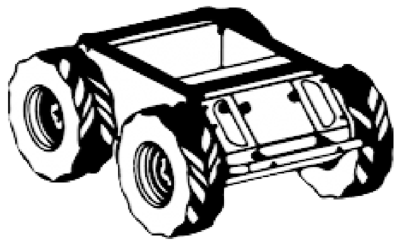
Heterogeneous Multi-Robot Sampling
Final Report

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 provides 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 UAV autonomously navigate to a target location per the 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 fall validation demonstration, we verified the multi-agent collaboration system and mobile robots' obstacle avoidance, as well as our robust and accurate temperature modeling algorithm. We've also proved our system's potential to be scaled up to a heterogeneous robot fleet and accomplish modeling tasks in a large open area. Our system still leaves room for improvement regarding operation efficiency, communication coverage.

This report documents the development progress towards the heterogeneous multi-robot sampling project.

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 manually with discretized and limited coverage, which may not provide enough information and requires tremendous human resources, especially for large areas. However, sensing from a satellite can cover a wide range of areas but with reduced 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 enables them to overcome their physical constraints. For example, the UAV can cover inaccessible aerial areas for UGV. The UGV can produce precise detections in the informative area and can lengthen the working duration. The system generates a distribution map of the temperature information across a self-defined region of interest to assist environmental scientists in monitoring the thermal environmental 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 expectations. So he decides to use the SAMP system and starts to work on the 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, where we outline the region of interest using a red bounding box. SAMP automatically deploys one UGV and one UAV to execute the temperature modeling task.

The 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, the UGV and UAV start to navigate to the target location while avoiding obstacles automatically. After reaching the target locations, the robots take temperature measurements and send them back to the master computer's modeling systems. The 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 assigns them to the UAV and UGV, respectively. The UAV and UGV then go to the next target locations to take samples and further update the model.

We keep conducting the online sampling process iteratively until the temperature model converges. During the sampling, if the UGV meets an unreachable area like hot springs or cliff, the system remarks that location as an interest point for the UAV. Besides, if a robot fails to navigate to the assigned target location within the time limit, a new target position is sent to the robot. If the robot gets stuck during the navigation, a recovery behavior would first be conducted, but if it does not help, then the new target location would be sent. If the robot fails to move to the new target location, then the return to the starting point command would 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, the UAV and UGV would navigate back to the starting point, and the modeling system outputs the final distribution model that can be a to Tom's thermal activity study.

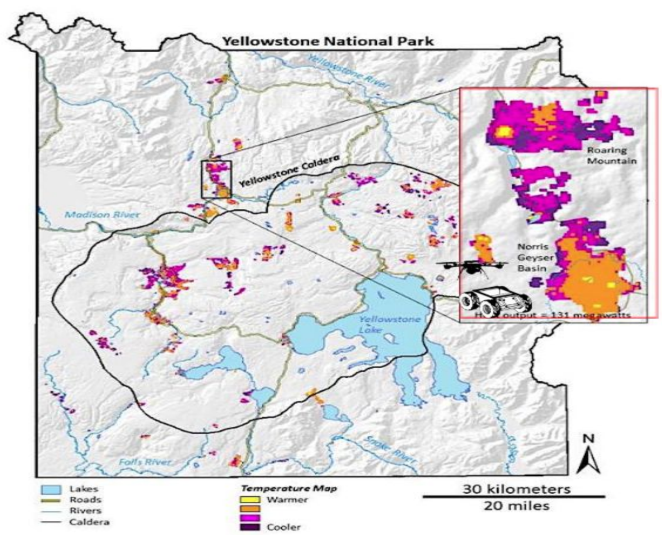


Figure 1. Yellowstone National Park map with thermal information indicated in different colors. The selected interest region is shown in the red bounding box. A UAV and UGV are deployed in the region of interest to take samples for generating the temperature distribution model.

3. System-level Requirements

3.1. Mandatory Requirements

i. 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 **10m×10m×5m**.	A demo covering nontrivial scale is expected. **This requirement has been changed to reduce the system running time in order to meet the time requirement of FVD**
M.P.2	The RMS error of the temperature distribution model shall be within 2 °C	The temperature distribution model is expected to be close to the ground truth temperature distribution.
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 samples 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 every 10 samples.	The system is expected to conduct an efficient model updating.
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 tasks 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 8.	The UGV is expected to avoid reasonably sized pieces of obstacles without human maneuvers. **This requirement has been changed according to the assumption that the height for the UAV to take temperature do not have obstacles.**
M.P.9	The system will last at least 15 minutes for each deployment.	The system is expected to avoid frequent recharging.

ii. 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 mechanisms.	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 scale up to multiple heterogeneous robots.	Extensibility consideration for deployment in various environments.
M.N.7	The system will cost less than 5000 dollars.	The sponsor can provide no more than 5000 dollars.

3.2. Desirable Requirements

i. 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 a 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 conditions 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.

ii. 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

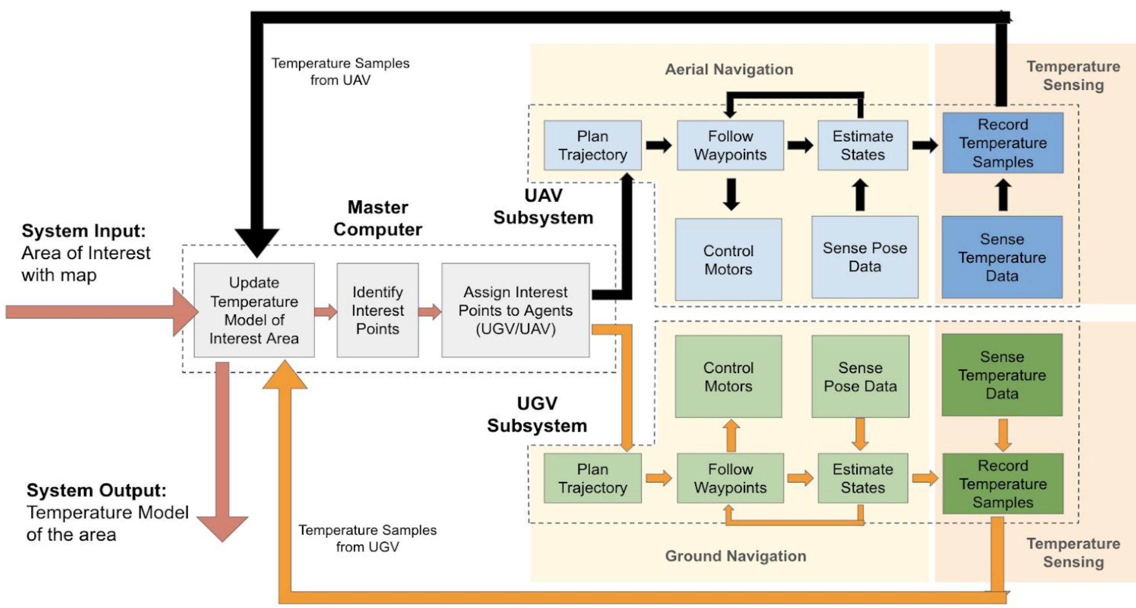


Figure 2. Functional architecture of the sampling project

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 of 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 and keeps updating this model in realtime after receiving each sample from the UAV/UGV subsystem. From the current distribution model, it identifies the next location to take samples from that would lead to the most improvement in the model, which we refer to as an "interest point." The master computer then allocates interest points to agents considering the different capabilities and 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 at the allocated interest point, it measures the temperature at this location and forwards 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 to the UAV with two main functional blocks, which are ground navigation and temperature sensing. The UGV subsystem contains the same functional sub-blocks as in the UAV subsystem that receives and navigates to the allocated interest point, records 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 the 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. System-level Trade Studies

The table of trade studies is shown in the appendix. The scale for weighing score ranges for 1 - 5. 1 is the worst and 5 is the best.

5.1. Robot Cluster Trade Study

A system-level trade study is conducted to compare heterogeneous and homogeneous robot clusters. The heterogeneous cluster includes both UAV and

UGV. The homogeneous UAV and UGV clusters are considered for comparison. The detailed morphology chart is shown in Table. 9 in the appendix.

i. **Sampling Efficiency:** Sampling efficiency directly determines how fast the desired temperature model can be generated. It is one of the essential criteria for the system-level trade study, with 30% of the entire weight. Efficiency directly depends on the maximum speed an agent can reach. The provided UAV could reach the maximum speed of 16m/s, and the provided UGV could only reach the maximum speed of 2m/s. Since UAV provides the maximum speed for the UAV + UGV cluster, the system also provides excellent efficiency..

ii. **Sample Accuracy**: Sample accuracy directly determines the quality of the desired temperature model. The temperature model's accuracy compared with the ground truth highly depends on the sample accuracy. Therefore, 30%, the most significant weighting factor, is also assigned to this criterion. Sample accuracy is discussed in terms of two factors, temperature accuracy and localization accuracy. The sample is expected to provide accurate temperature information, and the location at which the sample is taken needs to be as close to the desired location as possible. While we are assuming all different clusters are using the same kind of temperature sensor, the weighing scores are determined in terms of localization accuracy.

UAV only uses GPS to help localization, which typically gives an uncertainty of 3-5m. While other than GPS, UGV can improve its localization accuracy to be lower than 0.5m with the help of LiDAR and IMU. The UAV+UGV cluster is given a score in the middle.

iii. **Mobility**: The project aims to help scientific, environmental research, which is usually conducted in various non-trivial environments. The robot cluster is expected to have functional mobility for different environments. It is given the second priority with a weighting factor of 20%.

The UGV cluster is limited on the ground. Although UAV cluster's task space is expanded to 3D space, its mobility is still limited in complex environments such as a forest. UGV + UAV cluster can combine the mobility of both UGV and UAV with earning the highest mobility.

iv. **Duration**: M.P.9 sets a minimum duration for each sampling task, therefore, the duration is also an important criterion to compare those clusters. Duration concerns can influence our system's efficiency, while, it does not directly influence the quality of our final deliverable given plenty of time. As a result, a 15% weighting factor is given to duration. The provided UGV has a run time of 4 hours, while the UAV can only last for 16 minutes. UGV + UAV system performs in between.

v. **Cost:** The project is given a budget no more than 5000 dollars as stated in M.N.7. Although the robots are provided, we still don't want to cause any damage to them in case of expensive repair fees. The provided UAV is worth more than 17,000 dollars each, while the UGV is worth 12,000. The prices are considered for weighting cost influence.

5.2. Temperature sensor trade study

Temperature quality will directly influence sample quality and thus further influence model quality. Five common temperature sensors: Negative Temperature Coefficient (NTC) thermistor; Resistance Temperature Detector (RTD); Thermocouple and Infrared Thermometer are considered. The detailed morphology chart is shown in Table. 10 in the appendix. The specific weight scores are determined according to the technical specifications listed in Table.11

i. **Accuracy**: As stated in M.P.4, temperature samples must meet the accuracy requirement of 2 °C. Temperature accuracy directly influences our model performance, therefore it's given the highest weight of 35%.

ii. **Responsiveness**: The temperature sensors are expected to respond efficiently to temperature variation, thus speeding up the entire sampling process to meet D.P.1. The relatively high weight of 30% is considered reasonable for responsiveness.

iii. **Cost**: As stated in M.N.7, the entire budget is required to be less than 5000 dollars. Since multiple sensors are expected to be deployed on a single agent, and we also need to spare the rest of the budget for other components including computational power, etc. Therefore, the cost of temperature is also one of the important concerns with 25% of the total weight.

iv. **Range**: The temperatures are expected to provide enough range to cover the temperature variation in the area of interest. While the temperature variation in the outdoor area is not expected to be extremely large, a relatively low weighting factor of 10% is given to the range concerns.

6. Cyberphysical Architecture

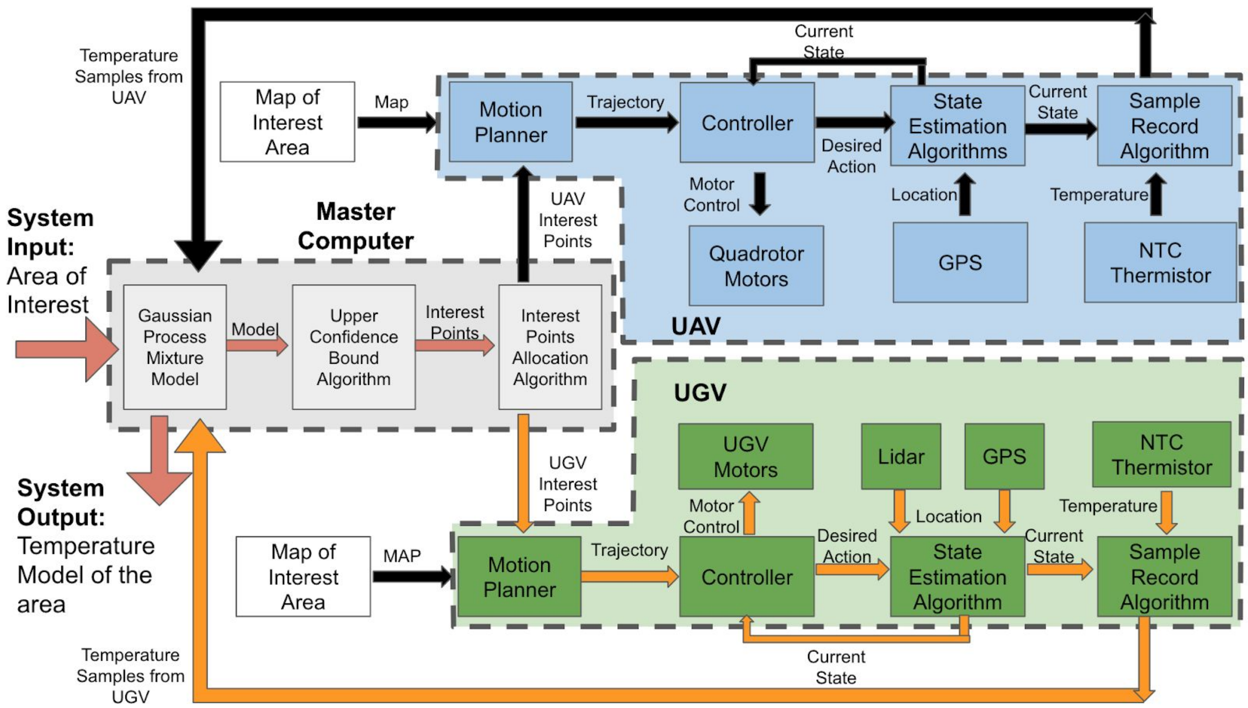


Figure 3. Cyberphysical Architecture and Information Flow

Figure 3 shows the specific hardware and software components of the system, as well as the information flow between them. The system cyberphysical architecture is composed of three major blocks: Master Computer, UAV Subsystem, and UGV subsystem.

6.1. Master Computer

The master computer plays the role of the central processor and commander of the system. The primary function of the master computer is the following:

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

- **Identify interest points.** After the temperature model is updated, the master computer uses the upper confidence bound algorithm to identify the next interest point for the UAV and UGV to do sampling. The interest points are determined to be the locations giving maximum information to the system. In our case, the interest points contain the most significant uncertainty before measuring.

- **Assign interest points to agents.** The master computer uses interest points allocation algorithm to assign the interest points. This algorithm considers the feature, including mobility, battery life, and the current location of UAV & UGV, which achieves the collaboration between them.

6.2. UAV and UGV Subsystems

The UAV and UGV subsystems include two significant functions: aerial navigation and temperature sensing. UAV and UGV have prior knowledge of the required region location before the deployment. After receiving the interest point from the master computer, the UAV and UGV would use their motion planners to do local path planning. Then, the UAV and UGV would process the navigation control loop, including the motion controller, quadrotor motors, state estimation algorithms, and GPS sensors. The motion controller would use the state data, as feedback and send commands to motors to control the movement. The state estimate algorithms would gather the location data from the GPS sensors (and a LiDAR sensor for UGV). After the UAV and UGV arrive at the interest point, they would gather the temperature data from the NTC Thermistor sensor and send the sample data back to the master computer.

7. System Description and Evaluation

7.1. Current System and Subsystem Descriptions

i. Overall 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 UAV autonomously navigate to the target location per the master computer's request and report the temperature measurements back to the master computer.

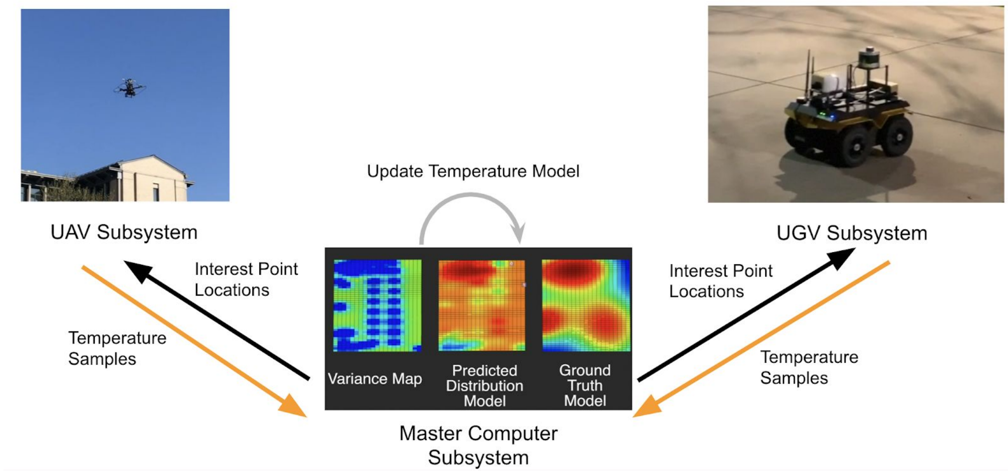


Figure 4. Heterogeneous Multi-Robot Sampling system depiction

ii. 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.

  Per the sponsor's requirements, the Mixture of Gaussian Mixture Models [10] is applied to this project. A typical example is shown in Figure 5. It demonstrates a proper generalization of environmental modeling, especially for temperature modeling. We have an assumption 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 the 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:** The existing temperature model needs updating until it converges. The next points at which the master computer wants the robots to take temperature are determined by an interest point identification algorithm. The master computer selects the point with the highest variance/uncertainty as the next interest point requiring temperature measurement. This interest point selection strategy greedily improves the accuracy of the temperature model prediction.

- **Interest Point Identification Algorithm:** The existing temperature model needs updating until it converges. The next points at which the master computer wants the robots to take temperature are determined by an interest point identification algorithm. The master computer selects the point with the highest variance/uncertainty as the next interest point requiring temperature measurement. This interest point selection strategy greedily improves the accuracy of the temperature model prediction.

- **Interest Point Allocation Algorithm:** After the interest points are selected, the master computer assigns those points to specific robots using the interest point allocation algorithm. The primary considerations are under the robot's mobility. For example, the master computer assigns the interest point above a ground obstacle to the UAV considering the limitation of the UGV's mobility. The second consideration is the measurement efficiency. The master computer assigns the next interest point to the robot having a quicker arrival time.

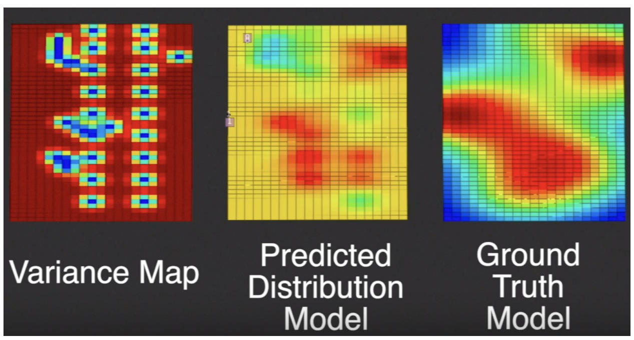


Figure 5.. Master Computer Simulation

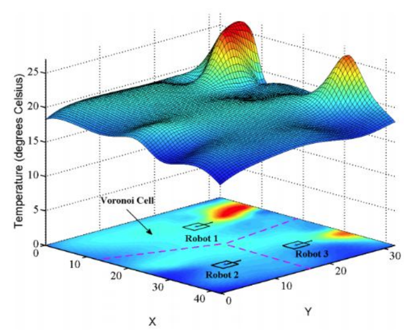


Figure 6. Example Gaussian Mixture Model [12]

- **Sub-System Performance:** The master computer can simulate the execution of the entire system. We simulate the system in ROS and Gazebo, and it 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 °C, the master computer stops the simulation and then outputs the final temperature distribution model. As shown in Figure 5, 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.

iii. UGV Subsystem Description

- **Hardware:** We are using a 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 to +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 an infrared temperature sensor on the UGV agent. An infrared thermometer is a small size thermally sensitive IR sensor with high accuracy (The accuracy with the object temperature range of 10ºC - 40ºC is shown in Figure. 10). One desired feature of the infrared thermometer is that it can provide real-time feedback with very high convergence rate. The temperature reading of the IR thermometer is based on infrared reflection on the surface of the measured object.

Figure 8. Bumblebee stereo camera [4]

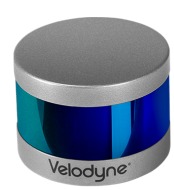


Figure 9. Velodyne VLP-16 LiDAR [3]

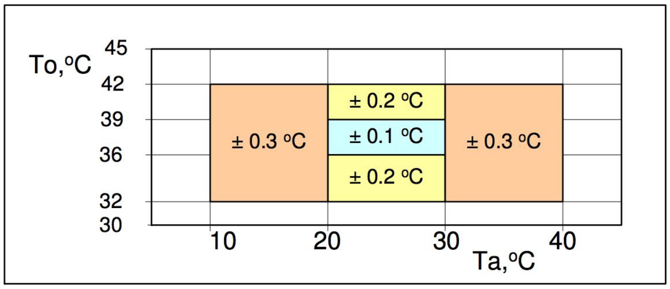


Figure 10. Preliminary Accuracy of the infrared Thermometer [5]

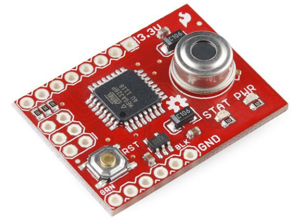


Figure 11. Infrared Thermistor[7]

The operating range of IR thermometer spans from −70 °C to +380 °C, and the temperature accuracy of IR thermometer varies from ± 0.1 °C to ± 4 °C. [5] Considering our application, the temperature range of the target object will be 0 °C to +40 °C, where the accuracy of the IR thermometer is within ± 0.5 °C. [5]

- **Software:** The 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 the 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 reading the temperature data from the serial port of the IR thermometer. UGV then forwards the temperature measurement to the Master Computer.

- **Sub-System Performance:** The motion planning, motion control, waypoint navigation, localization, and 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 established a transformation between the RTK GPS frame of coordination and Jackal's move_base frame, Odometry frame, to realize GPS waypoint navigation. Jackal can achieve the navigation accuracy of ± 0.3m and a temperature measurement accuracy of ± 1.3 °C. Its maximum speed can reach 8 m/s, and its operation duration can last 3 hours.

iv. UAV Subsystem Description

- **Hardware Platform:** We are using the 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, which 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 supports a variety of wireless communication links, including Wifi and XBee (wireless serial).

Figure 12. AscTec Pelican UAV

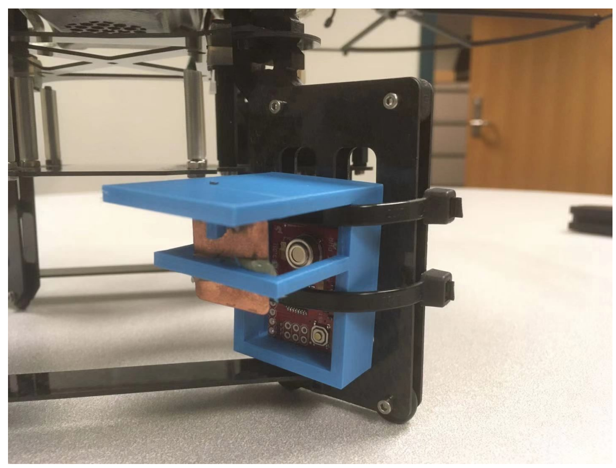


Figure 13. UAV Temperature Sensor Placement

- **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 can transfer ROS Messages into corresponding serial commands. After receiving the serial command, the Autopilot system can generate the command of motor speed and forward it to the PID motor controller. The Autopilot system contains the feedback control loop, which makes sure that the stop position is within the tolerance range of the target waypoint. The UAV would hover at the target waypoint until the GPS data converge and then go to the next waypoint.

- **Temperature Measurement**: We used the same IR thermometer as the Jackal on the Pelican UAV to measure the temperature. The IR thermometer was deployed with a copper pad so that it is able to measure the air temperature since the copper pad is very thin and its temperature is close to the air temperature around it. The temperature sensor is placed at the bottom of the UAV, as shown in Figure 13.

- **Sub-System Performance**: The UAV can realize motion control, localization, GPS waypoint navigation, and temperature measurement. The UAV is integrated into the ROS environment so that it can be controlled and provides real-time feedback via ROS Message. To ensure safety, the UAV requires manual control to take off. Once the UAV is hovering successfully, it would go to the target waypoint after receiving the ROS command, which contains the information of latitude, longitude, and height of the waypoint. The UAV would hover at the waypoint until the convergence of GPS and temperature data. The accuracy of waypoint navigation is within ± 0.5m. The accuracy of temperature measurement is about ± 1.2°C (when measuring ambient temperature).

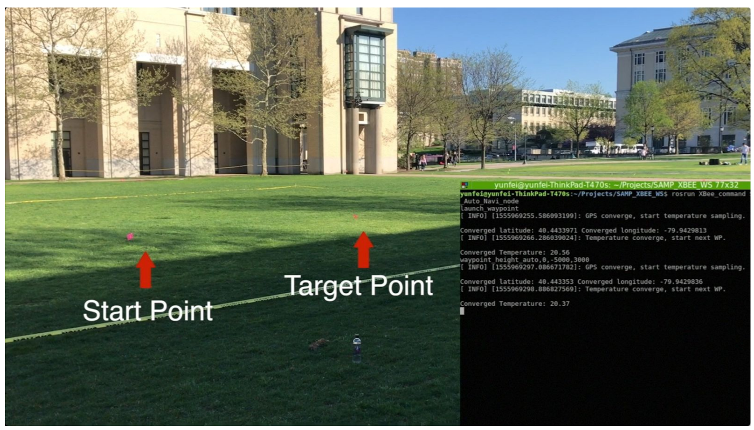


Figure 14. Waypoint Navigation of the UAV

7.2. Modeling Analysis and Testing

i. 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 experimented in the open area before CMU Newell-Simon Hall. We selected three test spots on the ground, as shown in Figure 15, and used the UAV and UGV to record GPS readings at each of these three locations for 1 minute. We found a standard 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 5.

Table 5. 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	UAV	UGV	UAV	UGV
(standard deviation at the same location)	1.22036e-5 (1.3575 m)	1.87252e-5 (2.0829 m)	3.96399e-6 (0.3474 m)	1.67721e-5 (1.4699 m)

ii. **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 requirements specified by M.P.7.

iii. **Temperature Variance:** We planned to use a 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 an 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.

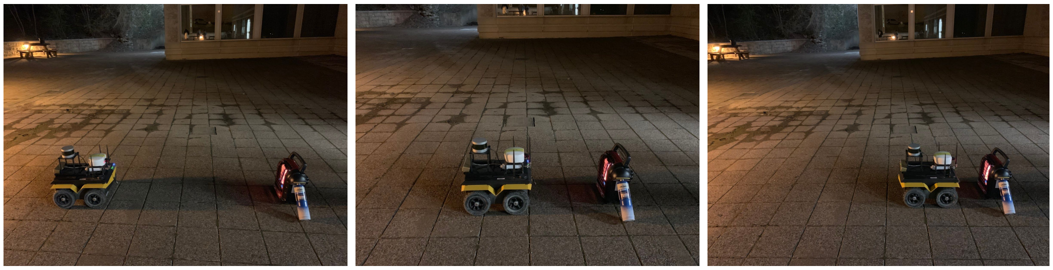


Figure 16. Test Field for Heat Source Test

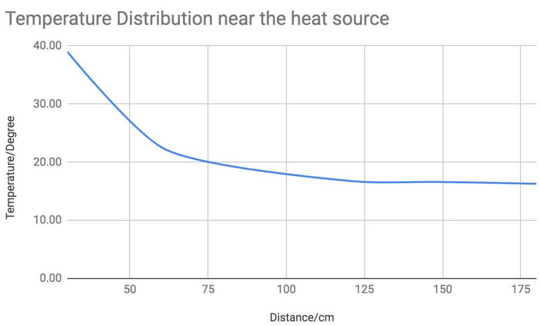


Figure 17. Temperature Distribution near the Heat Source

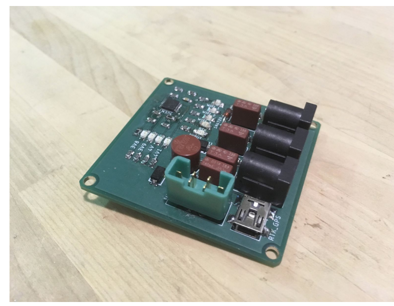


Figure 18. Power Distribution PCB

iv. **Power Distribution PCB:** We designed a Power Distribution PCB to provide power to the RTK GPS base as well as the WiFi Gates of the 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 a 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.

v. **Temperature Measurement Convergence:** To resolve the temperature convergence latency issue, we proposed a new temperature measurement system design (Figure 19), by using an infrared temperature sensor which can give instant feedback and a thin copper pad with good thermal conductivity. To prove the converging speed of this new design can meet our requirement, we designed an ice-water experiment (Figure 20a). We hold the copper pad using a plastic clip in the air and measured its surface temperature using the infrared thermometer. The measurement was around 23.0 ºC. When we moved the copper pad over the iced water, the temperature measurement dropped almost instantaneously to around 17 ºC. Then we moved it back, and the measurement rises instantaneously to 23.0 ºC. We also used the same experiment setup up to configure the best distance between the sensor and the copper pad that renders the best accuracy and convergence speed (Figure 20b). Our experiments show that 1 inch would be a suitable distance for this sensor with its measuring surface.

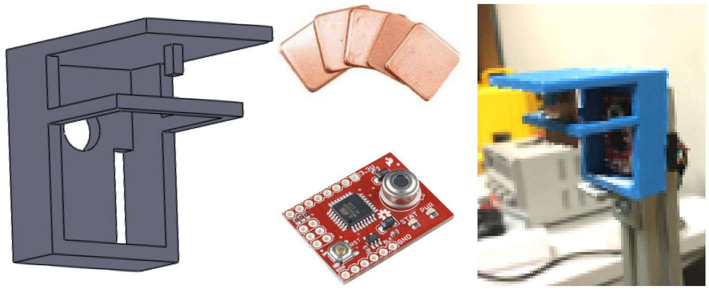


Figure 19. Current Temperature System Design

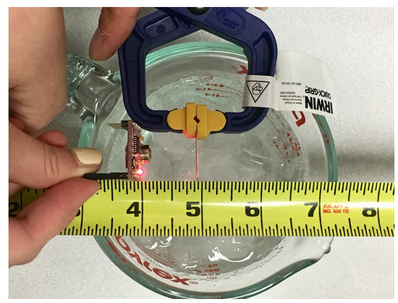


Figure 20. Ice-Water Experiments

vi. **UAV Altitude Control Analysis:** We analyzed the error source for the UAV's inaccurate height control. We first commanded the UAV to take off, and then we sent commands for the UAV to hover at different altitudes and estimated the actual hovering height for each command. The UAV's altitude controller uses pressure height readings as feedback. In Figure 21, we plotted the pressure height sensor signals during the experiment, with the corresponding commands overlaid in horizontal lines. The results serve as evidence that the altitude controller is working adequately, given the feedback from the pressure height sensor.

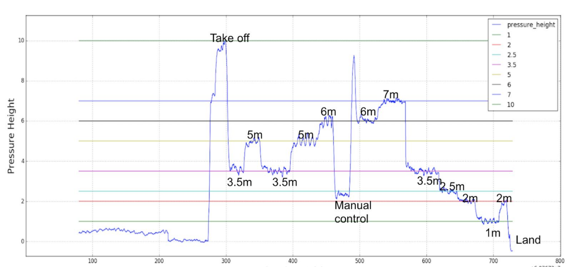


Figure 21. UAV Altitude Control Feedback vs Commands Feedback

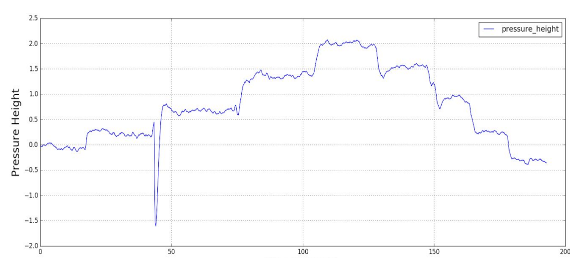


Figure 22. Pressure Height Sensor

Figure 22 shows the pressure height signal when we manually held the UAV at different heights (0, 0.5, 1, 1.5, 2 meters). The results show that the pressure height sensor can give stable feedback, but the actual height is misaligned. This problem can be compensated by calibrating the sensor.

vii. **UAV Temperature Measurement Analysis:** To verify the accuracy of the temperature sensor mounted on the UAV and how the winds generated by the propeller influence the readings, we conducted the UAV temperature measurement experiment. We commanded the UAV to take off and hover at 1.5 meters. We keep recording temperature readings during the entire process (Figure 23). The circled segments correspond to the temperature and pressure height readings when the UAV is hovering at 1.5 meters. The average temperature measurement is 13.8 ºC, and the measurement given by the ground truth sensor is 14.8 ºC. The error is in the acceptance interval of 2 ºC as specified by our performance requirements. When comparing the results between different trails, we found there is a standard offset of 1ºC between the ground truth and the UAV's reading in an environment where we experimented. We can calibrate the sensor reading to get rid of this offset.

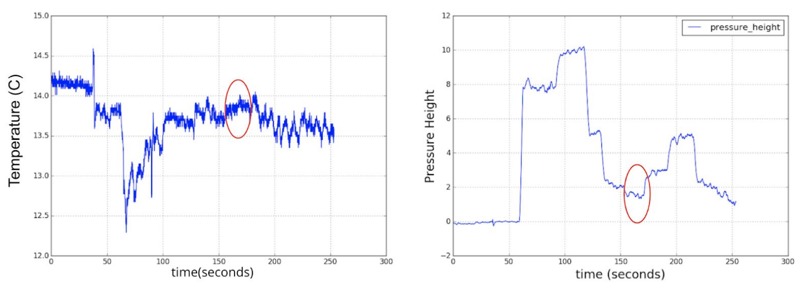


Figure 23. UAV Temperature Measurement Test

7.3. FVD Performance Evaluation

i. FVD procedure and validation criteria

Table 6. System Validation Experiment Procedure and Validation Criteria

Objective
To verify the working adaptive sampling system with Jackal UGV, Pelican UAV, and the master computer.
Procedure
1. Randomly place heat sources and obstacles in the 10m x 10m x 5m test field. 2. Initialize the temperature model with 20 manually-collected temperature samples as a booster of the Gaussian

mixture model.

3. Master compute updates build temperature model.
4.

Jackal asks the master computer for the next location to measure temperature.	Pelican asks the master computer for the next location to measure temperature.

5.

The master computer selects the next interest point for Jackal.	The master computer selects the next interest point for Jackal.

6.

Jackal navigates to the target position.	Pelican navigates to the target position.

7.

Jackal collects temperature measurements and sends them back to the master computer.	Pelican collects temperature measurements and sends them back to the master computer.

8. Loop through steps 3 to 7 until the model converges or the 20-minute time limit is reached. To be noted, the processes of Jackal and Pelican are done in parallel.
9. Demonstrate the accuracy of the predicted model by showing a video of single UGV agent sampling due to the limit of time and limited vertical temperature differences generated by the heat source.

Validation Criteria

- **System Integration**: Live functionality demonstration to show multi-agent collaboration and obstacle avoidance: 1) UAV and UGV collecting samples at different positions. 2) UAV taking measurement above obstacles. 3) UGV avoiding obstacles.
- **Model Accuracy**:
    - Demonstration using video: single UGV agent shall give an accurate temperature model with the mean difference between ground truth and predicted model less than 2 °C.
    - The ground truth model will be obtained by manually taking uniform samples from the area and estimated by interpolating the data.

ii. Performance evaluation

- **System Integration:** For FVD, the sampling system, including UGV, UAV, and the Master Computer, autonomously operated without human intersection for 20 minutes. During the validation period, Master computer assigned UGV and UAV 21 different target interest locations in total. Robots collected and reported 21 temperature samples. The temperature model updated every time the robot agent reported a new measurement. UAV never hit obstacles by navigating at a safe height. UGV never went into collision with other objects by planning obstacle-free trajectories. We used a video demo for FVD encore due to unfriendly weather conditions. The test in the video also validated this system's working pipeline. The only difference was that there were 23 samples collected during the test instead of 21. Our system met the requirement during both FVD and FVD encore as for system integration requirements.

- **Model Accuracy:** Master Computer assigned 32 interest locations for UGV in total. UGV measured 32 temperature measurements and the temperature model updated for 32 times within a 30-minute time limit. One team member then manually collected 50 temperature measurements using ground truth thermistor. The root-mean-square error between model prediction and ground truth is 1.5 °C and met our requirement for model accuracy. We showed the sample video to validate model accuracy for the FVD encore. Our system met the temperature model accuracy requirement.

7.4. Strong and Weak Points

i. Strong Points

- **Stable and robust system architecture:** Our heterogeneous robots operate the same functionalities and serve the same master computer. The robot agents share the same code base and obey the standard communication rules between the master computer. The temperature modeling algorithm and sampling algorithm also do not depend on the number of robot agents in the system. In general, these features establish a stable and robust system architecture, which can be easily scaled up to robot fleets and perform informative sampling in a broader scope.

ii. Weak Points

- **Operation Efficiency:** We put great effort into system integration and testing, but we did not take enough tries to push our robots to their operation limits, regarding speed. Jackal currently performs under the maximum speed of 1 m/s, while its maximum speed can reach 2 m/s. The current operation speed leads to a more than 30-minute time required to wait for the temperature model to converge. Tuning operation speed can make the system more efficient, and it may also require a more robust motion of the Jackal. For example, we may need a more robust localization algorithm so that the high speed can not mess up with Jackal's state estimation. While it needs more effort to improve the operation speed, there is no doubt that the system has room for improvement regarding operational efficiency.

- **Communication Coverage:** We are currently using four wifi boosters to establish a communication coverage over the 10m x 10m x 5m test field, even though the Pelican UAV still had failed connecting to the master computer for multiple times. Naively adding more wifi boosters to the field is not a feasible method to deploy the system in a large and sophisticated open area. We need a more robust and scalable communication method to make our use case come true. One potential solution could be to use satellites, and it needs a considerable amount of time and effort to investigate and deploy this method on our system.

8. Project Management

8.1. Schedule

As depicted in our updated Gantt Chart shown in figure 24, where "x" marks the expected finishing date of the task, we were able to keep up with the schedule that we updated at the beginning of the fall semester. The only milestone test passed the anticipated date was the integration test with UAV and master computer. We managed to finish the technical integration in time, but we decided to postpone our outdoor integrations test by one week as our safety pilot was out for an on-site interview to operate the system safely. This delay did not cause further delay in our schedule as we were able to conduct a whole system integration test, which incorporates the UAV integration by the next progress review.

Key Milestones	9/11/2019	9/23/2019	10/9/2019	10/23/2019	11/6/2019	11/18/2019
UAV Subsystem						
1.1.1 Setup the new temperature sensor		x				
1.1.2 Improve UAV altitude precision				x		
UGV Subsystem						
2.1.1 Setup the new temperature sensor		x				
2.2.5 Implement Obstacle Avoidance						x
Integrating and Testing						
4.1 UAV Integration				x	delayed	
4.2 UGV Integration			x			
4.3 Whole System Integration					x	
4.4 Whole System Integration with Obstacle avoidance						x

Figure 24. Fall schedule Gantt chart by the Fall Validation Demonstration

We believe our general scheduling process is effective. At the beginning of each sprint, the team usually has a meeting discussing the to-do list and work division to achieve the next milestone. During the meeting, the team re-estimate the workload of each sub-task and the potential risk of each task and coming up with a set of risk mitigation plans. For later milestones which require extensive outdoor tests, the team first plans testing date according to the weather forecast and then sets critical deadlines based on the testing data.

During the project implementation period, the team keeps updating progress to re-estimate the anticipated finish time and the risks. Based on the progress and the deadline, the team may create or reallocate tasks to achieve milestones in time. Take our complete system integration as an example, our initial plan of solving the communication latency was to switch to a higher-speed router, yet we faced unexpected difficulty in connecting the UGV to the new router due to the unique setting of Jackal. This problem subjects the team to the risk of not being able to conduct any system integration tests. Therefore, the entire team decided to tackle this communication problem with 1 team member further investigate Jackal's communication issue and the other 3 members working on different backup solutions. Finally, the backup solution of using a new router as a wi-fi booster worked, which helps us successfully achieved the milestone.

8.2. Budget

The total budget of the project is $5,000, and the cost of our project is $3573.55 (71.5% of budget), with $1,426.45 remaining. Prof. Katia Sycara sponsors the primary robot platforms. The final parts list, including quantity, brand, model, description, and cost of each part, as well as the total project cost, can be found in table 12 in the appendix.

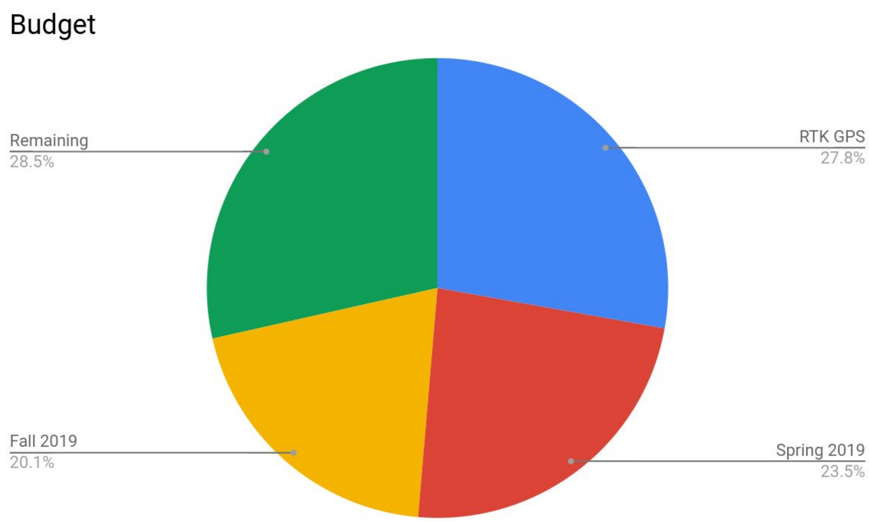


Figure 25. Budget spending status

According to our budget spending status, the major big-ticket item is RTK GPS purchased in the spring semester. We spent 23.5% of our budget in spring, not including RTK GPS, and spent 20.1% of the budget in Fall, including additional costs for testing equipment. In total, we spent $390.97 on heat source related equipment, and $446.65 on temperature sensor related devices.

While acknowledging that there exist unexpected costs in our budgeting process, mostly related to our tests with different temperature sensors and heat sources, our overall budgeting process is effective as we always tried to minimize cost when ordering parts and try to reuse as many existing parts as we can. We planned 60% of the budget at the beginning of the project, and left the rest of the budget for emergency use and purchasing testing equipment. The budgeting process can be further optimized if we could better identify the risk of the temperature converging speed of the temperature sensors and pay special attention to sensor response time in the beginning.

8.3. Risk Management

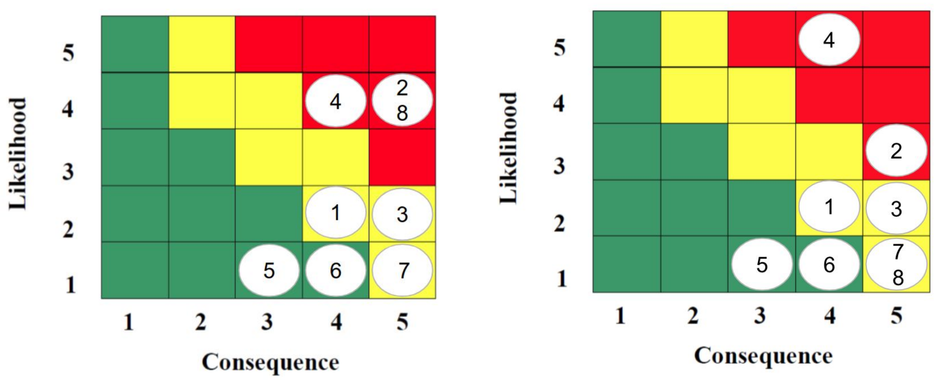
Table 7 shows the updated risk management. Risks (Risk ID: 2, 4, and 8) have been updated. The red number in the bracket indicates the change in the likelihood of the risk.

Table 7. Risk Management Table

ID	Risk	Type	Description	Likelihood	Consequence	Risk Management Evaluation
1	Electric System Failure	Technical	The battery or electric system fails due to incorrect operation.	2	4	Handled **successfully**. No electric system failure occurs.
2	Work Delay	Schedule	Heavy workload puts the team behind the schedule	3 (-1)	5	Handled **successfully**. We basically followed our schedule tightly.
3	Run Out of Budget	Financial	Run out of funds purchasing parts and repairing robots.	2	5	Handled **successfully**. We had more than $1000 left of our budget.
4	Latency for Real-time Operation	Technical	Communication latency between the master computer and UGV fails real-time operation.	5 (+1)	4	**Success:** We managed to solve the latency issue before FVD by applying an array of routers. **Failure:** The range limit of wireless communication caused the failure of the UAV sampling during FVD.
5	Poor Weather for Validation Tests	Schedule	Poor weather prevents/delays the system from outdoor experiments.	1	3	Handled **successfully** by recording videos before FVD and Encore.
6	Even Temperature Distribution	Technical	The temperate difference in the test field is close to or smaller than sensor noise.	1	4	Handled **successfully** by purchase heat source with larger power.

7	Poor Localization Accuracy	Technical	Localization accuracy is not high enough considering the size of the test field.	1	5	Handled **successfully** by applying RTK-GPS and EKF algorithm.
8	Slow Temperature Convergence	Technical	Temperature converges too slow for ground truth and onboard sensors to meet the time requirement.	1 (-3)	5	Handled **successfully** by applying the new temperature measurement solution using an infrared thermometer and copper pad.

Figure 26 shows the previous and updated risk likelihood-consequence table. The overall risk level of the system is reduced, but the riskiest tasks include Risk ID 2 and 4.



(a) (b)

Figure 26. Risk Likelihood-consequence Table: (a) original risk likelihood-consequence table, (b) updated risk likelihood-consequence table.

Generally speaking, the overall risk management of our team is done successfully. We managed to analyze all the critical risks that we met in our project, and the risk management task let us focusing on the status tracking of those risks as well as finding an ultimate solution for that risk. For example, we managed to solve the Risk number 8 by replacing our temperature to the new-designed IR temperature measurement solution. With that solution, we managed to reduce the likelihood of this risk from 4 to 1, and we never faced this risk during our experiments in the fall semester. The most valuable part of risk management is that we can predict the risk we are going to face in advance so that we can focus on solving those risks or preventing them from happening. The risk management also helps us for the scheduling since we can dedicate specific time to address possible risks.

We still have some improvements to do for our risk management. We fail to manage the risk of the coverage of our wireless communication, which causes the failure of our UAV sampling during the FVD. We have analyzed for this risk before the FVD, but our analyzed likelihood for this risk is too low since we have never faced this risk during our previous experiments. We can improve our risk management by doing a more detailed analysis of the likelihood of each risk.

9. Conclusions

9.1. Key Lessons learned

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

ii. **System robustness is important:** When the system becomes more and more complex, it is fundamentally essential to perform multiple tests to ensure the system's robustness. At the beginning of the fall semester, we believed the UGV's localization had been improved to meet the system requirements. However, in the tests before FVD, we found significant localization error, and after multiple tests, we finally realized that it is due to the incorrect transformation from the GPS to the map frame. This situation introduces instability and substantial risks to the final demonstration. It is necessary to conduct extensive experiments to confirm the functionality of each subsystem.

iii. **Plan outdoor tests beforehand:** Our system requires much outdoor testing, and the weather is one of our most significant constraints for testing. At the beginning of our testing phase, we intended 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 adverse weather conditions. Furthermore, from the beginning of the fall semester, the regulations for outdoor robot testing has been more strict. To reserve the testing field (e.g., the Cut and the soccer field at CMU Gesling Stadium), students need to make a reservation at least 2 weeks before. Therefore, we found it essential to plan and coordinate schedules among teammates as well as the testing field to get prompt tests.

iv. **Safety check before piloting robots:** Our team has paid much 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 mistake led to the drone crash and much additional effort in repairing the drone. We learned the importance of performing safety checks, even if the two tests are very close.

v. **Act early to mitigate the risks:** We have been facing the communication latency issue since we started to integrate the system. Because it is a severe problem, to ensure we have a good demonstration for each progress review, we chose to work around and not spend too much effort on actually resolving this issue. As a result, in the progress review before FVD when this became a huge risk to the system. From this, we learned that we should act early to mitigate the risks. Otherwise, they may change to substantial risks later.

9.2. Future Work

i. **Scale up the system:** In the current system, we only have one UAV and one UGV. One direction for future research is to scale up the system by increasing the number of robot agents and study the correlation between the number of agents and the amount of improvement in sampling efficiency. We need to implement the obstacle avoidance for the UAVs. We can also scale up the system by deploying the system to different types of terrains.

ii. **Plan with battery constraint:** In the current system, we only have one UAV and one UGV. One direction for future research is to scale up the system by increasing the number of robot agents and study the correlation between the number of agents and the amount of improvement in sampling efficiency. We need to implement the obstacle avoidance for the UAVs. We can also scale up the system by deploying the system to different types of terrains.

iii. **Leverage the known map constraint with SLAM:** Our current system assumes the global map of the given area is already known, which means the system has knowledge about the type of terrain at each location, and the interest point allocation algorithm directly utilizes this knowledge when assigning tasks to the agents. We believe we can leverage this constraint in the future extension of this project. With no prior knowledge at the beginning, the system can learn the terrain knowledge while the agents are exploring the area during the sampling process. We need to develop an additional SLAM module to achieve this goal.

iv. **Investigate more patterns for multi-agent collaboration:** In the current system, the UGV and UAV collaborate mainly in a way that increases the overall mobility: the UAV can traverse to location, which the UGV cannot reach. The collaboration between them, in terms of efficiency, is naturally achieved as the UAV can travel between different locations very fast, and hence it can take more samples. One possible future extension for the project is that we can investigate the more complex pattern of collaboration that can increase the overall accuracy and efficiency. One example would be to use the UGV as a moving charging station for UAV, as mentioned before.

Reference

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[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://www.sparkfun.com/datasheets/Sensors/Temperature/MLX90614_rev001.pdf

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[7] https://www.sparkfun.com/products/10740

[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.

10. Appendix

Table 8. Obstacle descriptions

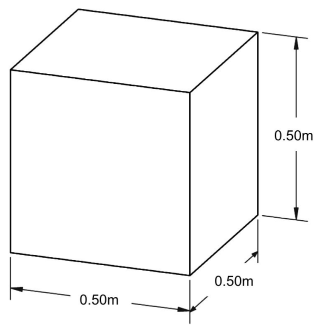
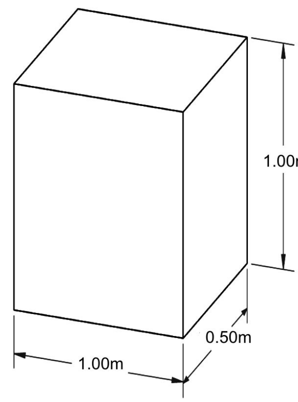
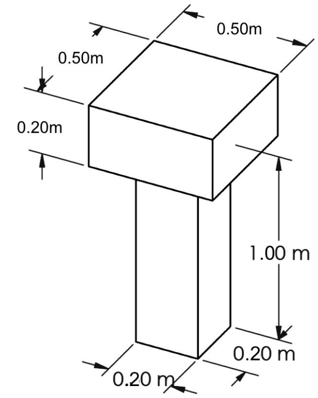
Obstacle			
			
Quantity	1	1	2

Table 9. 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 10. Morphology Chart for robot cluster trade study

Criteria	Weight Factor (100%)	NTC	RTD	Thermocouple	Infrared
Accuracy	35	4	5	2	4
Responsiveness	30	4	2	3	5

Cost	25	5	1	3	5
Range	10	3	4	5	4
Weighted Sum	100	4.15	3.00	2.85	4.55

Table 11. Technical Specifications for different Temperature Sensors [8]

Criteria	NTC	RTD	Thermocouple	Infrared
Accuracy (℃)	0.05 ~ 1.50	0.10 ~ 1.00	0.50 ~ 5.00	0.20 ~ 8.00
Responsiveness (s)	0.12 ~ 10	1 ~ 50	0.2 ~ 20	0.01
Cost ($)	Low	High	Medium	Low
Range (℃)	-50 ~ 250	-200 ~ 600	-200 ~ 1750	-70 ~ 380

Table 12. Final parts lists and the total project cost

Part Name (brand and description)	Quantity	Unit Price	Total Price
SensorPush Wireless Thermometer/Hygrometer for iPhone/Android - Humidity & Temperature Smart Sensor with Alerts. Developed and Supported in The USA	2	$49.99	$99.98
SensorPush G1 WiFi Gateway - Access your SensorPush Sensor Data from Anywhere via the Internet	1	$99.95	$99.95
OMAYKEY 2 Pack 100W Ceramic Heat Lamp with 1-pcs Digital-Thermometer, Infrared Reptile Heat Emitter Heater Lamp Bulb for Pet Brooder Coop Chicken Lizard Turtle Snake Aquarium, No Light No Harm	2	$16	$32
Readytosky RC 1-8s Lipo Battery Tester Monitor Low Voltage Buzzer Alarm Voltage Checker with LED Indicator for Lipo Life LiMn Li-ion Battery(4PCS)	1	$9.89	$9.89
TEMPer High Accurate USB Thermometer Temperature Sensor Data Logger Record for PC Laptop	4	$13.99	$55.96
MXTECHNIC USB 2.0 Expansion Spring Coiled Cable 4inch(in) Standard Spiral Flexible Active Extension USB 2.0 A-Male to A-Female Processors for Printers, Cameras, Mouse and Other USB Computers	4	$6.99	$27.96
Reach UAV Mapping Kit	1	$1,124.00	$1,124.00

Reach M+	1	$265.00	$265.00
R0805 100	30	$0.10	$3.00
10000pF Capacitor C0805	20	$0.10	$2.00
10A FUSE	5	$1.13	$5.65
Zener-Diode1N4733	5	$0.26	
R0805 1k	30	$0.36	$10.80
R0805 2k	30	$0.36	$10.80
R0805 3.83K	10	$0.36	$3.60
R0805 360	10	$0.10	$1.00
3A FUSE	10	$0.87	$8.70
60mA FUSE	5	$0.54	$2.70
R0805 910	10	$0.10	$1.00
LED BLUE CLEAR 1206 SMD	10	$0.40	$4.00
CONN PWR JACK KINKED PIN SOLDER	10	$0.73	$7.30
LED GREEN CLEAR 1206 SMD	30	$0.34	$10.20
IC OPAMP GP 1.2MHZ 14SOIC	5	$0.38	$1.90
IC REG LINEAR 5V 3A TO263-3 MIC29300-5.0WU	15	$3.58	$53.70
CONN RCPT USB2.0 MINI B SMD R/A	5	$0.65	$3.25
OliYin 10 Pairs MPX M6 Connector Plug Multiplex Socket for RC Lipo Battery Quadcopter/Buggy 6M	1	$8.98	$8.98
TVS DIODE 13.6V 22.5V DO214AC	5	$0.47	$2.35
LED RED CLEAR 1206 SMD	10	$0.46	$4.60
TVS DIODE 5V 9.66V DO214AC SMAJ5.0	12	$0.62	$7.44
CAP TANT 10UF 20% 10V 1411 TAJB106M010RNJ	20	$1.00	$20.00
CAP TANT 10UF 20% 35V 2312 TAJC106M035RNJ	20	$1.00	$20.00
LED YELLOW CLEAR 1206 SMD	10	$0.51	$5.10
Mr. Heater F232000 MH9BX Buddy 4,000-9,000-BTU Indoor-Safe Portable Propane Radiant Heater	1	$71.94	$71.94
Mr. Heater Buddy Series Hose Assembly 10-ft., Model# F273704	1	$24.15	$24.15
Mr. Heater Fuel Filter for Portable Big Buddy Heaters #F273699	1	$11.99	$11.99
Standard Propane Fuel Cylinder - Pack of 3	1	$27.25	$27.25
TEMPer High Accurate USB Thermometer Temperature Sensor Data Logger Record for PC Laptop	6	$13.99	$83.94

MXTECHNIC USB 2.0 Expansion Spring Coiled Cable 4inch(in) Standard Spiral Flexible Active Extension USB 2.0 A-Male to A-Female Processors for Printers, Cameras, Mouse and Other USB Computers	6	$6.99	$41.94
High Synthetic BGA Solder Paste Tin Rosin-Based Flux Paste Cream Activated Rosin for Circuit Board PCB BGA SMD PGA Repair Soldering Rework Station (80g)	1	$11.99	$11.99
GeToo 900 Series Soldering Tip for HAKKO 936,937,907, and X-Tronic Soldering Station, Set of 5 Shapes	1	$8.95	$8.95
DIKAVS Breadboard-friendly 2.1mm DC Barrel Jack (Pack of 10)	1	$7.99	$7.99
Tallysman Multi-GNSS Antenna for Reach M+	1	$65.00	$65.00
ANBES Soldering Iron Kit Electronics, 60W Adjustable Temperature Welding Tool, 5pcs Soldering Tips, Desoldering Pump, Soldering Iron Stand, Tweezers	1	$18.99	$18.99
AM2315 - Encased I^2C Temperature/Humidity Sensor	2	$29.95	$59.90
Qunqi 400 tie Point Experiment Mini Breadboard 5.5×8.2×0.85cm	2	$5.69	$11.38
WYPH Mini Nano V3.0 Module ATmega328P 5V 16MHz CH340G Chip Microcontroller Development Board USB Cable for Arduino (Pre-soldered Nano 3pcs)	1	$12.35	$12.35
HiLetgo 2pcs ESP8266 NodeMCU LUA CP2102 ESP-12E Internet WiFi Development Board Open Source Serial Wireless Module Works Great with Arduino IDE/Micropython (Pack of 2PCS)	1	$12.99	$12.99
EDGELEC 120pcs Breadboard Jumper Wires 10cm 15cm 20cm 30cm 40cm 50cm 100cm Optional Dupont Wire Assorted Kit Male to Female Male to Male Female to Female Multicolored Ribbon Cable	1	$6.98	$6.98
Dual Laser Infrared Thermometer, Zenic Professional Non-Contact Digital Temperature Measuring Gun with Adjustable Emissivity for Cooking/Brewing/Automobile & Industries, -50-650℃, D:S=12:1	1	$26.49	$26.49
SwimWays Kelsyus Original Canopy Chair	2	$60.99	$121.98
Arcshell Rechargeable Long Range Two-Way Radios with Earpiece 2 Pack UHF 400-470Mhz Walkie Talkies Li-ion Battery and Charger Included	1	$25.99	$25.99
TP-Link AC1200 Smart WiFi Router - 5GHz Gigabit Dual Band MU-MIMO Wireless Internet Router, Long Range Coverage by 4 Antennas(Archer A6)	1	$44.99	$44.99
JIUWU IC Chipset GPU CPU Thermal Heatsink Copper Pad Shim Size 20 x 20 x 0.3mm Pack of 20	1	$7.69	$7.69

SparkFun Electronics SEN-10740	1	$49.95	$49.95
FTDI, Future Technology Devices International Ltd UMFT201XB-WE	1	$10.41	$10.41
TalentCell Rechargeable 12V 6000mAh/5V 12000mAh DC Output Lithium Ion Battery Pack for LED Strip and CCTV Camera, Portable Li-ion Battery Bank with Charger, Black (Multi-led Indicator)	1	$33.99	$33.99
SparkFun IR Thermometer Evaluation Board - MLX90614	1	$34.95	$34.95
FTDI Cable 5V VCC-3.3V I/O	2	$17.95	$17.95
UNI-T UT332 Digital Thermo-hygrometer Temperature Humidity Moisture Meter Sensor w/USB & Power Saving Mode	1	$120.38	$120.38
Energizer Rechargeable AA and AAA Battery Charger	1	$18.97	$18.97
Rechargeable AAA Batteries	1	$17.97	$17.97
Hiland HLDS032-B Portable Table Top Patio Heater, 11,000 BTU, Use 1lb or 20Lb Propane Tank, Stainless Finish	1	$72.99	$72.99
Propane Fuel Cylinders, 4 pk./16 oz.	1	$29.99	$29.99
Push Cart Dolly by Wellmax, Moving Platform Hand Truck, Foldable for Easy Storage and 360 Degree Swivel Wheels with 330lb Weight Capacity, Yellow Color	1	$63.97	$63.97
Hiland HLDS032-B Portable Table Top Patio Heater, 11,000 BTU, Use 1lb or 20Lb Propane Tank, Stainless Finish	1	$72.99	$72.99
Cat 7 Ethernet Cable, Danyee Nylon Braided 50ft CAT7 High Speed Professional Gold Plated Plug STP Wires CAT 7 RJ45 Ethernet Cable (Black 50ft)	4	$21.99	$87.96
TP-Link AC1200 Smart WiFi Router - 5GHz Gigabit Dual Band MU-MIMO Wireless Internet Router, Long Range Coverage by 4 Antennas(Archer A6)	3	$44.99	$134.97
TalentCell Rechargeable 12V 6000mAh/5V 12000mAh DC Output Lithium Ion Battery Pack, Portable Li-ion Battery Bank with Charger, Black (Multi-led Indicator)	3	$33.99	$101.97
Valley Enterprises 2.1mm x 5.5mm Straight DC Male Power Plug with Anderson Powerpole Connectors, 18 Gauge Wire	1	$12.49	$12.49
TalentCell Rechargeable 12V 6000mAh/5V 12000mAh DC Output Lithium Ion Battery Pack for LED Strip and CCTV Camera, Portable Li-ion Battery Bank with Charger, Black (Multi-led Indicator)	1	$33.99	$33.99
Coleman Propane Fuel Case of 6	1	$39.98	$39.98
Total Cost			**$3,573.55**