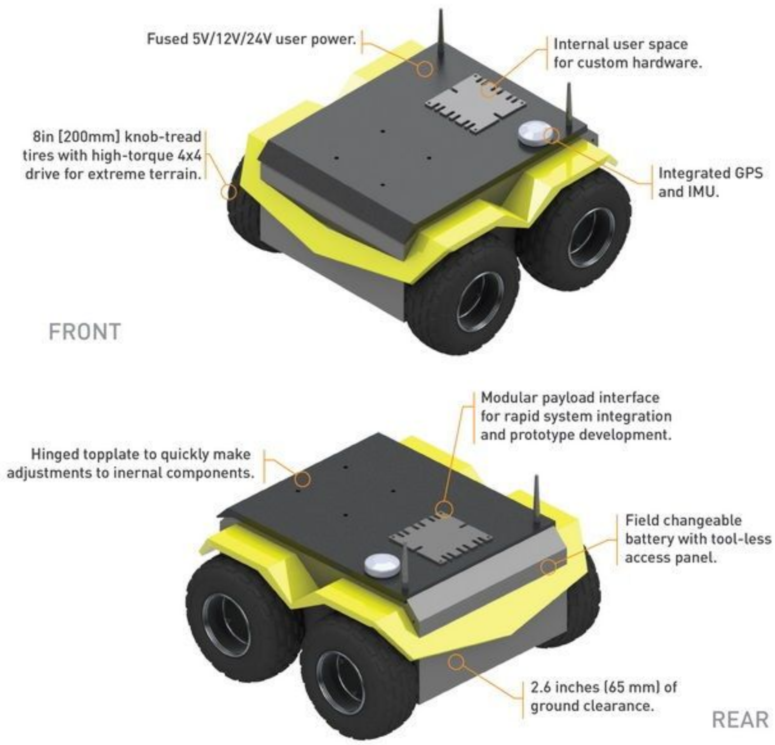


Figure 7. Jackal UGV [1]

Additionally, we also installed a Negative Temperature Coefficient (NTC) sensors on the UGV agent. An NTC thermistor is a thermally sensitive resistor whose resistance exhibits a large, precise and predictable decrease as the core temperature of the resistor increases over the operating temperature range [5]. One desired feature of NTC sensors is that they experience a large change in resistance per Celsius, hence they have a much steeper resistance-temperature slope compared to other sensors (platinum alloy RTDs in Figure 10).

Figure 8. Bumblebee stereo camera [4]

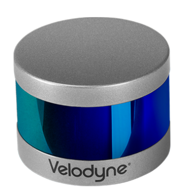


Figure 9. Velodyne VLP-16 LiDAR [3]

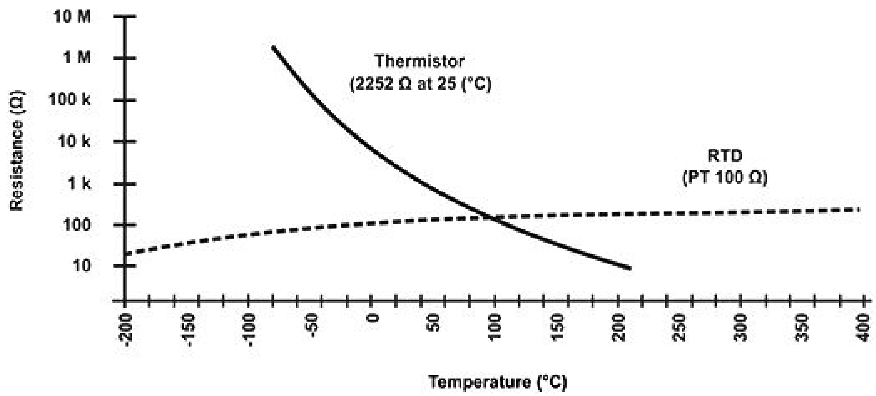


Figure 10. Thermistor performance characteristics [5]

The operating range of NTC spans from −55 °C to +200 °C, and the values of temperature sensitivities of NTC usually range from -3% to -6% per °C, depending on the specifics of the production process and the material used [5]. Considering our application, we plan to use glass encapsulated NTC thermistors. Encapsulating the thermistor in glass provide long-term stability and reliability for high-accuracy temperature sensing, as well as protecting the sensor during operation [5, 6].

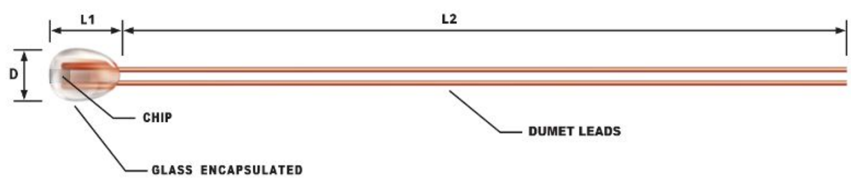


Figure 11. NTC Thermistor[7]

- **Software**

UGV’s Motion Planner receives the allocated interest point from the Master Computer. This interest point is then mapped into the task space and assigned as the target location. The Motion Planner then generates an obstacle-free trajectory from the current location to the target. We are currently using A* algorithm to make sure planned trajectories’ optimalities are guaranteed.

We are using a PID controller to control the UGV motors and command the ground vehicle to follow the waypoints generated by the Motion Planner. During the process of navigation, the Extended Kalman Filter fuses encoder, IMU and GPS signals to improve localization accuracy. Once the agent arrives at the target sample location, it stops and measures the current temperature by interpreting the voltage on the NTC thermistor to temperature values. The temperature measurement is then forwarded to the Mater Computer.

- **Current status**

The measured motion planning, motion control, waypoint navigation, localization, temperature measurement algorithms are all implemented in ROS. To improve localization accuracy, we integrated an RTK GPS to Jackal instead of using its built-in GPS sensor and we establish a transformation between the RTK GPS frame of coordination and Jackal's move_base frame, Odometry frame, so as to realize GPS waypoint navigation. Per spring validation test requirements, Jackal is able to achieve the navigation accuracy of +/- 0.3 and a temperature measurement accuracy of +/- 1.3 ℃. Its maximum speed can reach 8 m/s and its operation duration can last 3 hours.

6.2.4. UAV Subsystem Description

- **Hardware Platform**

We are using Intel AscTec Pelican UAV as the platform for the UAV subsystem. This platform contains an onboard computer with Intel® Core™ i7 processor. The quadrocopter offers plenty of space and various interfaces for individual components and payloads.[6] The LLP(Low-Level Processor) is the data controller, processes all sensor data and performs the data fusion of all relevant information with an update rate of 1 kHz. There is an onboard Hokuyo Laser Scanner with up to 30m range. The platform support varies of wireless communication links including Wifi and XBee (wireless serial).

Figure 12. AscTec Pelican UAV

- **Navigation Algorithm**

  The waypoint navigation algorithm of the UAV uses the GPS data to do the localization and takes the data from the pressure sensor to estimate the height. It contains three major parts: ROS Interface, Autopilot system, and PID motor controller. The ROS interface is able to transfer ROS Messages into corresponded serial commands. After receiving the serial command, the Autopilot system will be able to generate the command of motor speed which will be fed to the PID motor controller.

  The Autopilot system contains the feedback control loop which will make sure that the stop position is within the tolerance range of the target waypoint. The UAV will hover at the target waypoint until the GPS data is converged and then go to the next waypoint.

- **Temperature Measurement**

  The temperature measurement is performed using an NTC thermistor based USB temperature sensor. We implemented a ROS wrapper for the temperature sensing on board which reads temperature data from the sensor (an HID device) and publish the temperature data. The temperature sensor is placed at the bottom of the UAV as shown in Figure 13.

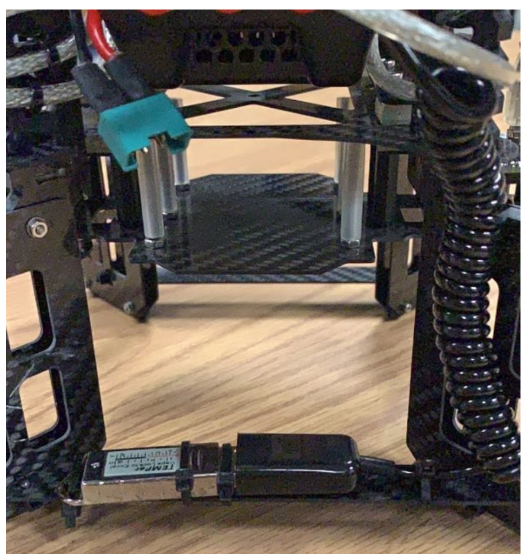


Figure 13. UAV Temperature Sensor Placement

- **Current Status**

  The UAV is able to realize motion control, localization, GPS waypoint navigation, and temperature measurement. The UAV is integrated into the ROS environment so that it is able to be controlled and provide real-time feedback via ROS Message. For safety concern, the UAV requires manual control to take-off. Once the UAV is hovering successfully, it will go to the target waypoint after receiving the ROS command which contains the information of latitude, longitude, and height of the waypoint. The UAV will hover at the waypoint until the convergence of GPS and temperature data. The accuracy of waypoint navigation is lower than 0.5m. The accuracy of temperature measurement is about 1.2°C.

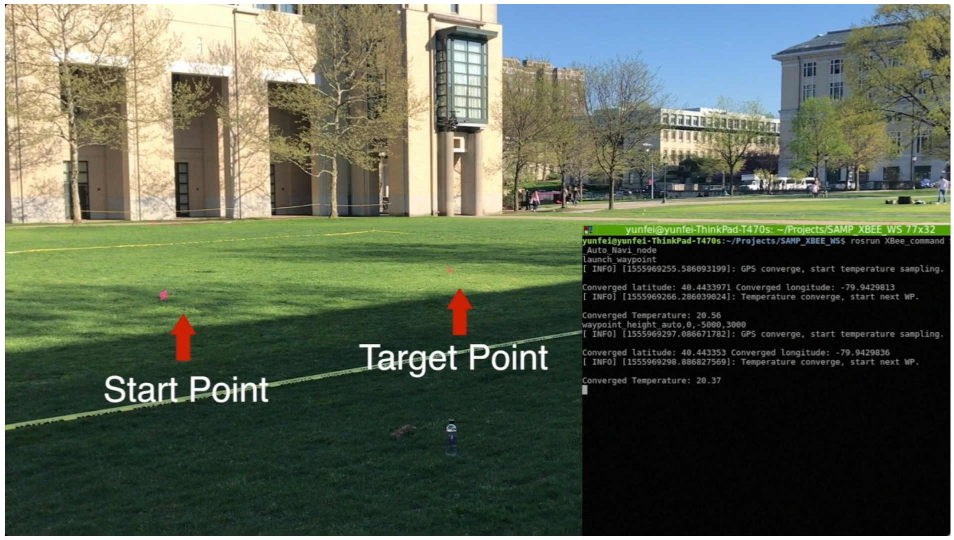


Figure 14. Waypoint Navigation of the UAV

6.3. Modeling Analysis Test

6.3.1. Built-in GPS Accuracy

We gathered a set of GPS data to analyze the drift and precision of the built-in GPS on Jackal UGV and AscTec Pelican UAV, and also to verify whether the system can meet the localization accuracy specified in M.P.7.

Figure 15. GPS Test Spots

We conducted the experiment in the open area before CMU Newell-Simon Hall. We selected three test spots on the ground as shown in Figure 15, and use the UAV and UGV to record GPS readings at each of these three locations for 1 minute. We found a common offset between UAV and UGV GPS coordinates. The localization error of UGV GPS can reach 2.08m, which fell beyond the requested accuracy specified in M.P.7. The statistical results are summarized in Table 6.

Table 6. Built-in GPS Test Results

	Latitude		Longitude	
Offset at the same location UAV -> UGV	-3.98177e-5 (-4.4291 m)		2.77001e-5 (2.4277 m)	
Precision (standard deviation at the same location)	UAV	UGV	UAV	UGV
	1.22036e-5 (1.3575 m)	1.87252e-5 (2.0829 m)	3.96399e-6 (0.3474 m)	1.67721e-5 (1.4699 m)

6.3.2. RTK GPS Accuracy

To increase the localization accuracy of the UAV and UGV, we decided to integrate RTK GPS to the system. We also conducted a similar test to analyze the coordinate offset and GPS precision. The test was conducted at the same locations as the Built-in GPS Test (Figure 15). We found the UAV and UGV are in the same GPS coordinates with the same RTK-GPS base station, and the localization error was around 0.1m which meets the requirement specified by M.P.7.

6.3.3. UGV Waypoint Navigation

To verify the system performance with regard to M.P.6, we conducted UGV Waypoint Navigation Test. We first conducted the test in the Odometry frame, as the base frame of UGV is Odometry frame, and we have to integrate all other frames to it. Based on that, we further tested the robustness of coordinate transformation between GPS and Odometry frame. During the test, we found some heading error in UGV's waypoint navigation and as a result, we calibrated UGV's IMU to fix it.

6.3.4. UAV Waypoint Navigation

To verify the system performance with regard to M.P.6, we conducted a UAV Waypoint Navigation Test. We have tested the accuracy of three different Navigation modes of the UAV: Height Mode, Relative Mode, and Absolute Mode. During the test, the UAV was deployed to the same start point and went to the same waypoint with different navigation modes. After measuring the MSE between the land position and the target position, we found that the Relative Mode has the lowest error which is less than 0.5m.

6.3.5. Temperature Variance

We planned to use Mr. Heater Portable Radiant Heater as the heat source in our test field. To interpret the temperature distribution created by it, we placed the Jackal UGV (with the temperature sensor mounted at the back) at different distances towards the heat source, and recorded the measurements at each location. We started with a distance of 180 cm away from the heat source and each measurement was taken after we moved the Jackal UGV 30 cm closer to the heat source until the robot was 30 cm away from the heat source. Figure 16 shows the test field we conducted the experiment where the air temperature was around 16 ºC. Figure 17 shows a plot of the results. We believe these results have demonstrated that the temperature distribution created by this heat source would have enough variance for our system to construct an informative temperature model.

Figure 16. Test Field for Heat Source Test

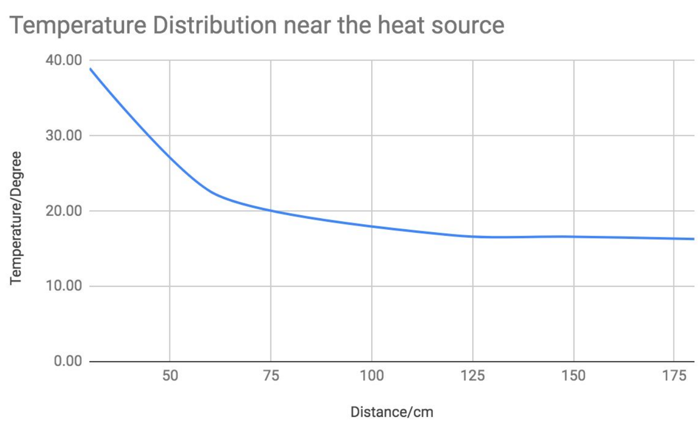


Figure 17. Temperature Distribution near the Heat Source

6.3.6. Power Distribution PCB

We designed a Power Distribution PCB to provide power to the RTK GPS base as well as the WiFi Gates of ground truth temperature sensors. The Power Distribution Board used a 3-cell LiPo Battery as the input. It provides 3 channels of 5V 2A DC output and 1 channel of 5V 35mA DC output. After analyzing the current requirement of the PDB, we selected MIC 29500 as our regulator. We also analyzed the relationship between the voltage and power capacity of the battery and built a power display circuit based on our analysis. The layout of the PCB is based on the analysis of the heat distribution of the regulator.

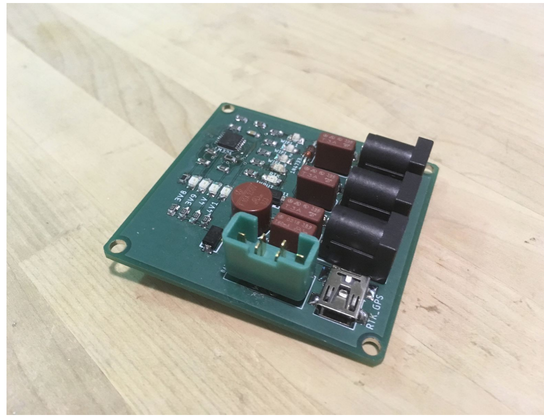


Figure 18. Power Distribution PCB

6.4. SVD Performance Evaluation

6.4.1. Test 1: Master Computer Subsystem Validation Experiment

Table 7. SVD Performance of Master Computer Subsystem

Criteria	Requirement	Performance
RMS Error of Temperature	< 1 ºC	0.35 ºC
Iterations before temperature model converge (average variance less than 1 ºC)	< 50 Loops	30 +/- 10 Loops

6.4.2. Test 2 & 3: UGV/UAV Subsystem Validation Experiment

Table 8. SVD Performance of UAV and UGV Subsystems

Criteria	Requirement	Performance of UAV	Performance of UGV
Mean Location Error	< 2 m	0.38m	0.1m
Mean Temperature Error	< 2 ºC	1.2 ºC	0.4 ºC

6.5. SVD Conclusions

In SVD we have demonstrated that our system has great navigation accuracy, with an average error of 0.38m for the UAV and 0.1m for the UGV. The sampling and modeling algorithm on the master computer generalizes well to different distributions. The algorithm shows good convergence with an average root means square error of 0.35 ºC. Although it depends on the temperature difference of ground truth distribution, the number of iterations is usually about 30 (+/- 10) for the model to converge.

However, SVD has also revealed a few weaknesses of the system. Firstly, sunlight during the test would exert a large influence on the temperature measurements, as the sensor would be heated up by the sunlight. Secondly, the convergence speed of temperature sensors is slow. It takes about 3 to 5 minutes for a 5 ºC temperature gap. Additionally, there is communication latency with the UAV and UGV, and the communication channel freezes occasionally when sending commands and transmitting packages.

There are several ways we can further improve the current system. We need to improve temperature measurement efficiency and reduce the convergence time. We plan to replace the ground truth sensor with laser infrared thermometer and replace onboard sensors with more sensitive ones that have a quicker response to temperature changes. To reduce the influence of sunlight, one solution is to manufacture a canopy above the onboard temperature sensors. After some tests, we believe the transmission speed of the router, to a certain extent, is to be blamed for the communication latency. Hence, to improve this, we plan to use a different router with a larger bandwidth. Additionally, for the SVD, out of safety concerns, we are manually introducing heat source after the UAV has landed on the ground. This could be further improved by using safer heating elements, for example, heating blanket.

7. Project Management

7.1. Work Breakdown Structure

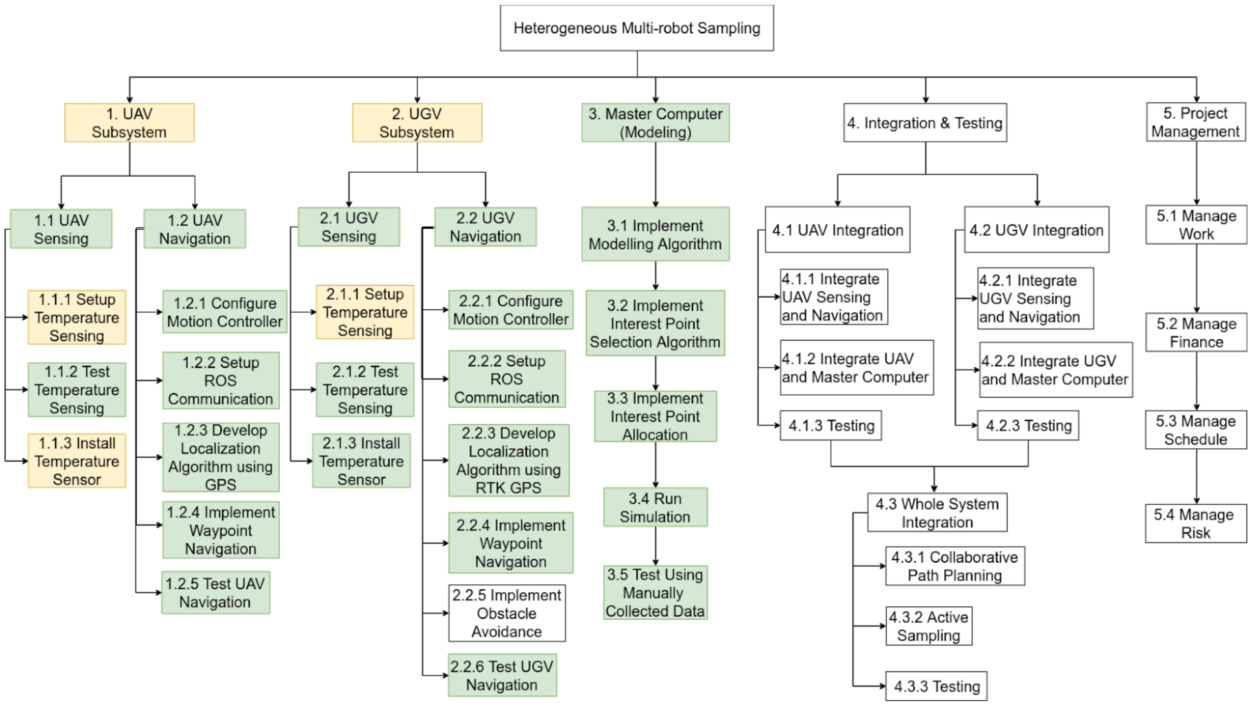


Figure 19. Work Breakdown Structure (WBS) for the system

Figure 19 shows our work breakdown structure for the project. The second level of the WBS has five components including three of the subsystems, integration, and project management tasks. The UAV and UGV subsystems share the similar work structure, and we divide both subsystems to sensing and navigation systems which can proceed in parallel. For the master computer system, after implementing three algorithms individually, simulation with intel lab data will first be conducted and followed by testing using manually collected temperature data. In the Integration & Testing branch, UAV integration with master computer and UGV integration with the master computer will also first perform in parallel and followed by the whole system integration. During the entire project phase, risk management, work management, finance management as well as schedule management will be iteratively conducted.

Finished tasks are marked in green. Yellow indicates in-progress work and works in white need to be done in Fall. In the spring semester, we basically finished all three subsystems, yet we encountered the problems with long temperature convergence time and the low GPS localization accuracy during our development of the UAV, UGV subsystem, and we decided to shift obstacle avoidance function to fall and setup RTK GPS in spring.

7.2. Schedule

Schedule and major remaining milestones in fall are summarised in Table 9, and a Gantt chart is shown in Figure 20. We are currently a little bit off schedule as we encountered long temperature convergence and low localization accuracy problem. Solving these problems dragged our schedule, so we leave the obstacle avoidance system to fall and will start with improving sensing convergence time in fall.

Table 9. Fall schedule milestones by the Preliminary Design Review on 18 March 2019

Intended Finish Date	Milestone Description
15 September	Finish temperature sensor update with high accuracy and convergence rate.
30 September	Finish UAV temperature measurement while hovering over the intended position.
15 October	Finish heterogeneous sampling in an obstacle-free region
30 October	Finish obstacle avoidance motion planning for UGV
15 November	Finish obstacle avoidance motion planning for UAV
30 November	Finish heterogeneous sampling in the required region with obstacles

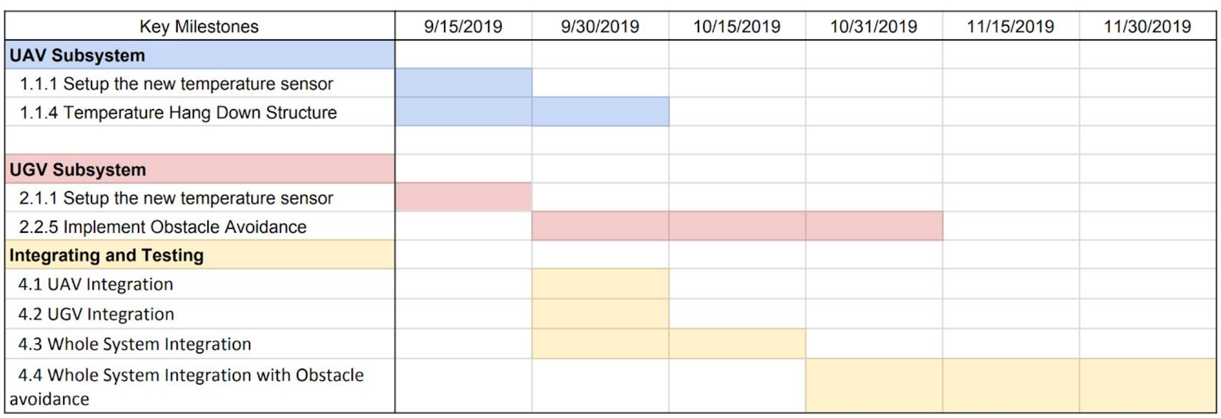


Figure 20. Fall schedule Gantt chart by the Fall Validation Demonstration

To catch up on the schedule, we will first work harder and finish setting up temperature sensors. As our subsystems are ready for integration without obstacle avoidance system, we will start integration Schedule and major remaining milestones while implementing the obstacle avoidance system to ensure enough time for overall system integration.

7.3. Test Plan

7.3.1. Progress Reviews

Table 10. Progress Reviews

Milestone	Test Description
PR7	Temperature measurement convergence test
PR8	Temperature sensor hang-down structure test
PR9	UGV/UAV/Master Computer Integration Test without obstacles
PR10	UGV Obstacle Avoidance Test
PR11	UAV Obstacles Avoidance Test
PR12	UGV/UAV/Master Computer Integration Test with obstacles

7.3.2. Fall Validation Experiments

Table 11. System Validation Experiment

Location	An outdoor area within the dimension 20m x 20m x 5m
Criteria	M.P.1 Generate a temperature distribution model for an area of interest within the dimension 20m x 20m x 5m. M.P.2 The RMS error of the temperature distribution model shall be within 3 °C. M.P.3 Self-select informative point which reduces local variance by at least 3% at each time. M.P.4 Collect temperature sample with error within +/- 2 °C. M.P.5 Update the model after receiving every 10 samples. M.P.6 Navigate autonomously in the area with a success rate greater than 80%. M.P.7 Achieve sample localization accuracy better than +/- 2 m. M.P.8 Plan obstacle-free path through randomly deployed obstacles. M.P.9 Last at least 15 minutes for one deployment.
Equipment	UGV, UAV, Master Computer, Obstacles, Stopwatch, Temperature Sensor, Tape Measure

Procedure	1. Measure the ground truth temperature distribution, with 0.5m resolution and 0.5m over the ground, over the test region. 2. Initialize temperature model with randomly collected samples. 3. Deploy UAV and UGV in the test field. 4. The master computer assigns interest points for UGV/UAV to take temperature measurements respectively. 5. UAV/UGV navigates to the interest points with a collision-free path. 6. UAV/UGV measures ambient temperature and reports to the master computer. 7. Master computer updates temperature distribution model with existing measurements. 8. Loop through step 3 - 7 until the average temperature variance is less than 2 ℃. 9. Calculate the root mean square error compared with the ground truth measurements.

7.4. Budget

Table 12. Total Project Budget

Product	QTY	Cost	Description
Ground Truth Temperature Sensor	12	$49.99	$599.88
Ground Truth Temperature Sensor WiFi Gateway	1	$99.95	$99.95
Heat Source	2	$16	$32
Battery Monitor	1	$9.89	$9.89
On-board Temperature Sensor	4	$13.99	$55.96
Temperature Sensor Extension Cable	4	$6.99	$27.96
RTK-GPS Set (2 Rovers and 1 base)	1	$2,000	$2,000
Total		$2,865.64	

The planned project budget is $2,865.64 as shown in Table 12. Since robot platforms are provided by our sponsors, the big-ticket item is our RTK-GPS system including base and rover. We have spent $2,366.51 (81.58% of the total budget) up to date. The remaining MRSD budget is $2,633.49. There are no anticipated big-ticket items to purchase in fall, but items including testing facilities, spare components might be needed.

7.5. Risk Management

The updated risk management table is shown in Table 13. Risks (Risk ID: 1-5) have been updated and new risks (Risk ID 6-10) has been added. The red number in bracket indicates the change in the likelihood of the risk.

Table 13. Risk Management Table

ID	Risk	Type	Description	Likelihood	Consequence	Risk Reduction Plan
1	Electric System Failure	Technical	The battery or electric system fails due to incorrect operation.	2 (-1)	4	• Add reverse voltage and overvoltage protection. • Document and regulate operation. • Prepare spare parts.
2	Work Delay	Schedule	Heavy workload puts the team behind the schedule	4 (-1)	5	• Optimize the WBS to break down the workload into manageable pieces.
3	Run Out of Budget	Financial	Run out of funds purchasing parts and repairing robots.	2 (+1)	5	• Make purchasing decision carefully after the trade study.
4	Latency for Real-time Operation	Technical	Communication latency between master computer and UGV fails real-time operation.	4 (0)	4	• Shut down unnecessary sensor publications. • Use a higher speed router.
5	Poor Weather for Validation Tests	Schedule	Poor weather prevents/delays the system from outdoor experiments.	1 (-3)	3	• Monitor upcoming weather. • Schedule tests beforehand.
6	Even Temperature Distribution	Technical	The temperature difference in the test field is close to or smaller than sensor noise.	1 (-1)	4	• Use sensors with higher sensitivities based on previous experimental results. • Add heat sources to the test field to increase temperature variance.
7	Poor Localization Accuracy	Technical	Localization accuracy is not high enough considering the size	1 (-3)	5	• Use RTK GPS instead of built-in GPS.

			of the test field.			
8	Slow Temperature Convergence	Technical	Temperature converges too slow for ground truth and onboard sensors to meet the time requirement.	4	5	• Use temperature sensors with a faster response time.

- Risk ID 1: As we become more familiar with the electrical systems of UAV and UGV and follow the operating rules, the electrical system failure risk is reduced by 1.
- Risk ID 2: Work delay due to a tight schedule is still one of our biggest risks, as we cannot always accurately estimate the time for the task. However, by actively using project management tool Asana, we are able to track the progress and update the schedule in time.
- Risk ID 3: The risk of ran out of the budget is increasing as we spent more, but since we planned ahead, the likelihood is still very low.
- Risk ID 4: We temporarily solved the latency problem by shutting down the sensors. It is effective to achieve SVD requirements, but it may cause problems when developing the obstacle avoidance system. We will test the transmission speed with a different router in fall.
- Risk ID 5: We can mitigate the risk of having poor weather for validation tests by planning ahead and track the temperature.
- Risk ID 6: After conducting a test with our current heat source, the temperature difference is around 10 ºC which will give us enough temperature difference.
- Risk ID 7: Localization accuracy problem is solved by using RTK GPS.
- Risk ID 8: We added this risk as we realized the temperature convergence time for the sensor is large, and we are planning to change the type of temperature sensors.

Figure 21 shows the previous and updated risk likelihood-consequence table. The overall risk level of the system is reduced, but the current most risky tasks include Risk ID 4, 2, 8.

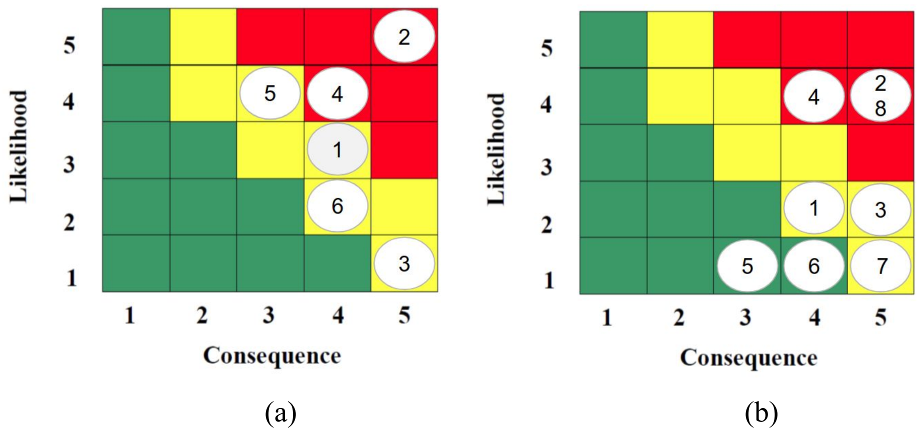


Figure 21. Risk Likelihood-consequence Table: (a) original risk likelihood-consequence table, (b) updated risk likelihood-consequence table.

8. Conclusions

8.1. Key Lessons learned

Clear documentation can save a lot of time:

Due to the lack of documentation of setting up our sponsored UAV (Asctec Pelican), we spent a lot of time setting up the environment by searching different error messages online. This experience makes us aware of the importance of the clear documentation that with a clearly documented guide, we could save one week on trying to find environmental problems.

System robustness is important:

When we were testing UGV GPS waypoint navigation, we marked the system working after it successfully navigate to the GPS waypoint. However, when we conducted a test before SVD, we found large localization error and later we realized that is due to the uncalibrated IMU which makes the result not stable. It is necessary to conduct extensive experiments to confirm the functionality of each subsystem.

Plan outdoor tests beforehand:

Our system requires a lot of outdoor testing, and the weather is one of our biggest constraints for testing. At the beginning of our testing phase, we tended to plan the outdoor test when we finished all the system function implementation, but the actual test could be delayed for around one week due to the bad weather condition. Therefore, we found it important to plan one week ahead and coordinate schedule among teammates to get prompt tests.

Safety check before piloting robots

Our team has paid a lot of attention to safe operation, and a safety check is performed each time before piloting a robot for both UGV and UAV. However, during one of our tests before SVD, we performed two consecutive UAV tests with a one-minute break in between. The flight mode on the RC of the drone is accidentally changed from position mode to velocity mode during the handover of the RC without our pilot noticing it. This led to the drone crash and a lot of additional effort in repairing the drone. We learned the importance to perform safety check even if the two tests are very close.

Time management for validation test

The final thing we learned is about validation test time management. As we are conducting three tests during SVD, we focused on each performance at the beginning, but we found we would easily exceed the time limits without planning the flow carefully. This makes us aware of the necessity to time and rehearsal for the entire validation beforehand.

8.2. Resultant Key Activities in Fall

Use Git and keep documenting developed subsystems

We will keep using git to maintain version control of our code and keep documenting our developed subsystems so that members in our group or future developers can easily take over the work and continue improving the systems.

Conduct multiple tests for subsystems

To make sure the system is robust, we will conduct extensive unit tests and the overall validation test during the fall semester.

Conduct a safety check before each robot deployment

Having learned the importance of the safety check, we will develop a safety checklist and perform a safety check every time before deploying the robot even if two tests are very close.

Carefully design the flow and carefully allocate time for the validation test

The final thing we learned is we also need to carefully design the flow of the validation test and prepare verbal presentation during the test, and make a smooth transition between tests in order to finish the tests effectively in time.

Reference

[1] https://pubs.usgs.gov/sir/2014/5137/pdf/sir2014-5137.pdf
[2] https://www.generationrobots.com/en/402144-jackal-unmanned-ground-vehicle.html
[3] https://www.clearpathrobotics.com/jackal-small-unmanned-ground-vehicle/
[4] https://velodynelidar.com/vlp-16.html
[5] https://voltrium.wordpress.com/machine-vision/home/stereo-products/
[6] http://www.asctec.de/en/uav-uas-drones-rpas-roav/asctec-pelican/
[7] http://www.resistorguide.com/ntc-thermistor/
[8] https://www.ametherm.com/blog/thermistor/glass-encapsulated-thermistors-automotive-and-industrial-applications/
[9] https://www.ametherm.com/thermistor/ntc-thermistors-glass-encapsulated
[10] https://www.ametherm.com/blog/thermistors/temperature-sensor-types
[11] http://db.csail.mit.edu/labdata/labdata.html
[12] Luo, Wenhao, and Katia Sycara. "Adaptive Sampling and Online Learning in Multi-Robot Sensor Coverage with Mixture of Gaussian Processes." *2018 IEEE International Conference on Robotics and Automation (ICRA)*, 2018, doi:10.1109/icra.2018.8460473.

9. Appendix

Table 14.. Obstacle descriptions

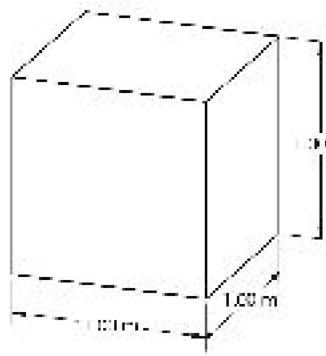
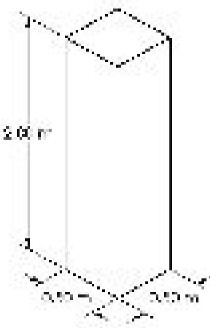
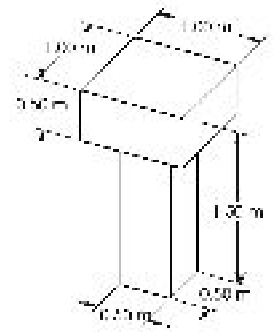
Obstacle			
Quantity	2	2	4

Table 15. Morphology Chart for robot cluster trade study

Criteria	Weight Factor (100%)	UGV Cluster	UAV Cluster	UAV + UGV
Sampling Efficiency	30	2	5	5
Sample Accuracy	30	4	2	3
Mobility	20	2	3	5
Duration	15	5	1	4
Cost	5	5	1	3
Weighted Sum	100	3.35	2.80	4.10

Table 16. Morphology Chart for robot cluster trade study

Criteria	Weight Factor (100%)	NTC	RTD	Thermocouple	Semi-sensor
Accuracy	35	4	5	2	1
Responsiveness	30	5	2	3	1
Cost	25	5	1	3	3

Range	10	3	4	5	1
Weighted Sum	100	4.45	3.00	2.85	1.50

Table 17. Technical Specifications for different Temperature Sensors [8]

Criteria	NTC	RTD	Thermocouple	Semi-sensor
Accuracy (℃)	0.05 ~ 1.50	0.10 ~ 1.00	0.50 ~ 5.00	1.00 ~ 5.00
Responsiveness (s)	0.12 ~ 10	1 ~ 50	0.2 ~ 20	5 ~ 100
Cost ($)	Low	High	Medium	Medium
Range (℃)	-50 ~ 250	-200 ~ 600	-200 ~ 1750	-70 ~ 150