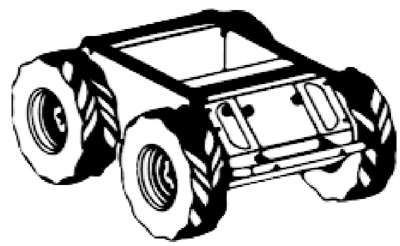
Heterogeneous Multi-Robot Sampling
Conceptual Design Review

Team G: SAMP



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1. Project Description

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 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 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.

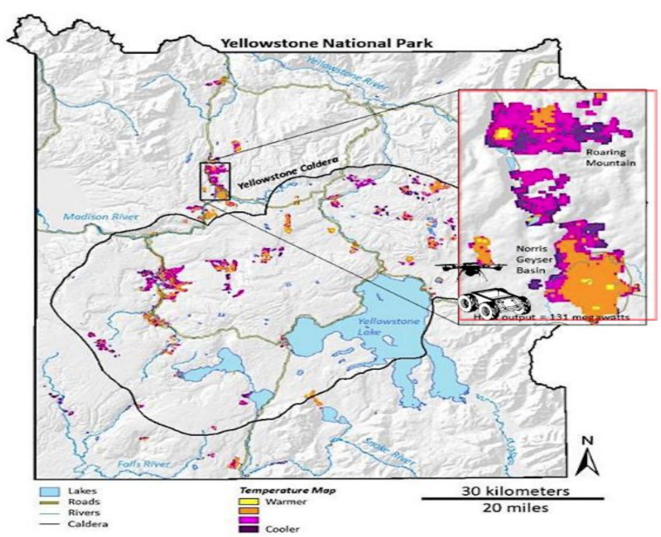

Figure 1. Yellowstone National park map with thermal information indicated in different colors. The selected interest region is shown in the red bounding box. A UAV and a UGV are deployed in the region of interest to take samples for generating the temperature distribution model.

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 temperature model for an area within the dimension of 20m×20m×5m.	A demo covering nontrivial scale is expected.
M.P.2	The accuracy of the temperature distribution model will be greater than 80%.	The temperature distribution model is expected to be close to 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 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 each sample.	The system is expected to conduct efficient model updating.
M.P.6	Both UAV and UGV will reach and take temperature samples at the assigned locations with 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 obstacle-free trajectory through randomly-deployed obstacles. The quantities and dimensions of obstacles are listed in Table.12.	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 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

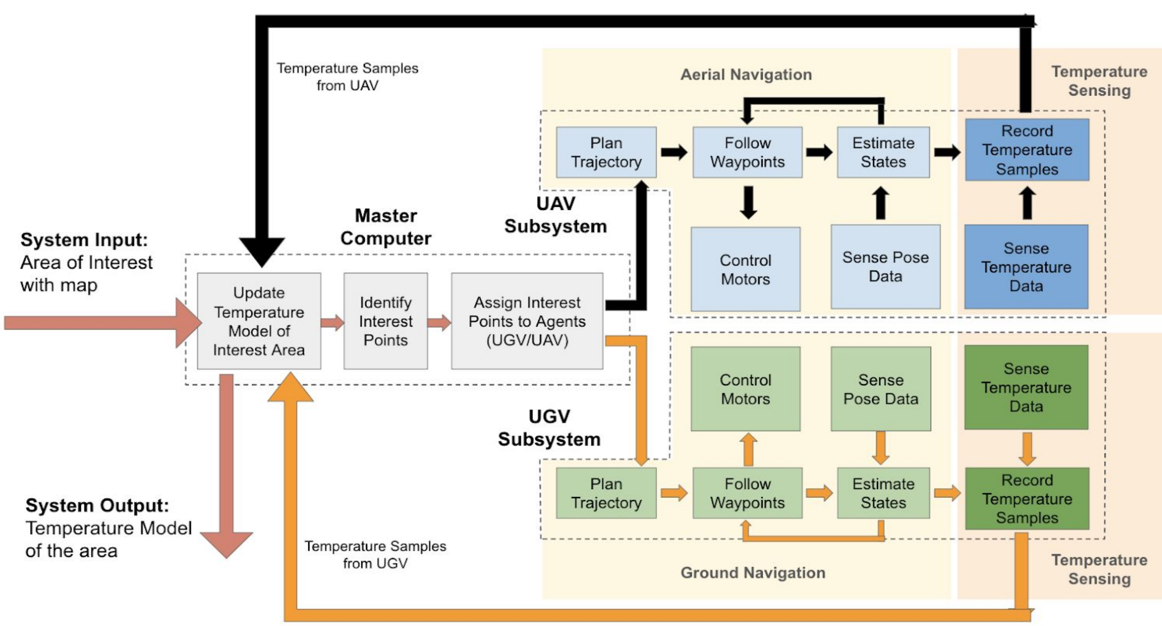

Figure 2. Functional architecture of the sampling project

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 Mater 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 Mater 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 Mater 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. 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.13 in the appendix.

5.1.1. Sampling Efficiency

Sampling efficiency directly determines how fast the desired temperature model can be generated. It is one of the most important 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 good efficiency.

5.1.2. 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 largest weighing factor is also assigned to this criteria.

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 actually 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 will give 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.

5.1.3. Mobility

The project aims to help scientific environmental researches, which are usually conducted in various non-trivial environments. The robot cluster is expected to have good 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 is able to combine the mobility of both UGV and UAV to earn the highest mobility.

5.1.4. Duration

M.P.9 sets a minimum duration for each sampling task, therefore, the duration is also an important criteria 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.

5.1.5. 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 repairing 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. Four common temperature sensors: Negative

Temperature Coefficient (NTC) thermistor; Resistance Temperature Detector (RTD); Thermocouple and Semiconductor-based sensors are considered. The detailed morphology chart is shown in Table.14 in the appendix. The specific weight scores are determined according to the technical specifications listed in Table.15

5.2.1. Accuracy

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

5.2.2. Responsiveness

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

5.2.3. 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.

5.2.4. 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 concern.

6. Cyberphysical Architecture

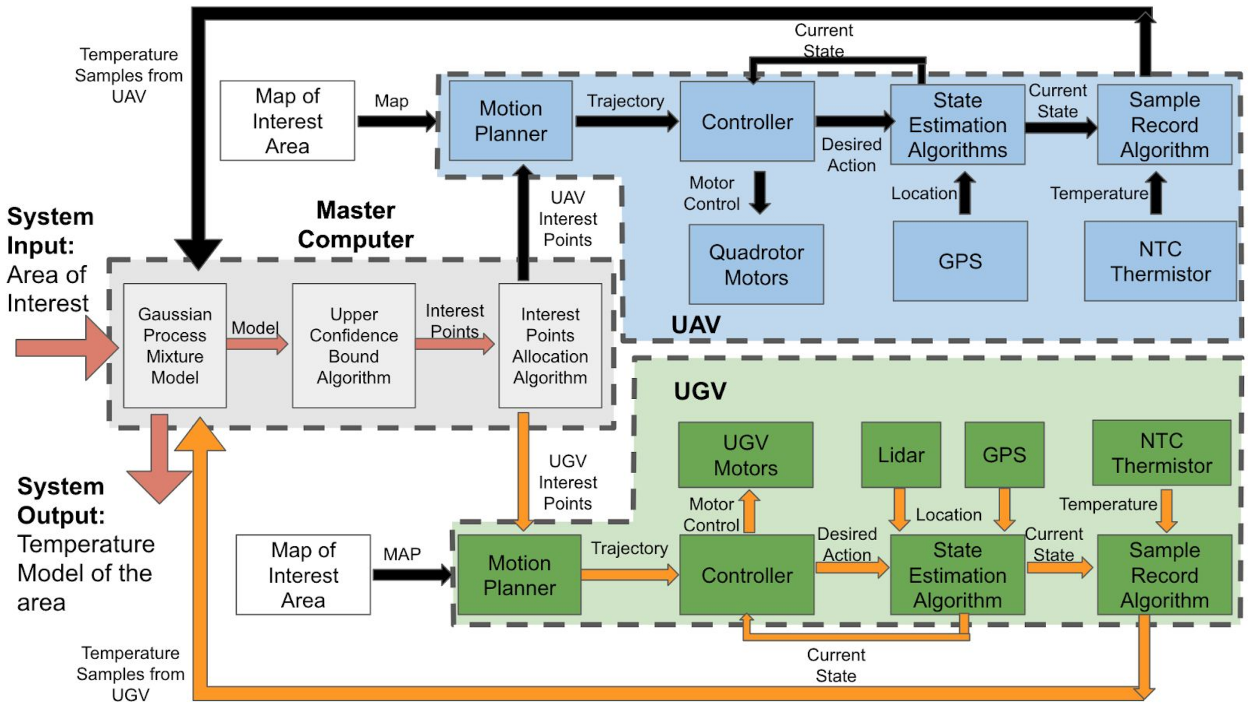

Figure 3. Cyberphysical Architecture and Information Flow

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.

6.1. 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.

6.2. 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.

7. Subsystem Descriptions

7.1. Master Computer

7.1.1. 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.

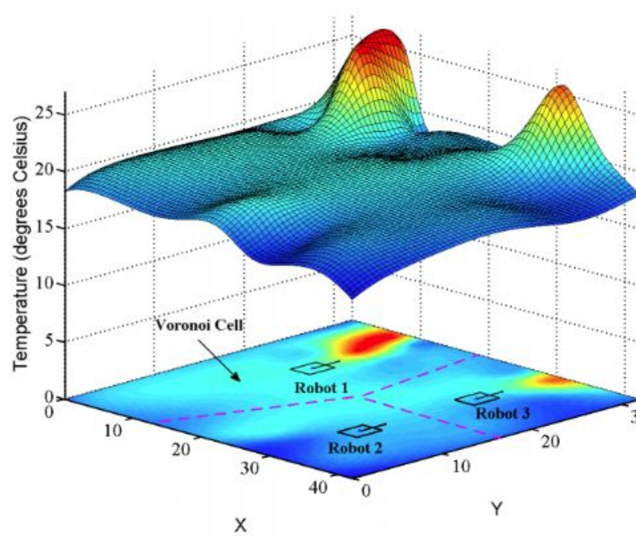

Figure 4. Example Temperature Gaussian Mixture Model [10]

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 4. It demonstrates a good generalization of environmental modeling, especially for temperature modeling.

7.1.2. 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 applies Upper Confidence Bound algorithms to select the next interest points, which would give the most temperature information according to the current model. The upper confidence bound is determined the sample noise as well as the number of times sampled before. The higher the upper confidence bound for interest point, the more accurate the model will be after the temperature samples are taken.

7.1.3. Interest Point Allocation Algorithm

After the interest points are selected, Master Computer would assign those points to specific robots by interest point allocation algorithm. The major considerations are under 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.

7.2. UGV Subsystem

7.2.1. Hardware

We will be using Jackal UGV for 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.

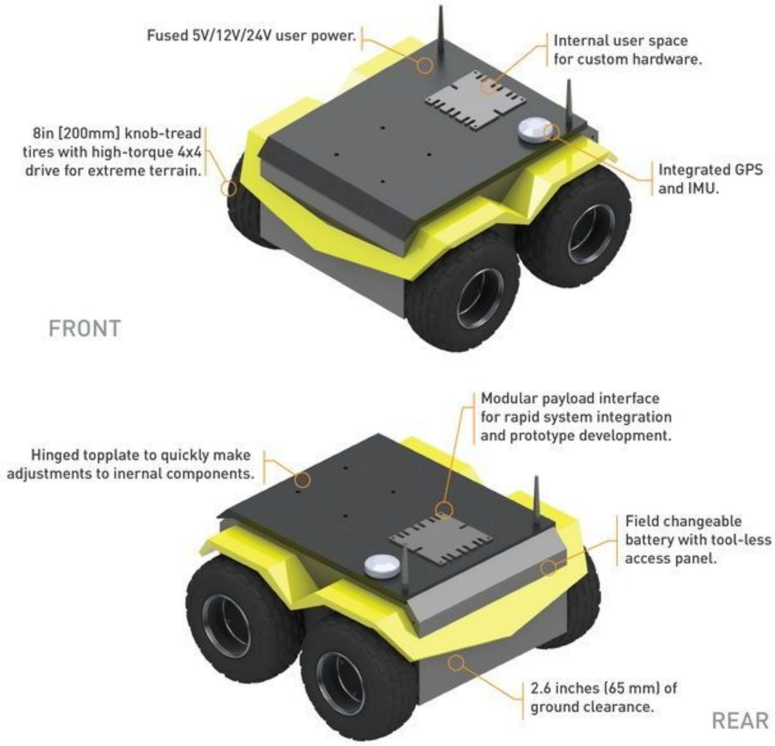

Figure 5. Jackal UGV [1]

Additionally, we plan to install 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 8).

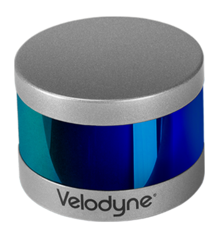

Figure 6. Bumblebee stereo camera [4]

Figure 7. Velodyne VLP-16 LiDAR

[3]

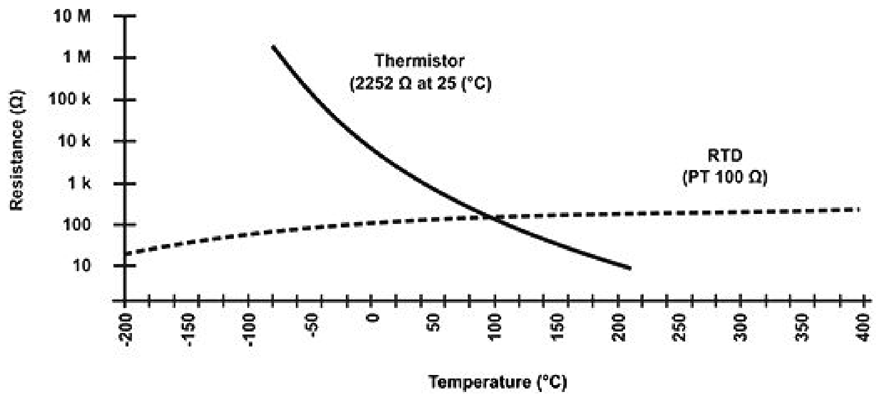

Figure 8. Thermistor performance characteristics [5]

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].

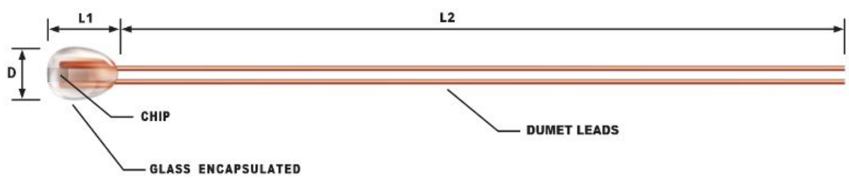

Figure 9. NTC Thermistor[7]

7.2.2. 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 plan to deploy D* algorithm so that we can generate an optimal path while avoiding local obstacles.

We plan to use 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 State Estimation Algorithm keeps reading the LiDAR and GPS values to estimate whether the target location is achieved.

Once the agent arrives 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.

7.3. UAV Subsystem

7.3.1. Hardware Platform

We will be 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 10. AscTec Pelican UAV

7.3.2. Software

The navigation algorithm of UAV subsystem is similar as the software of UGV subsystems since they are playing a similar role. The detail of their control algorithms will be different due to the difference of their dynamic models.

8. Project Management

8.1. Work plan and Tasks

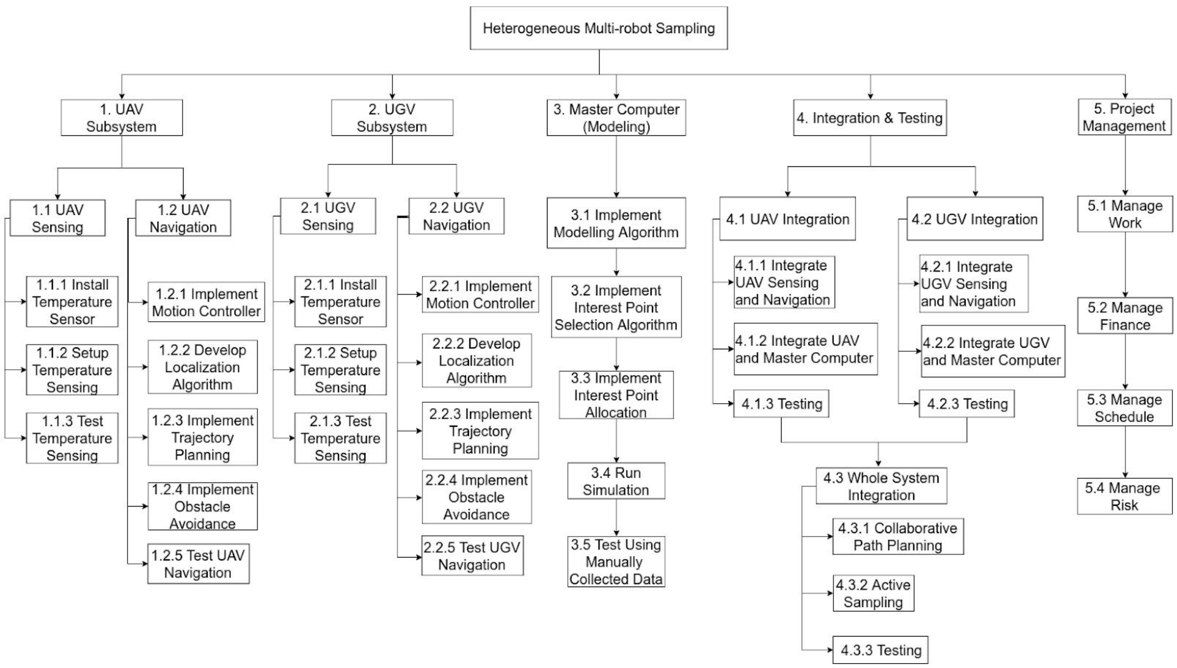

Figure 11. Work Breakdown Structure (WBS) for the system

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 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.

8.2. Schedule

The detailed spring schedule of each task specified in WBS and milestones are shown in the Gantt chart. The intended fall schedule is shown in table 16 in Appendix. We plan to finish three subsystems individually in spring and leave the integration and testing tasks to fall semester. As the three subsystems are independent, we decide to use a sequential method to proceed so that teammates can participate in every system design and implementation. Teammates can also help each other during the project execution.

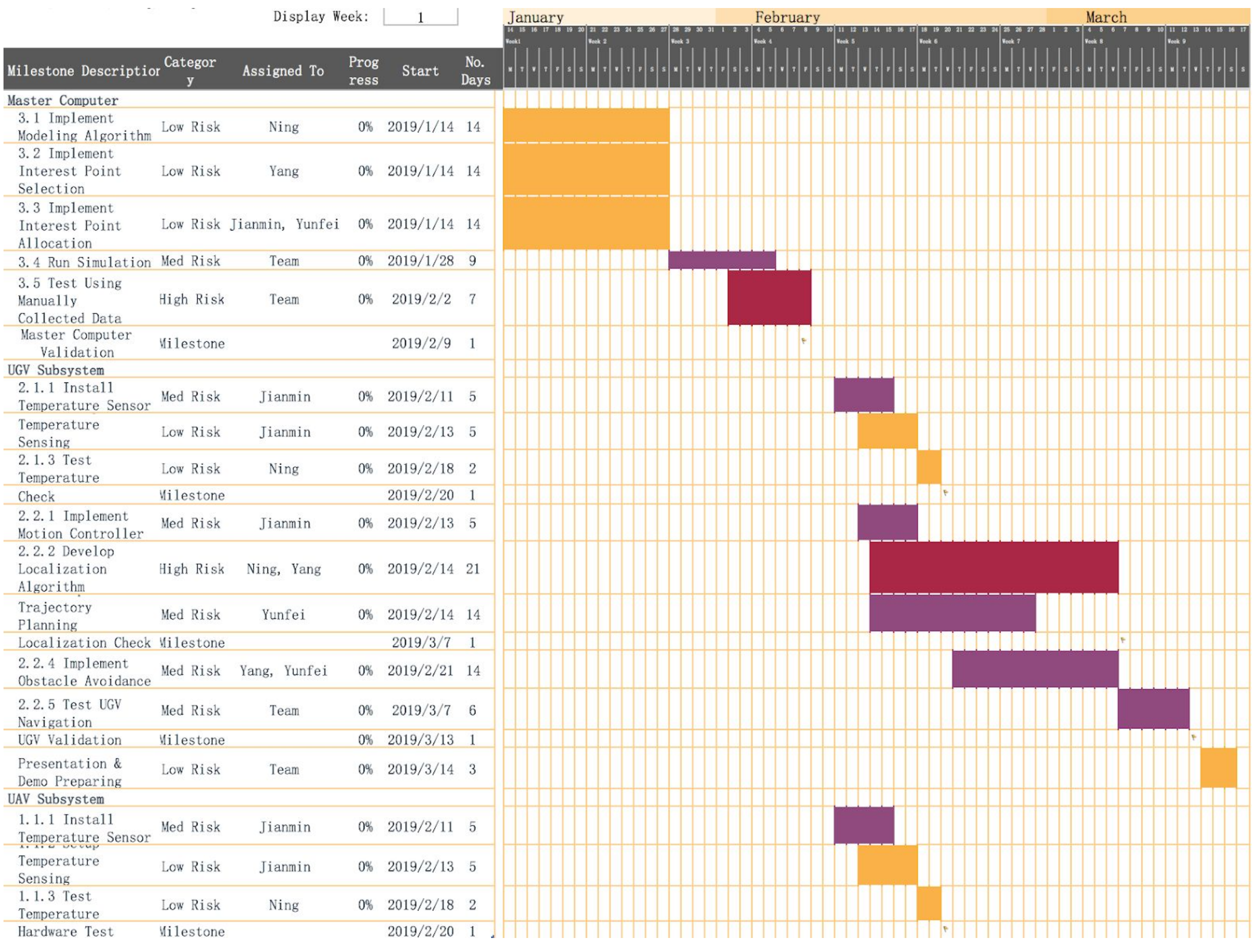

Figure 12. Spring schedule Gantt chart by the Preliminary Design Review on 18 March 2019

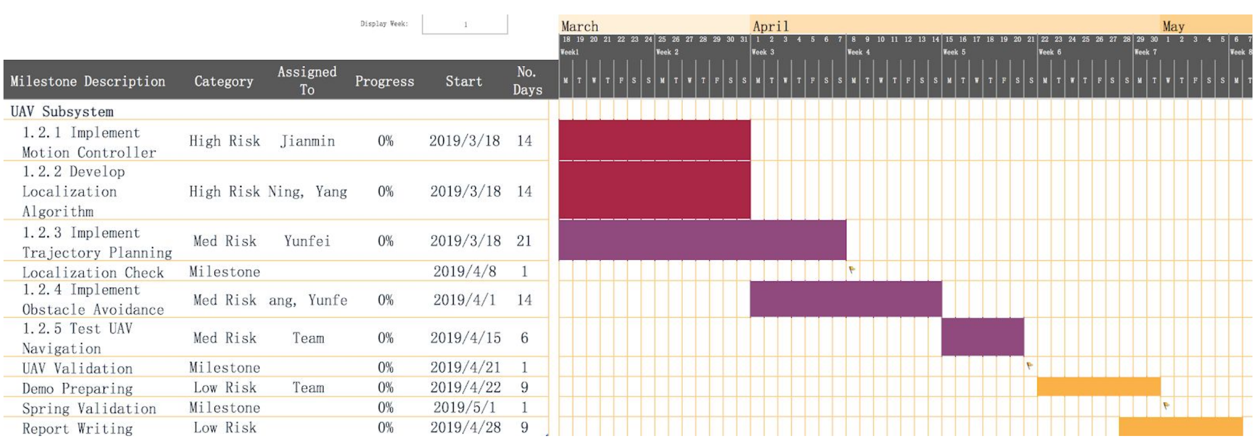

Figure 13. Spring schedule Gantt chart by the Critical Design Review on 6 May 2019

In the spring semester, we start with the master computer subsystem by implementing three main algorithms in parallel. After finishing implementing algorithms, all team members will run simulation and test together. We have the first group milestone on 9 Feb 2019. Similarly, we assign milestones after each major task to make sure we can achieve all progress review goals. The different colors in the Gantt chart represent different risk level: yellow stands for low risk, purple stands for mid risk and red represents a high risk. Generally, the integration tasks have a higher level of risk and the localization tasks are assigned with higher risk level based on team members' past experience.

Our preliminary design review goal is finishing Master Computer subsystems that given temperature samples, the subsystem can generate accurate distribution model and UGV subsystems that given the target location, UGV can navigate to that point without collision and take accurate samples that satisfied out performance requirements by 13 March 2019

The Spring validation Experiment goal, as well as the Critical Design Review goal, is finishing Master Computer, UGV subsystems and UAV subsystem that given a target location, the UAV can take off, navigate to the point, take temperature measurement and landing satisfying the performance requirements by 22 April 2019.

8.3. System Validation Experiment

8.3.1. Spring Validation Experiments

Table 5. Master Computer Subsystem Validation Experiment

Location	No specific requirement.
Criteria	Temperature Model's Root Mean Square Error less than 1 ℃
Equipment	Master Computer, Intel Lab Data [9]
Procedure	1. Master computer updates temperature model. 2. Master computer determines next interest points. 3. Master computer allocates points to UAV/UGV. 4. Return temperature data from dataset. 5. Loop through 1-4 until the model converges.

Table 6. UGV Subsystem Validation Experiment

Location	An outdoor area within the dimension 20m x 20m x 5m
Criteria	1. Location error: less than 2m 2. Temperature error: less than 2 °C
Equipment	UGV, Tape measure, Stopwatch, Temperature Sensor
Procedure	1. Power on UGV. 2. Assign an interest point to UGV agent (and command it to stop once arrived) 3. After the UGV agent stops, measure the errors between the arrived location and desired location. 4. Export the recorded temperature sample from UGV and measure the error between the measured temperature and ground truth.

Table 7. UAV Subsystem Validation Experiment

Location	An outdoor area within the dimension 20m x 20m x 5m
Criteria	1. Location error: less than 2m 2. Temperature error: less than 2 °C
Equipment	UAV, Tape measure, Stopwatch, Temperature Sensor
Procedure	1. Power on UAV agent 2. Assign an interest point to UAV agent (and command it to collect temperature data and land once arrived) 3. After the UAV agent lands, measure the errors between the arrived location and desired location. 4. Export the recorded temperature sample from UAV and measure the error between the measured temperature and ground truth.

8.3.2. Fall Validation Experiments

Table 8. System Validation Experiment

Location	An outdoor area within the dimension 20m x 20m x 5m
Criteria	Temperature Model's Root Mean Square Error less than 1 ℃
Equipment	UGV, UAV, Master Computer, Temperature Sensor

Procedure	1. Power on the entire system 2. Take samples manually by external temperature sensors to generate the ground truth temperature distribution model 3. Run the Master Computer, UAV and UGV to take samples and update the temperature distribution model 4. Export the predicted model and compare it with the ground truth model

8.4. Responsibilities of Each Team Member

Table 9 shows the responsibilities of team members which were assigned based on their interest and strengths. A 'P' indicates the primary responsibility while a 'S' indicates the secondary responsibility.

Table 9. Team Member Responsibility

Tasks	Jianmin Zheng	Yunfei Shi	Yang Zhang	Ning Wang
Master Computer - Modeling				P
Master Computer - Interest Point Selection			P	
Master Computer - Interest Point Allocation	S	P		
Master Computer - Test	S	S	P	S
UAV and UGV - Hardware	P			S
UAV and UGV - Localization			P	S
UAV and UGV - Planning	S	P		
UAV and UGV - Control	P			
UAV and UGV - Test	S	S	S	P
System- Integration and test	S	P	S	S

8.5. Budget

Table 10. Project Budget

Product	QTY	Cost	Description
Wireless Temperature Sensor	40	$ 1,960	Used for ground truth generation
Temperature Sensor on Robot	8	$800	Used for sampling data collection
Jackal	1	Sponsored	UGV platform
Intel AscTec Pelican UAV	1	Sponsored	UAV platform
Velodyne VLP-16 LiDAR	1	Sponsored	Used for UGV localization
Thinkpad Laptop	1	$1,500	Used as Master Computer
Wifi Amplifier	2	$100	Amplify wifi signal to enhance the wireless connection
Total		$4,360	

8.6. Risk Management

Table 11. Risk Analysis

Risk Detail	Management Strategy	Risk Type
The battery and electrical system may be damaged due to incorrect operation of the team member.	1. Optimize the electrical design to protect the electric system. 2. Set up technical documents to regulate the operation of the team members.	Technical
Temperature variance smaller than sensor noise	1. Increase local temperature features when demo. 2. Use sensors with higher sensitivities based on previous experiment results	Technical
Some part of work may be delayed due to personal fair and affect following work packages.	1. Append all the work to owners, make every team member be responsible for certain part of works. 2. Optimize the WBS, break down the workload into manageable pieces.	Schedule

The robot mechanically break due to crash	1. Add a layer of safety constraints. 2. Develop a safety checklist with teammates to ensure the operation is correctly performed during testing.	Technical
Team members may have a tight schedule in some weeks for homework and may not catch the milestone	1. Take everybody's assignment schedule into consideration when developing the project schedule. 2. Keep documenting the tasks and works while proceeding, so if an emergency occurs, team members can take over to finish tasks on time for the milestone.	Schedule
Run out of funds for sensors and repairing robots	1. Make robot safe using technical risk solutions 2. Make purchasing decision carefully after research.	Financial

9. 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://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

[10] 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 12.. Obstacle descriptions

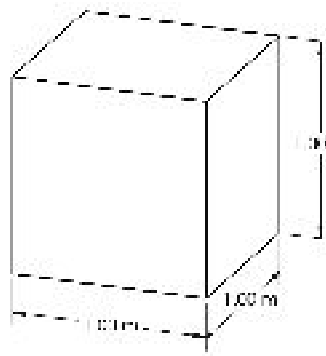
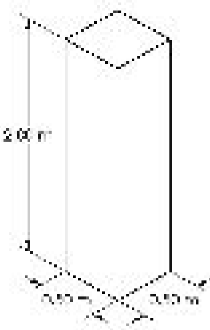
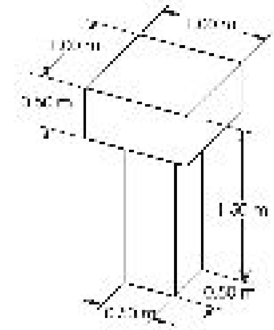
Obstacle			
Quantity	2	2	4

Table 13. 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 14. 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 15. 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

Table 16. Milestones of Fall 2019

Milestone	Date
1. UAV Integration and Testing	September 22
2. UGV Integration and Testing	October 4
3. System Integration and Testing	November 20