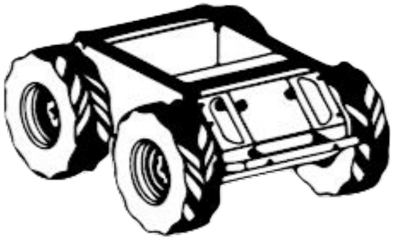
Heterogeneous Multi-Robot Sampling

Critical Design Review



Team G: SAMP

Project Description:

Conventional Environmental Modelling

- Manual Sampling
- Discretized and limited coverage
- Tremendous manpower

Robotics Automation Environmental Modelling

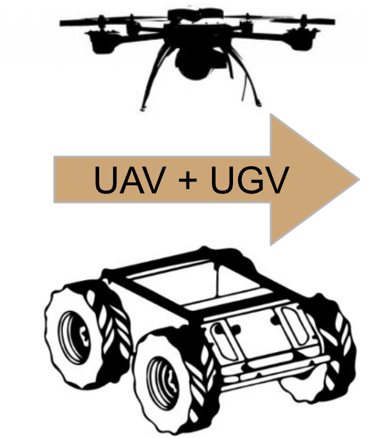
- Efficient and automated solution
- Better mobility and coverage
- Frequent modelling update

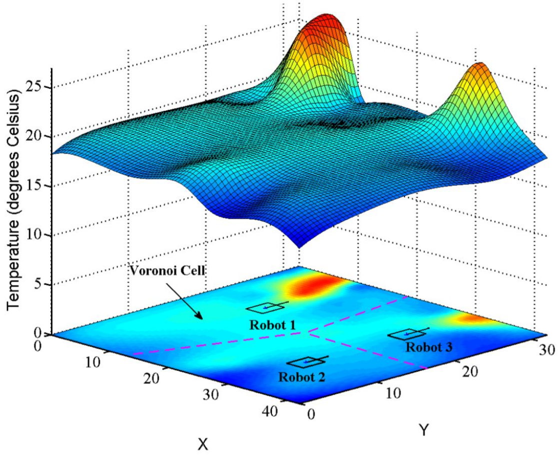
http://www.ecofishresearch.com/our-services/nvironmental-compliance-effects-monitoring

Project Description:

We aim to deliver a UAV-UGV team that performs online environmental sampling and modeling collaboratively given an outdoor area with different terrains.

https://secondnexus.com/environment/yellowstone-caldera-nasa-supervolcano/

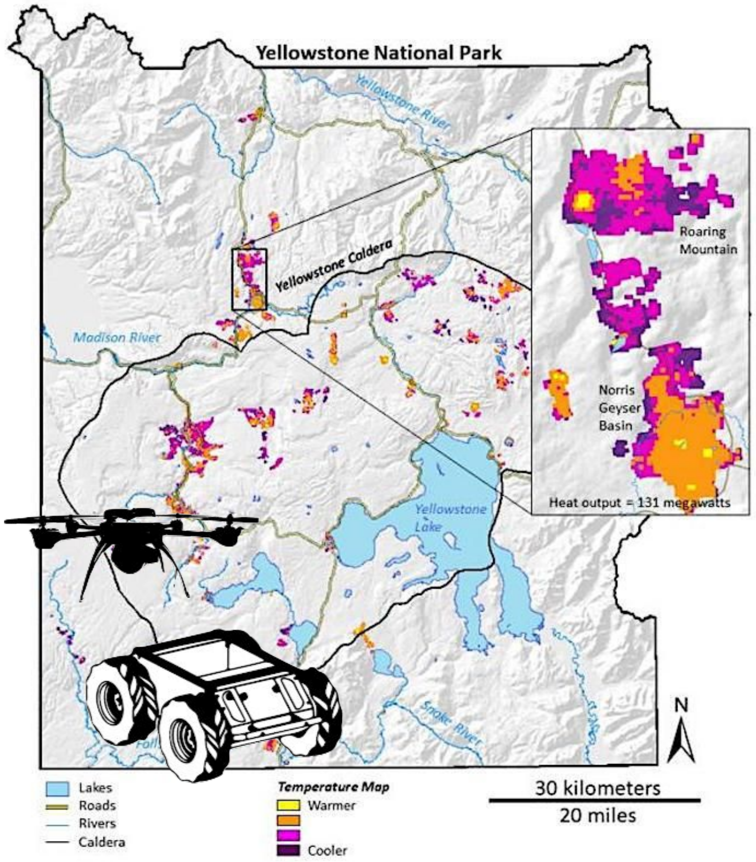




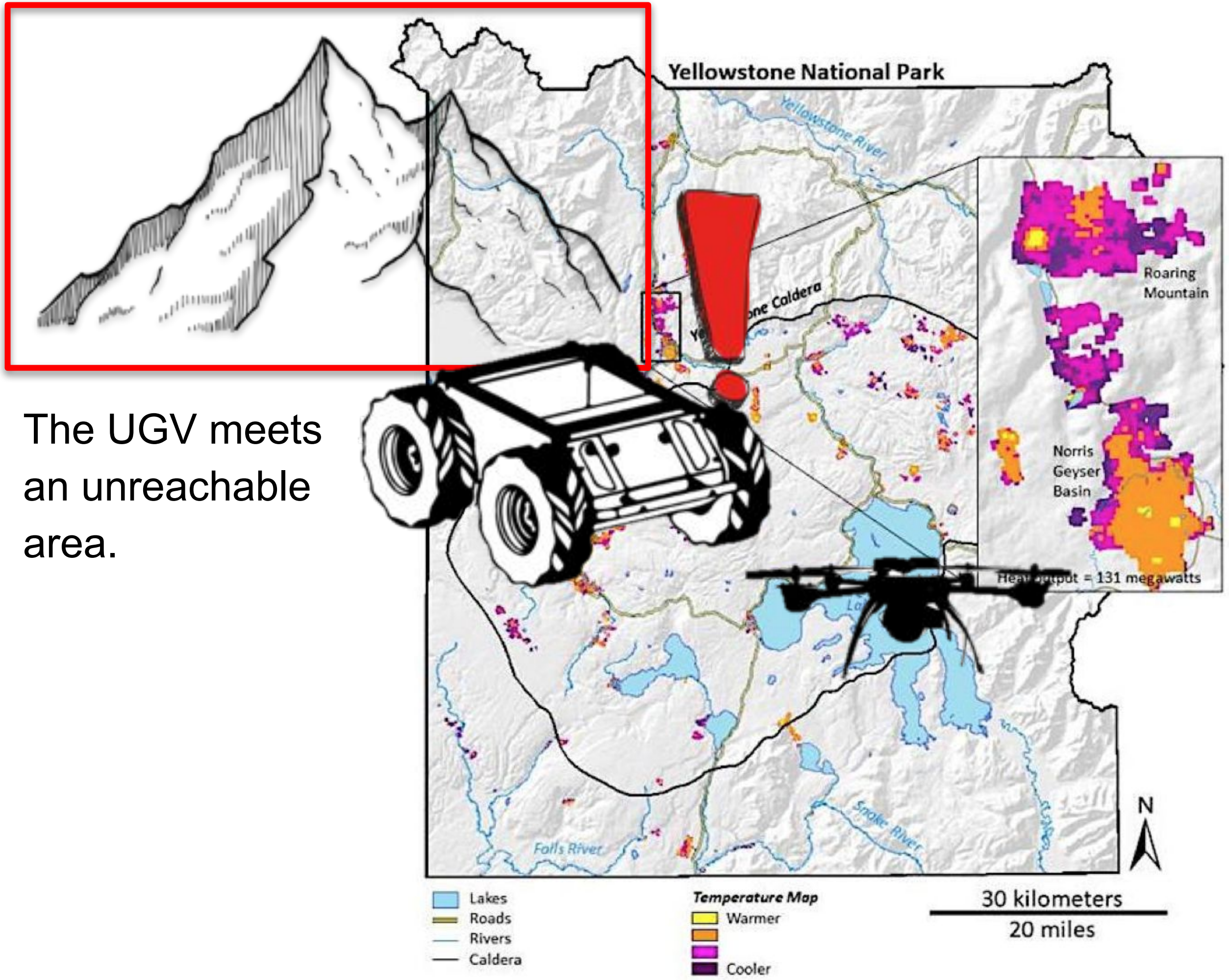
Wenhao and Katia, ICRA, 2018

Use Case: Scientific Monitoring

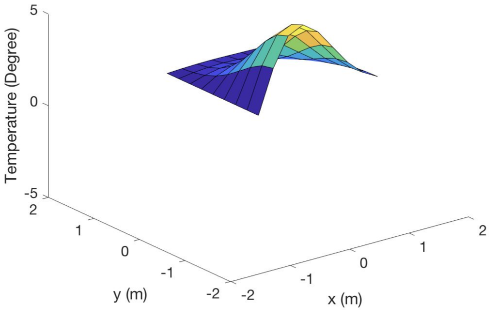
- Environmental Scientist Tom wants to study Yellowstone's thermal activity.
- Tom first tells the system the region where he wants to monitor the temperature.
- One UAV and one UGV enter the region and start collecting temperature samples collaboratively.

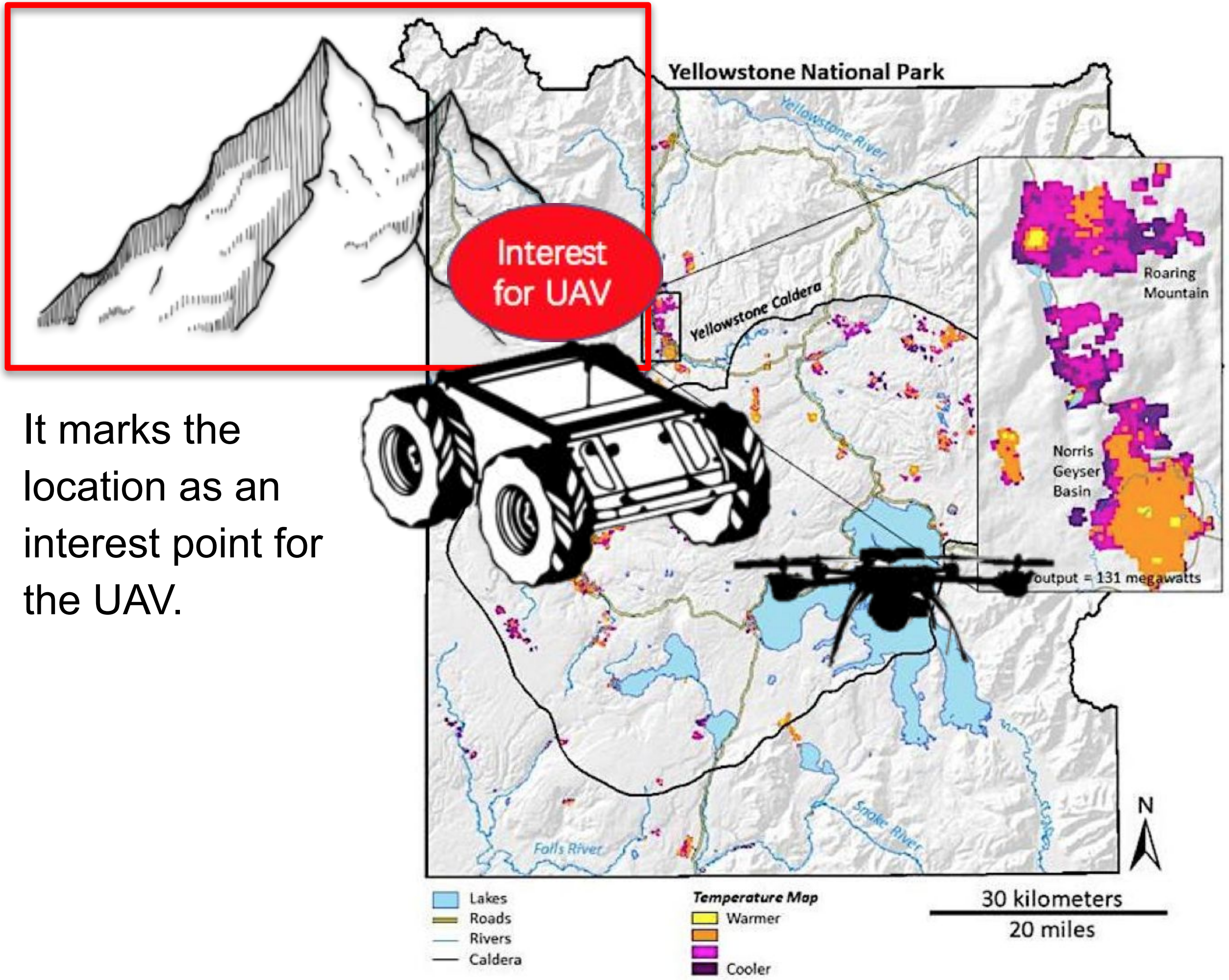


https://robohub.org/coordinated-uav-docking/
https://pubs.usgs.gov/sir/2014/5137/pdf/sir2014-5137.pdf

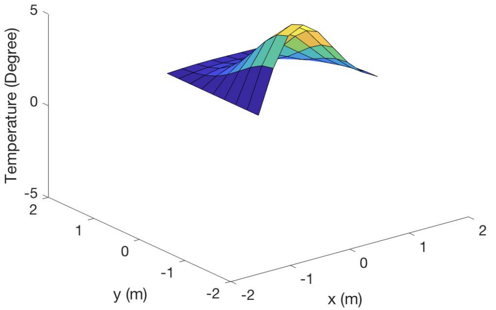


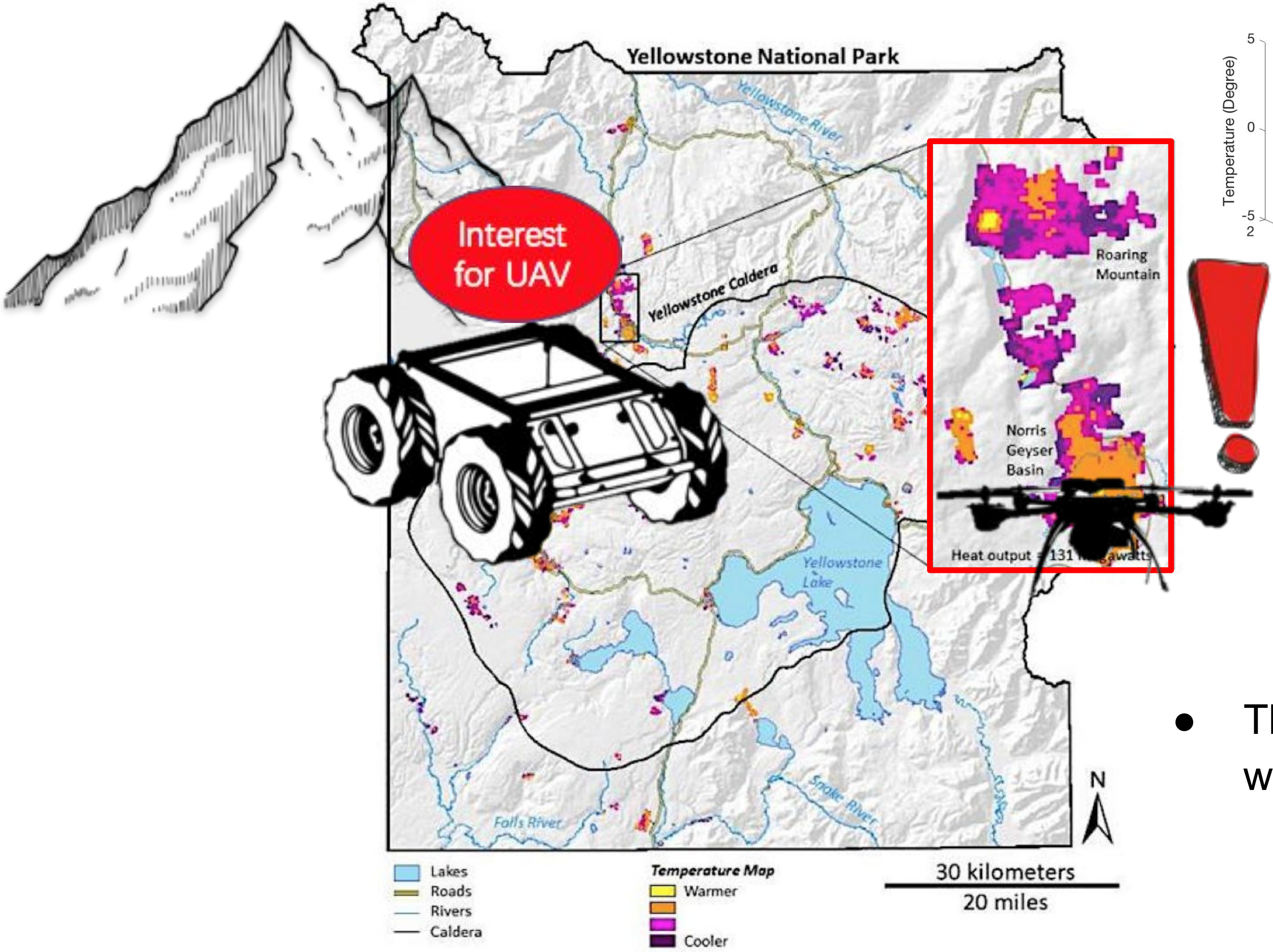
- The UGV meets an unreachable area.

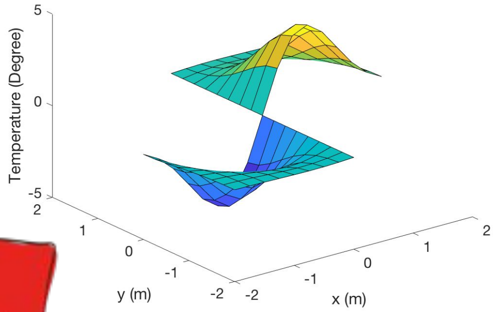




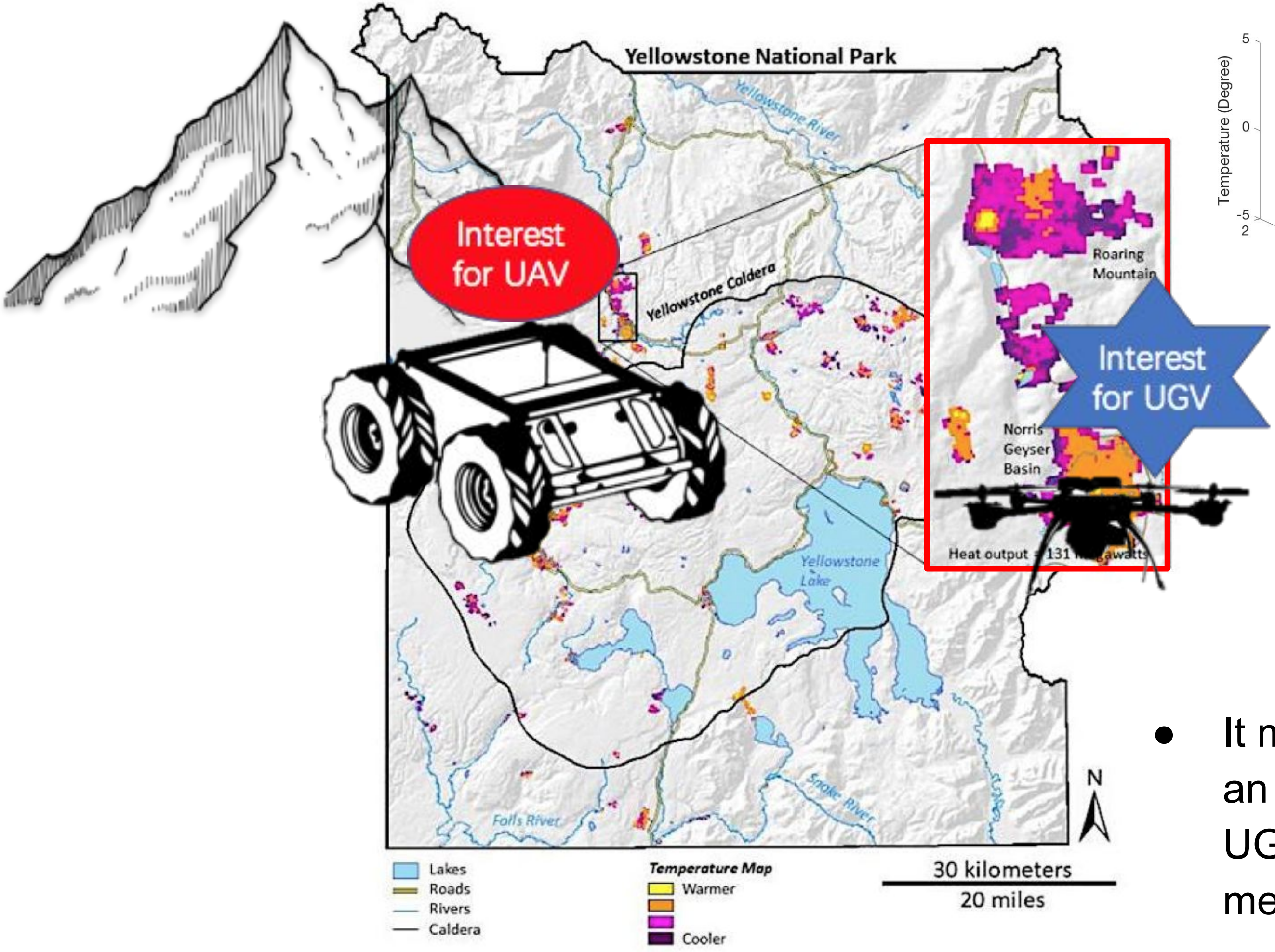
- It marks the location as an interest point for the UAV.

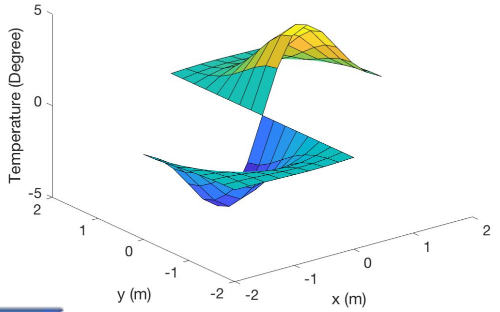




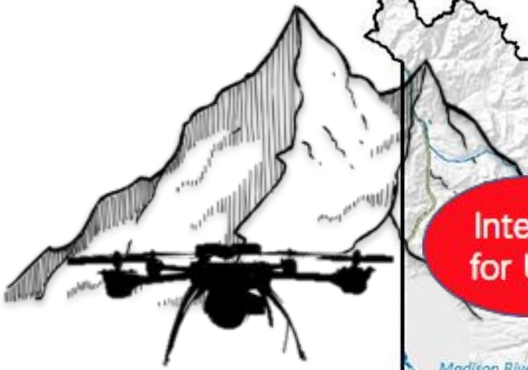


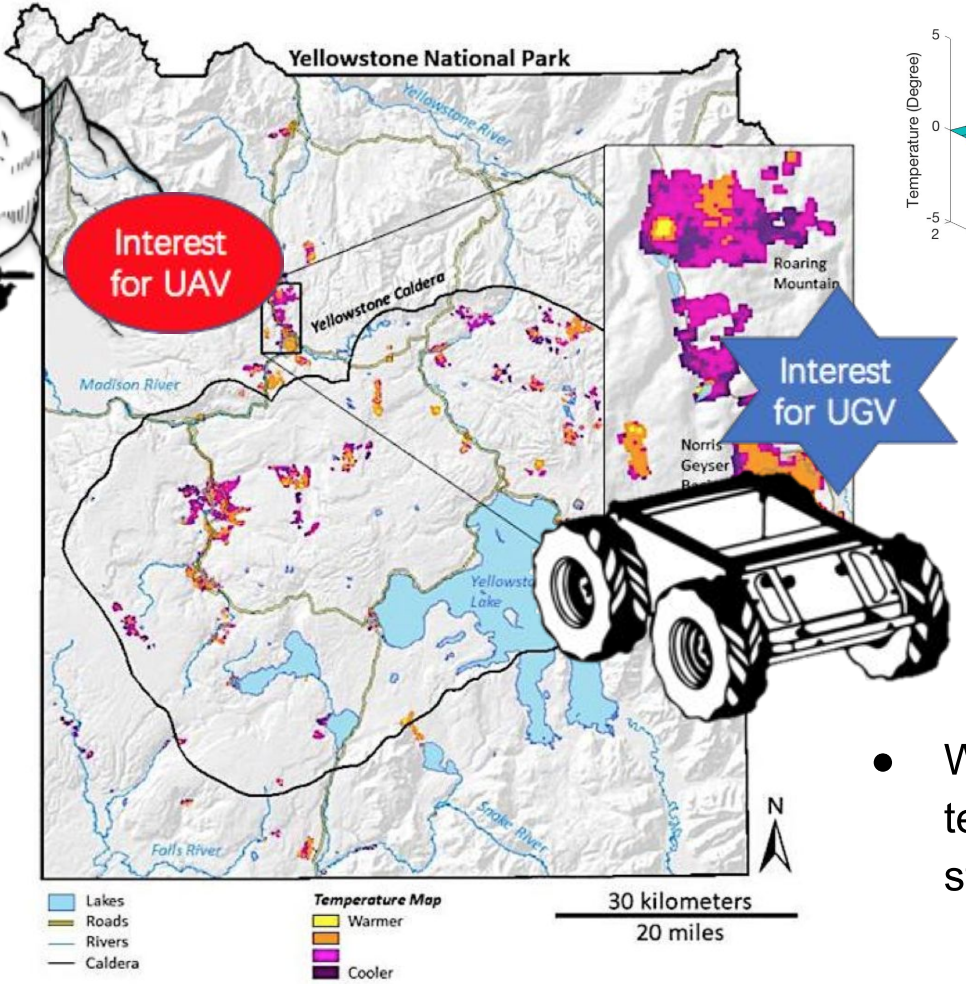
- The UAV meets an area with dense information

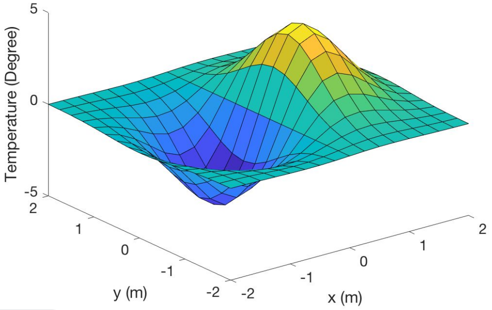




- It marks the location as an interest point for the UGV for accurate measuring.







- UAV and UGV go to next interest points for sampling.

- When finished, robot team returns to the starting point.

Functional Requirements:

F.R.1 Generate an environmental phenomenon distribution model for the area of interest.

F.R.2 Self-Identify informative locations to take samples from.

F.R.3 Collect accurate samples at discrete locations across the area.

F.R.4 Correct and update the model during sampling.

F.R.5 Navigate autonomously in the given terrain.

F.R.6 Plan obstacle-free paths autonomously.

Performance Requirements:

M.P.1 Generate an temperature distribution model for an area of interest within the dimension 20m x 20m x 5m.

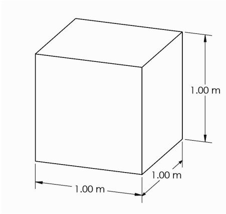
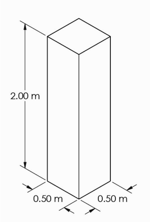
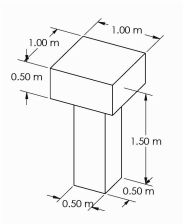
M.P.2 The RMS error of the temperature distribution model shall be within 3 °C.

M.P.3 Self-select informative point which reduces local variance by at least 3% at each time.

M.P.4 Collect temperature sample with error within +/- 2 °C.

M.P.5 Update the model after receiving every 10 samples.

Performance Requirements:

Obstacle	Quantity
	2
	2
	4

M.P.6 Navigate autonomously in the area with success rate greater than 80%.

M.P.7 Achieve sample localization accuracy better than +/- 2 m.

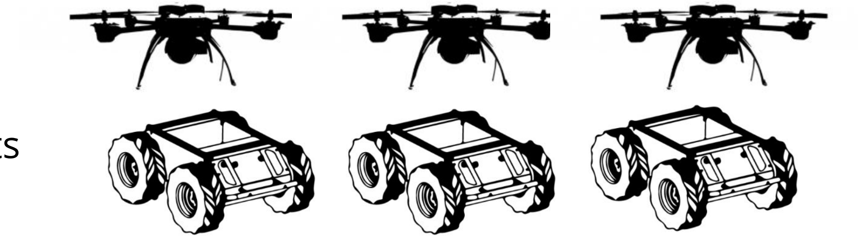
M.P.8 Plan obstacle-free path through randomly deployed obstacles.

M.P.9 Last at least 15 minutes for one deployment.

Nonfunctional Requirements:

The system will:

1. Have safety features:
    a. UAV and UGV have no sharp edges.
    b. UAV has drone blade guards
    c. Emergency Stop
2. Be environmental friendly:
    a. Maintain a low noise level
    b. Not damage operating environment
3. Have high extensibility:
    a. Scale up to multiple heterogeneous robots



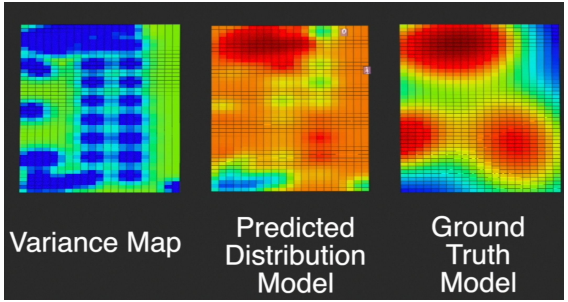
Overall System Depiction

UAV Subsystem

Interest Point Locations

Temperature Samples

Update Temperature Model



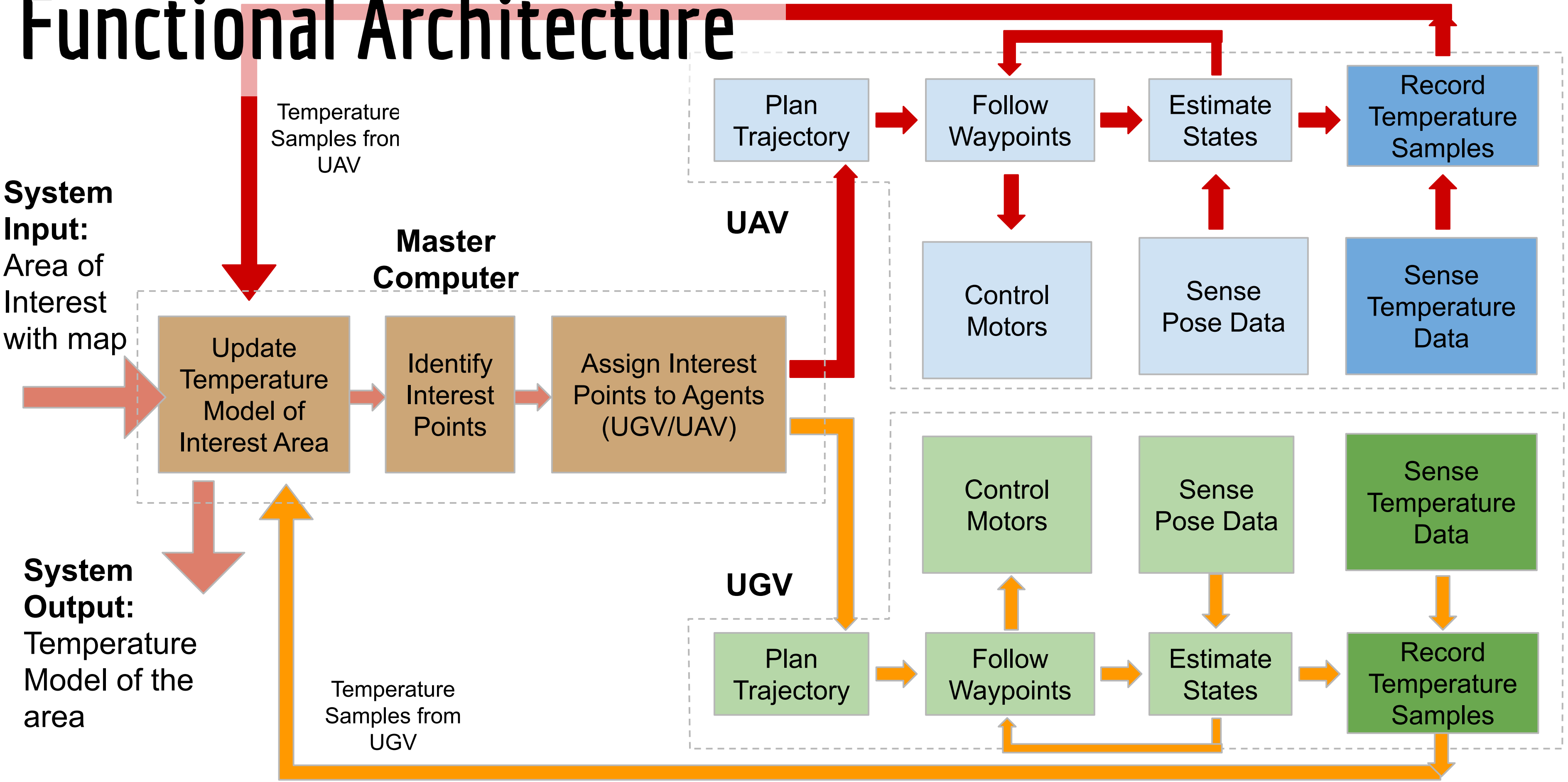
Master Computer Subsystem

UGV Subsystem

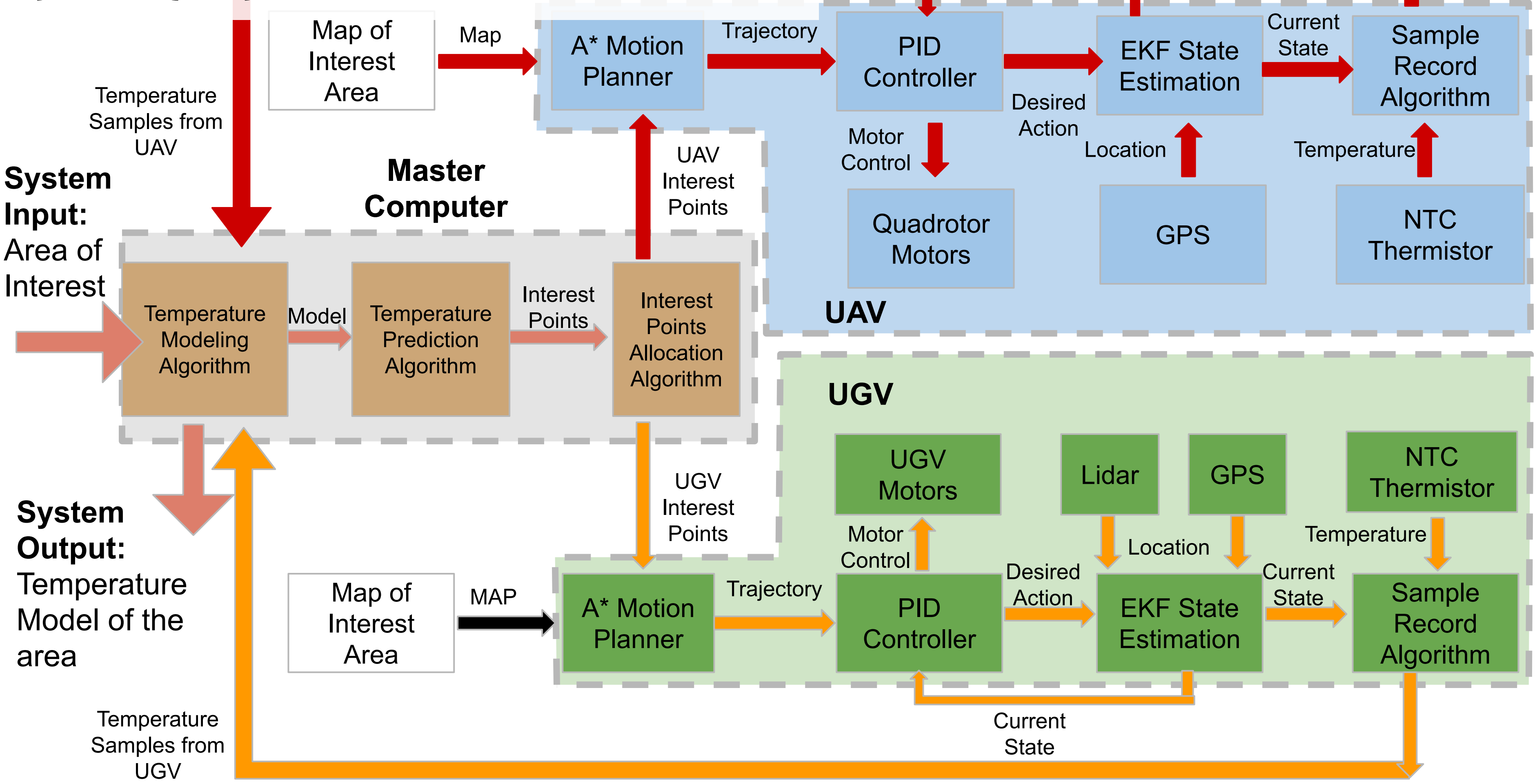
Interest Point Locations

Temperature Samples

Functional Architecture



Cyberphysical Architecture



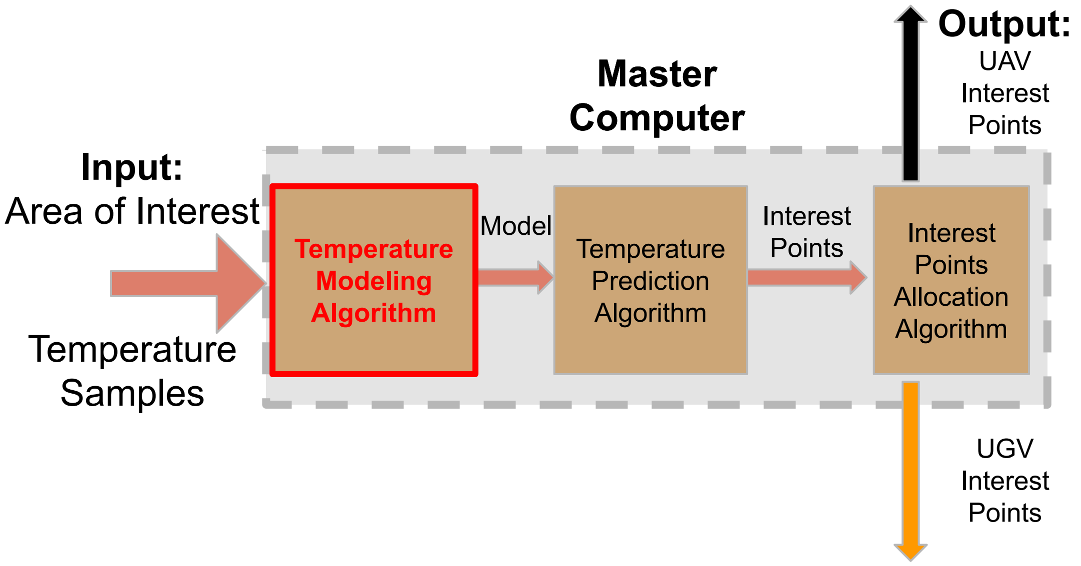
Targeted Requirement

ID	Requirement
M.P.1	Master Computer can generate an temperature distribution model for an area of interest within the dimension 20m x 20m x 5m.
M.P.2	The RMS error of the temperature distribution model shall be within 1 °C compared to ground truth.
M.P.3	Master Computer shall self-select informative point that reduces local variance by at least 3% at each time.
M.P.4	UAV/UGV shall collect temperature sample with error within +/- 2 °C.
M.P.5	Master Computer shall update the model after receiving every 10 samples.
M.P.6	UAV/UGV shall navigate autonomously in the area with success rate greater than 80%.
M.P.7	UAV/UGV shall achieve navigation accuracy better than +/- 2 m.

Master Computer Description

Procedure:

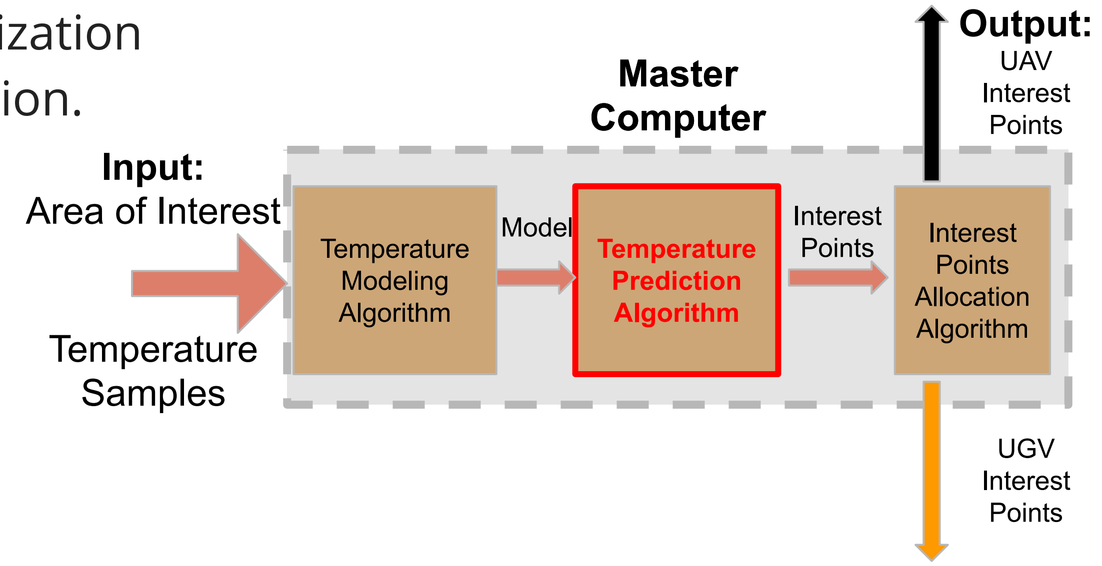
1. Mixture of Gaussian Process Models for temperature modeling.



Master Computer Description

Procedure:

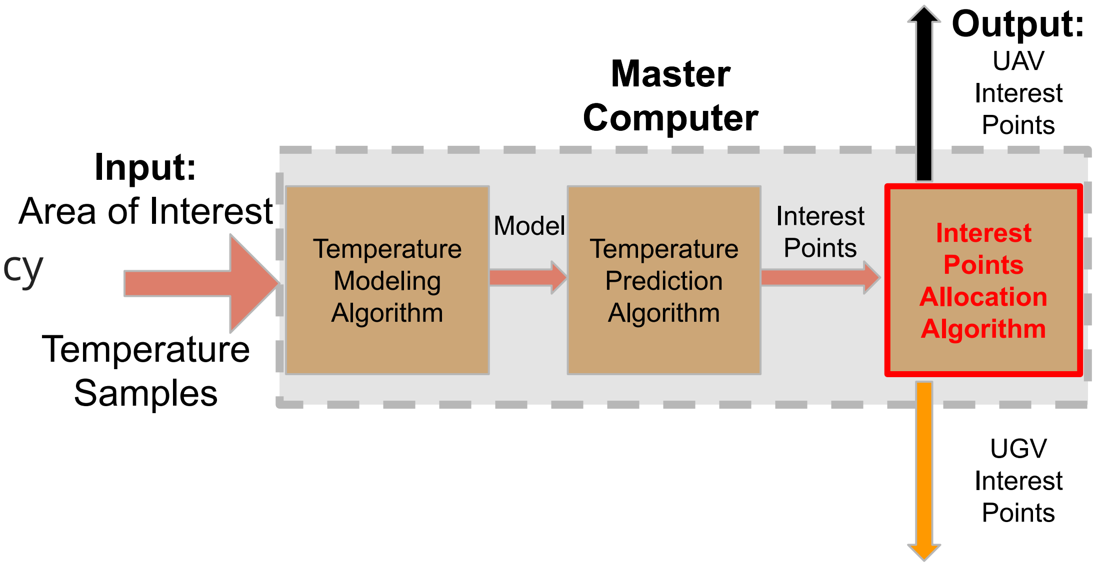
2. Expectation and Maximization for temperature prediction.



Master Computer Description

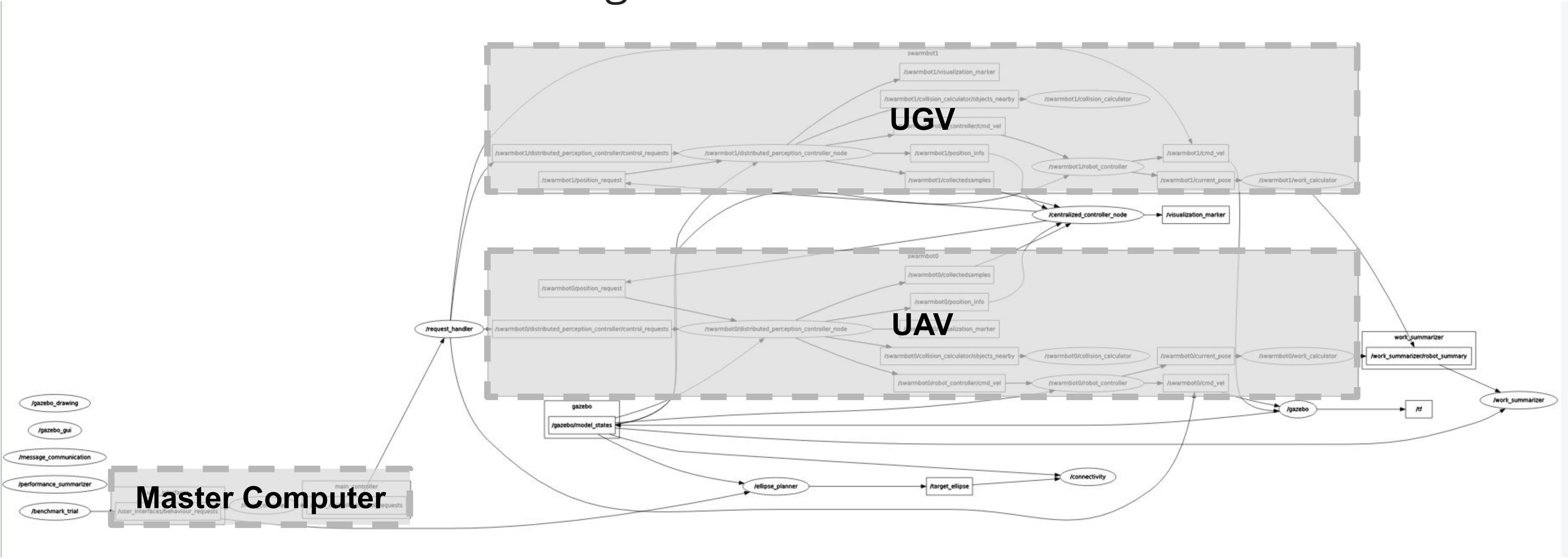
Procedure:

3. Interest point allocation
    a. UAV/UGV Mobility
    b. Utility
        i. Prediction Accuracy

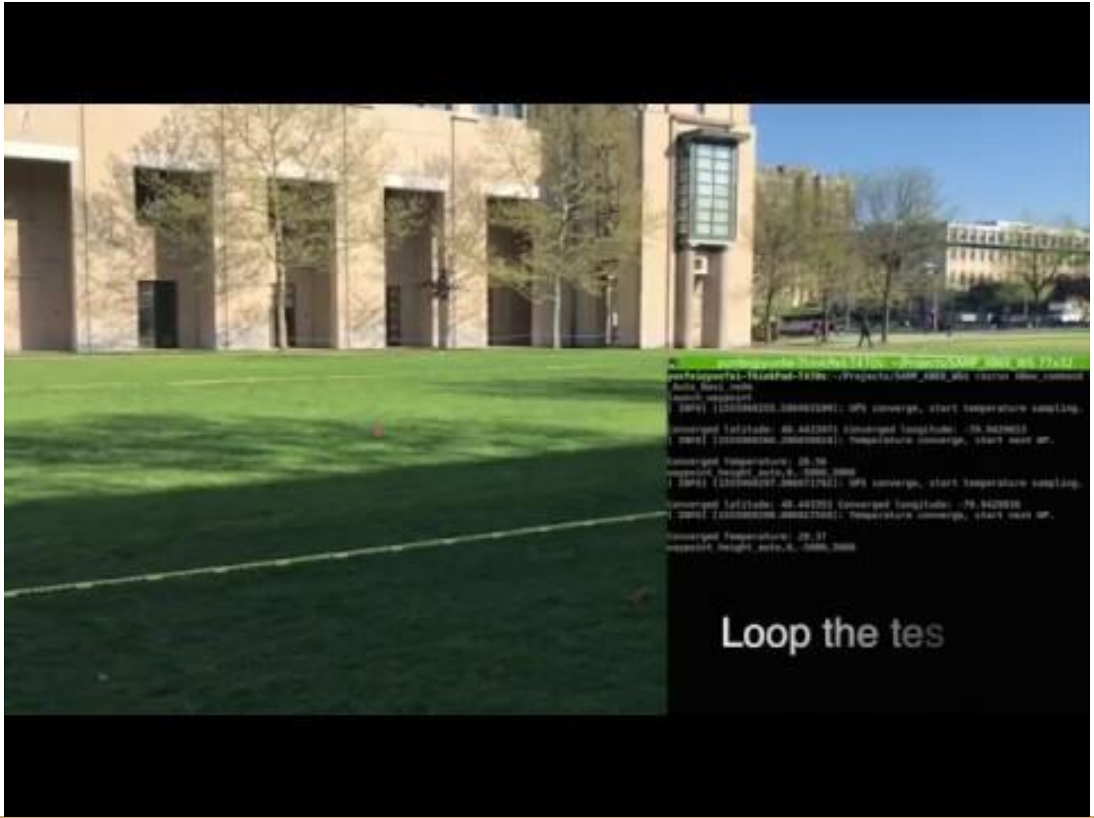


Master Computer Status

Validated and simulated algorithms in ROS.



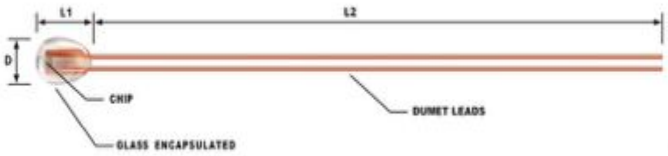
Master Computer Status



UGV Subsystem Description

Jackal UGV

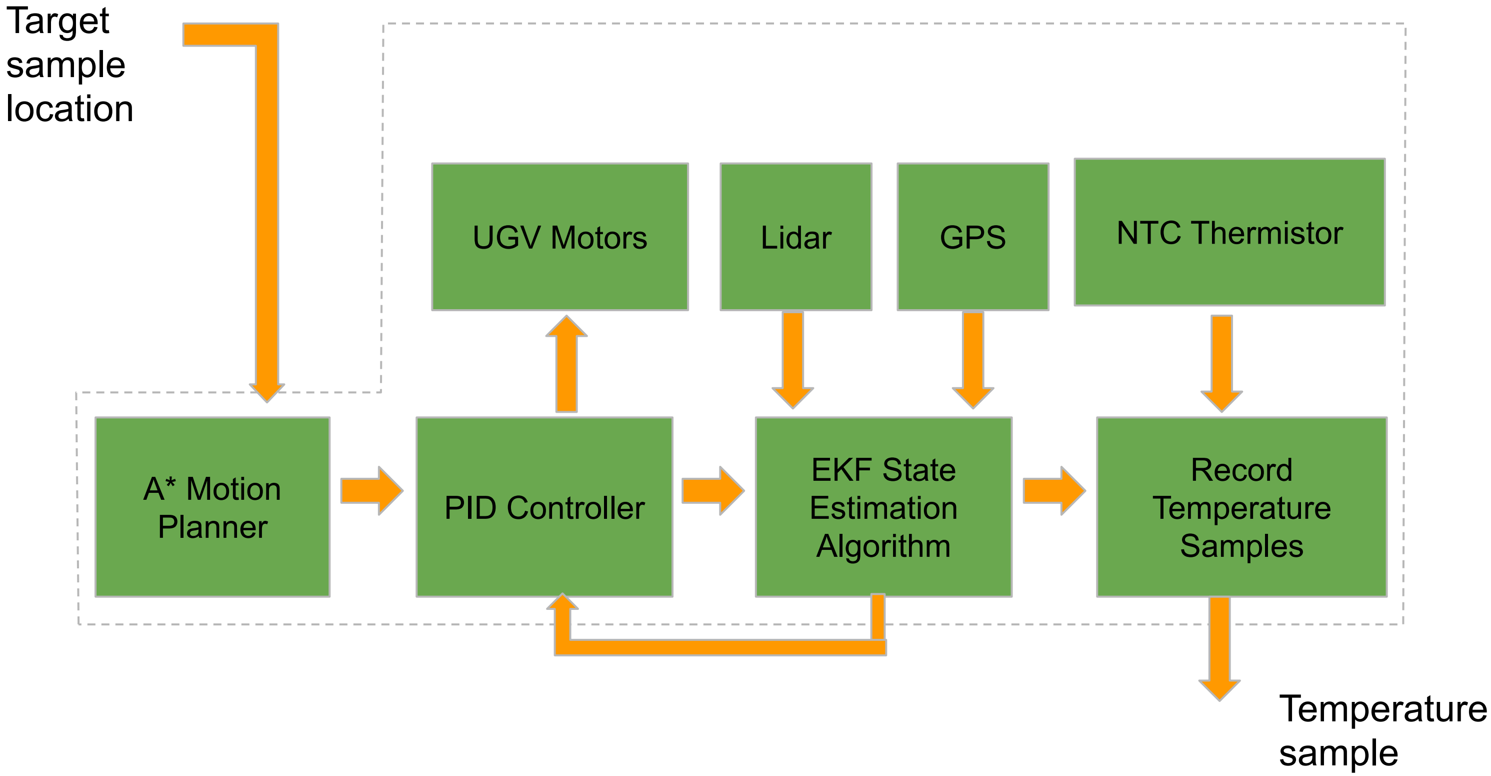
- lightweight and waterproof
- flexible platform for integrating sensors and utilizing its ROS API
- Intel i5 onboard computer
- GPS
- wireless connectivity via both Bluetooth and wifi
- payload up to 20kg
- 4 hours duration with standard loads
- Velodyne VLP-16 LiDAR



NTC Thermistor

- operating range: −55 °C to +200 °C
- temperature sensitivities: -3% to -6% per °C
- experience large change in resistance per Celsius

UGV Subsystem Description



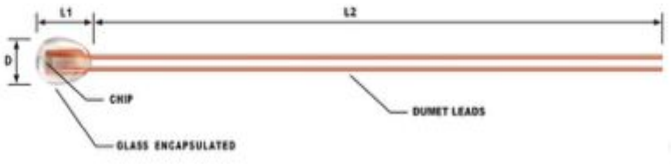
UGV Subsystem Status

- Realize motion control, localization, GPS waypoint navigation, temperature measurement all in ROS
- Maximum speed: 8 m/s
- Navigation accuracy +/- 0.3 m
- Temperature accuracy +/- 1.2 ℃

UAV Subsystem Description

AscTec Pelican UAV

- Intel® Core™ i7 on-board computer
- Lightweight and robust
- Hokuyo Laser Scanner (up to 30m range)
- GPS
- Wifi and XBee (wireless serial)
- AscTec Autopilot sensor board
- 16 minutes flight time
- 16 m/s maximum speed



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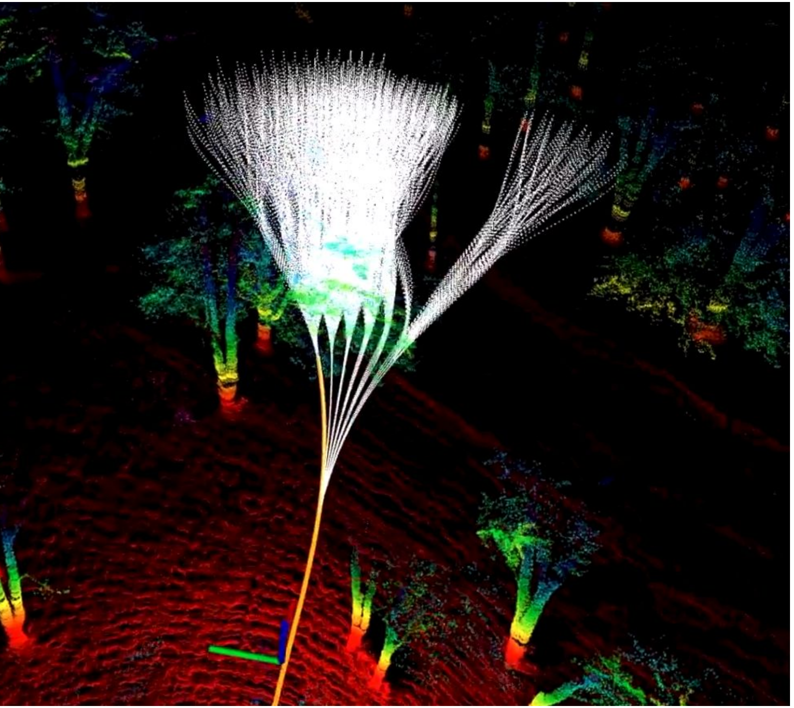
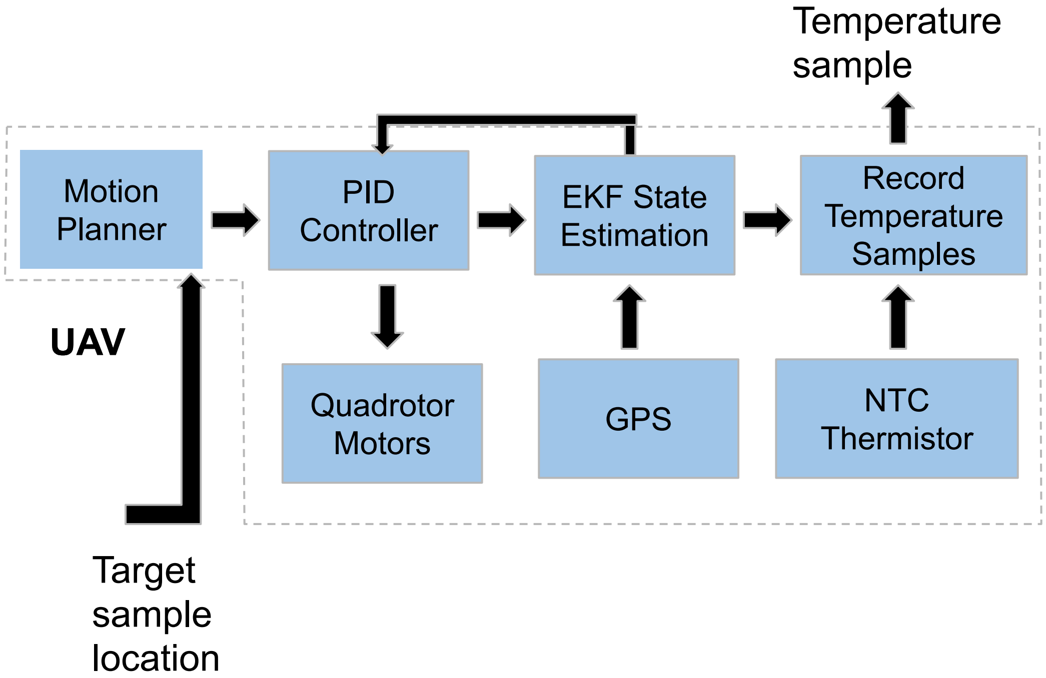
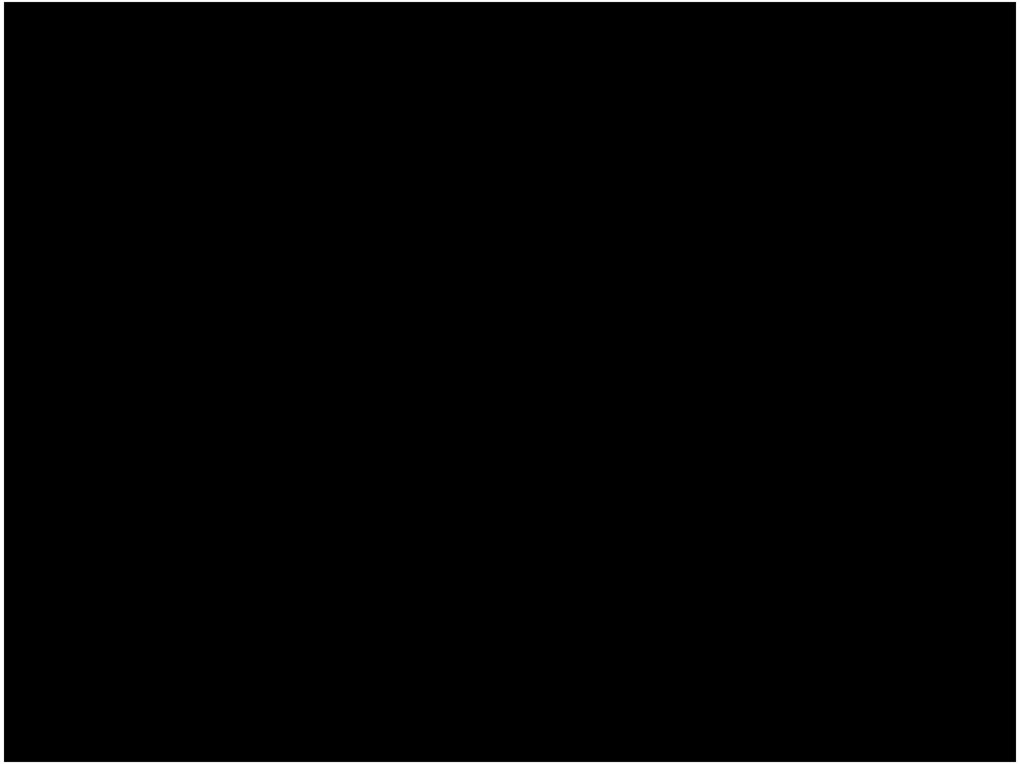
UAV Subsystem Description





UAV Subsystem Status

- Realize motion control, localization, GPS waypoint navigation, temperature measurement all in ROS.
- Require manually takeoff.
- Navigation accuracy +/- 0.38 m
- Temperature accuracy +/- 1.2 ℃



Modeling Analysis Test

- Built-in GPS Accuracy
  - Gathered data to analyze the drift and precision of UAV/UGV GPS
  - Found a common offset between UAV and UGV GPS coordinates.
  - Localization accuracy is around **2.5 m** which fails performance requirement.

- RTK GPS Accuracy
  - Gathered data to analyze the drift and precision of UAV/UGV GPS
  - UAV and UGV fall in the same GPS coordinates with the same RTK-GPS base station.
  - Localization accuracy is around **0.1 m** which meets performance requirement.

Modeling Analysis Test

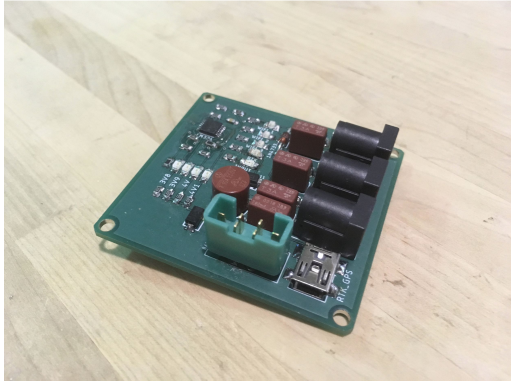
- UGV Waypoint navigation
  - Tested waypoint navigation in Odometry frame.
  - Tested coordinate transformation robustness between GPS and Odometry frame.
  - Calibrated UGV's IMU to fix the heading error.

- UAV Waypoint navigation
  - Tested manual control in 3 different modes: Velocity, Height, Position
  - Tested motor control using ROS command.
  - Tested accuracy of onboard GPS
  - Tested waypoint navigation in 3 different modes: Height Mode, Relative Mode, Absolute Mode

Modeling Analysis Test

- Temperature Variance
  - Collected temperature samples around a heating element to model the created temperature distribution.
  - Found the heat source could generate a distribution temperature difference up to **14 °C** when the environment temperature was 16°C.

- Power Distribution PCB
  - Analysed current requirement of RTK GPS base which is **35mA**, and Temperature Gate which is **2A**
  - Analysed efficiency of regulators which is about **40%**
  - Analysed the relationship between the input voltage and battery capacity



SVD Performance Evaluation

Test 1 (Master Computer):

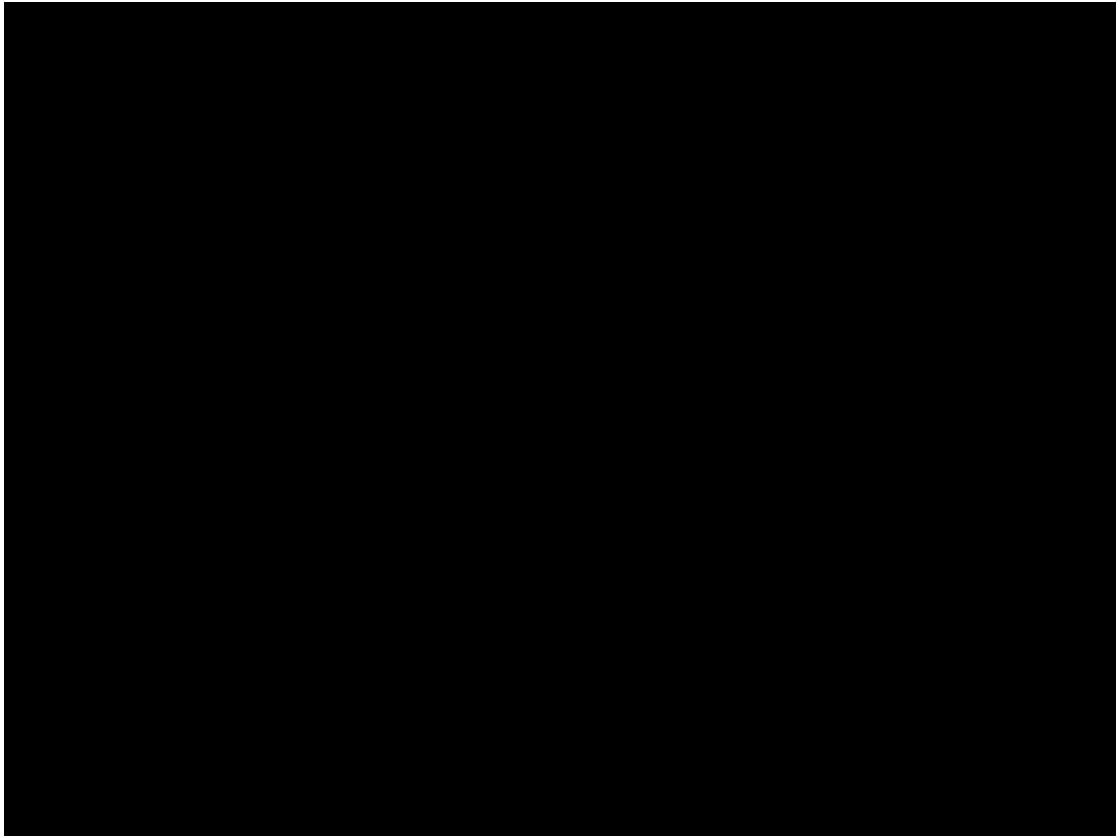
Name	Requirement	Performance
Root mean square error of Temperature	<1 ℃	0.35 ℃
Iterations before temperature model converges (average variance less than 1 ℃)	<50 Loops	30 +/- 10 Loops

SVD Performance Evaluation

Test 2 and 3 (UAV and UGV):

Name	Requirement	Performance of UAV	Performance of UGV
Mean location error	<2 meters	0.38m	0.1m
Mean square error of Temperature	<2 ℃	1.2 ℃	0.4 ℃

Video Excerpt



SVD Conclusions

Strength:

+ Great navigation accuracy of both UAV and UGV.
+ Great convergence and generality of informative sampling algorithm.
+ Complete simulation system for unit tests.

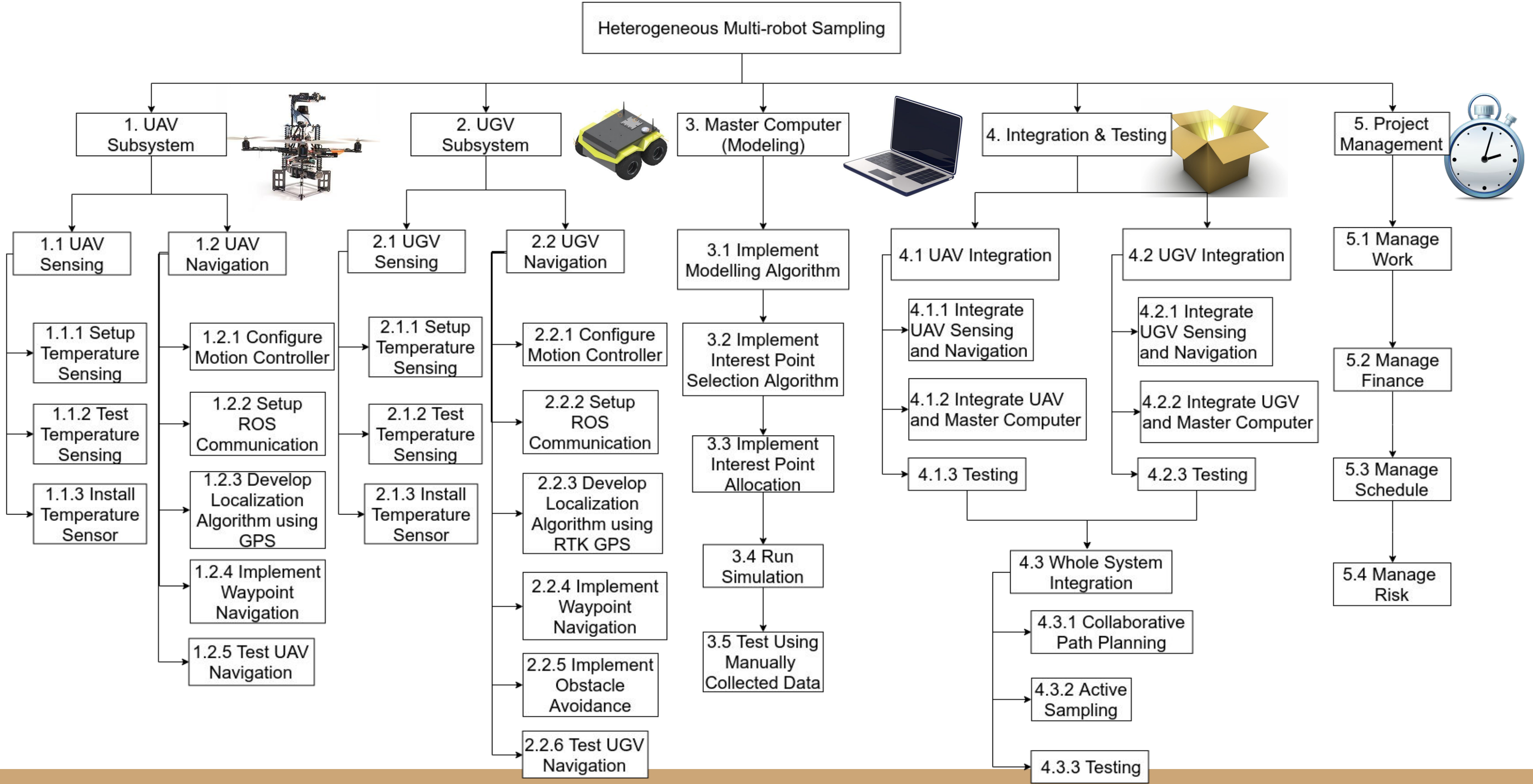
Weakness:

- Current temperature sensor convergence rate could be as low as 3 ~ 5 minutes for a 5 ℃ temperature gap.
- Communication latency, including latency and occasional freeze.

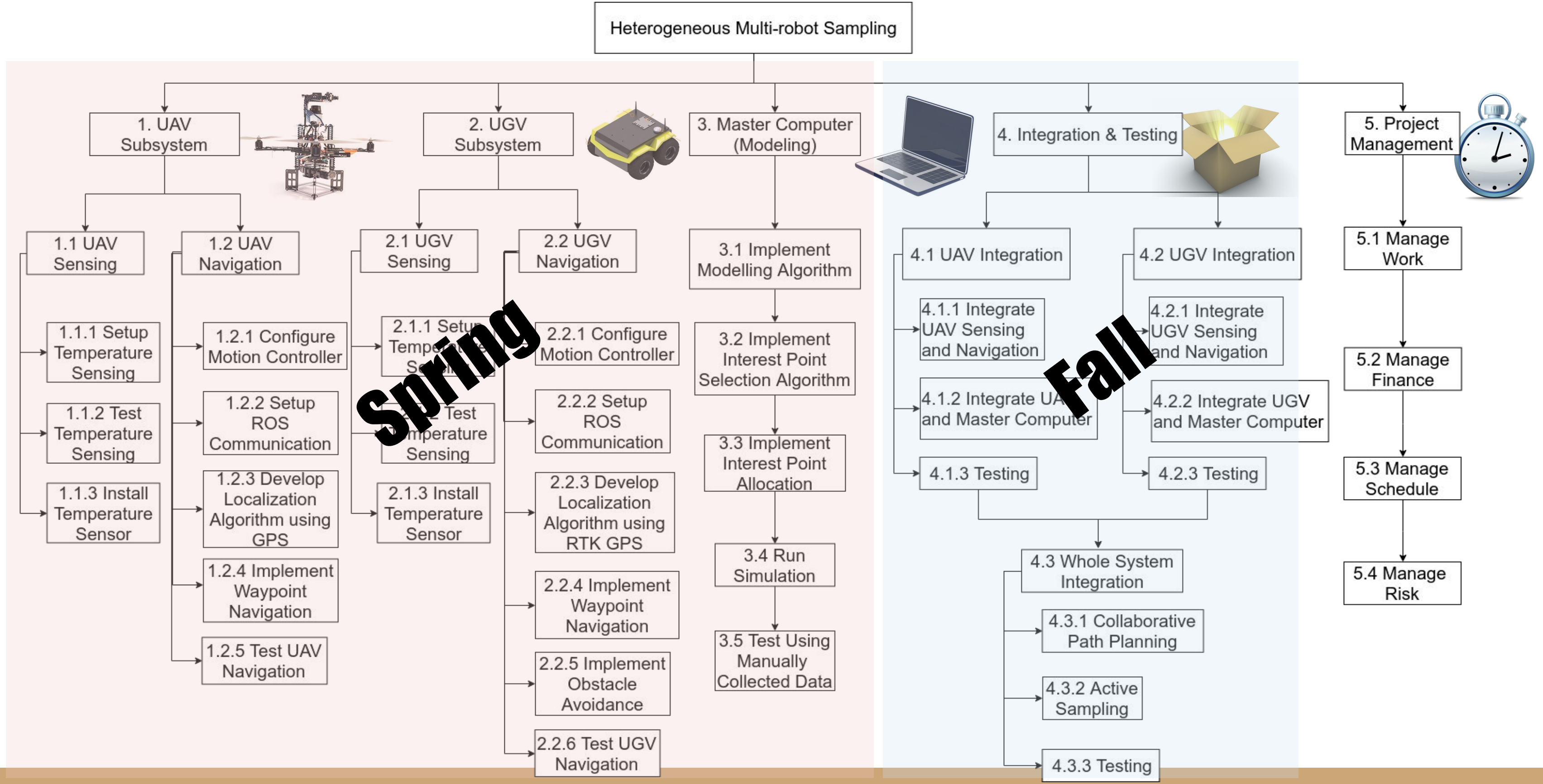
Future improvement:

- Improve temperature measurement efficiency.
- Refinement of heat source.

Work Breakdown Structure

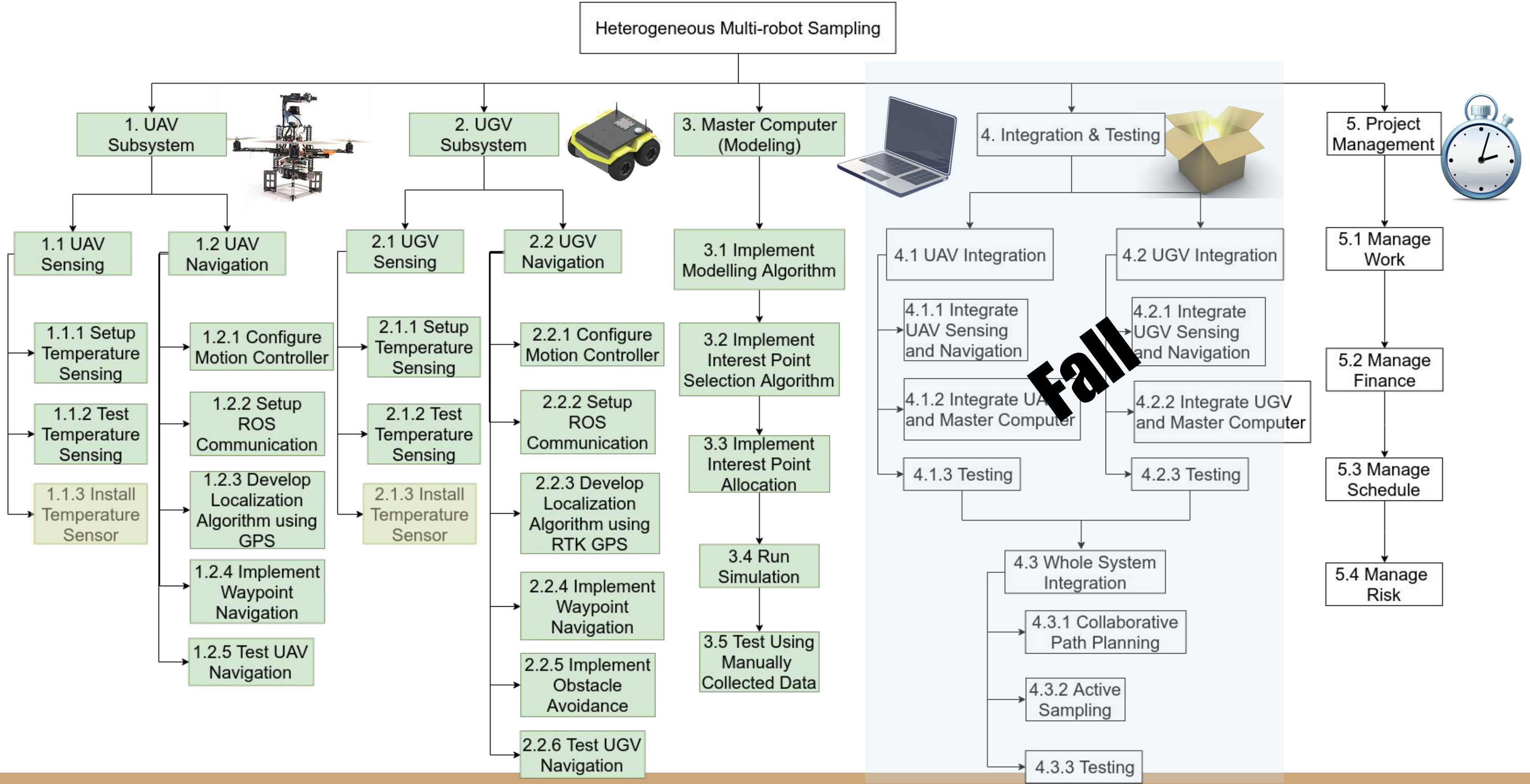


Schedule



Heterogeneous Multi-robot Sampling
Spring
Fall
1. UAV Subsystem
1.1 UAV Sensing
1.1.1 Setup Temperature Sensing
1.1.2 Test Temperature Sensing
1.1.3 Install Temperature Sensor
1.2 UAV Navigation
1.2.1 Configure Motion Controller
1.2.2 Setup ROS Communication
1.2.3 Develop Localization Algorithm using GPS
1.2.4 Implement Waypoint Navigation
1.2.5 Test UAV Navigation
2. UGV Subsystem
2.1 UGV Sensing
2.1.1 Setu
Tempe
Se
Test
mperature
Sensing
2.1.3 Install Temperature Sensor
2.2 UGV Navigation
2.2.1 Configure Motion Controller
2.2.2 Setup ROS Communication
2.2.3 Develop Localization Algorithm using RTK GPS
2.2.4 Implement Waypoint Navigation
2.2.5 Implement Obstacle Avoidance
2.2.6 Test UGV Navigation
3. Master Computer (Modeling)
3.1 Implement Modelling Algorithm
3.2 Implement Interest Point Selection Algorithm
3.3 Implement Interest Point Allocation
3.4 Run Simulation
3.5 Test Using Manually Collected Data
4. Integration & Testing
4.1 UAV Integration
4.1.1 Integrate UAV Sensing and Navigation
4.1.2 Integrate UA
and Master Computer
4.1.3 Testing
4.2 UGV Integration
4.2.1 Integrate UGV Sensing and Navigation
4.2.2 Integrate UGV and Master Computer
4.2.3 Testing
4.3 Whole System Integration
4.3.1 Collaborative Path Planning
4.3.2 Active Sampling
4.3.3 Testing
5. Project Management
5.1 Manage Work
5.2 Manage Finance
5.3 Manage Schedule
5.4 Manage Risk

Schedule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Fall
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4.3.2 Active Sampling
4.3.3 Testing
5.2 Manage Finance
5.3 Manage Schedule
5.4 Manage Risk

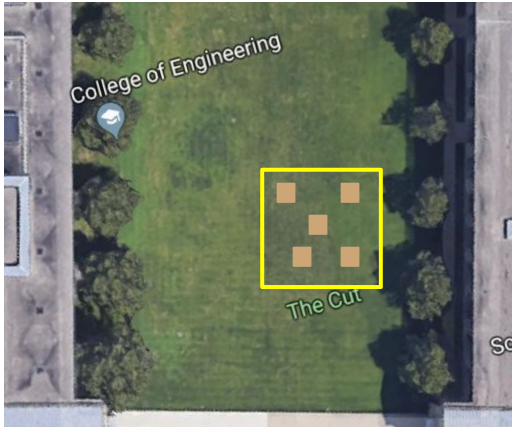
Remaining Schedule

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

High-Level Test Plan

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

Fall Validation Experiment



Integrated system Validation Experiment

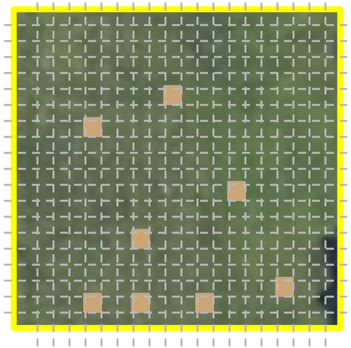
Location: An area of 20m x 20m x 5m near CMU CUT

Equipment: UGV, UAV, Master Computer, Obstacles, Stopwatch, Temperature Sensor, Ruler

Criteria: M.P.1 - M.P.9

UGV and UAV should finish collaborately building a temperature distribution map , whose root mean square error compared with the ground truth should be less than 3 ℃, for the required area with in 20 minutes

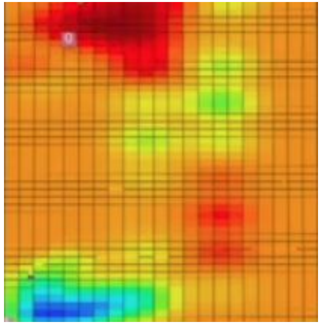
Fall Validation Experiment

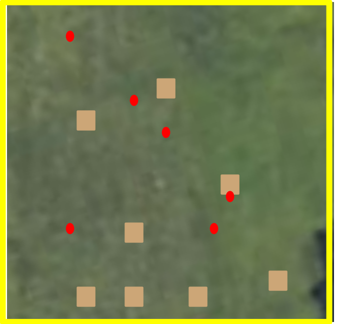


Procedure:

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

Fall Validation Experiment





Procedure:

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2. Initialize temperature model with random collected samples.
3. Deploy UAV and UGV in the test field.
4. Master computer assigns interest points for UGV/UAV to take temperature measurements respectively.
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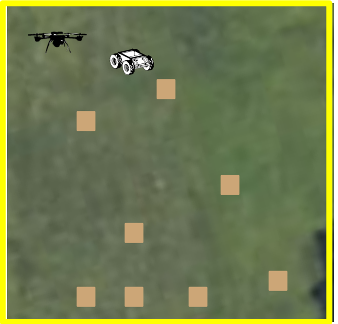
Fall Validation Experiment



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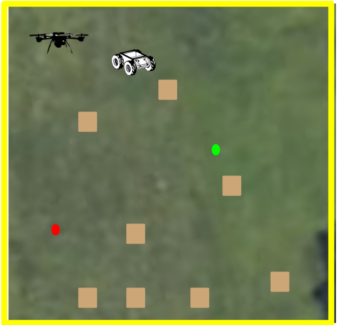

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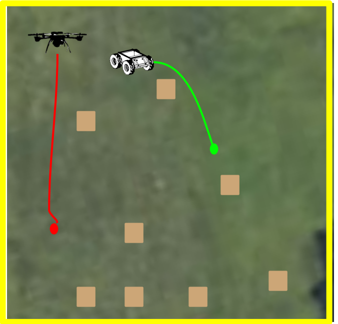

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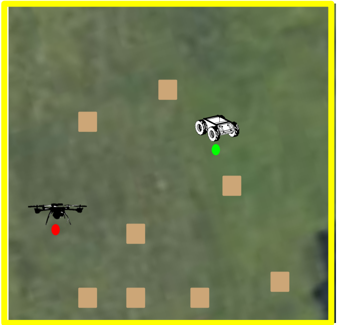

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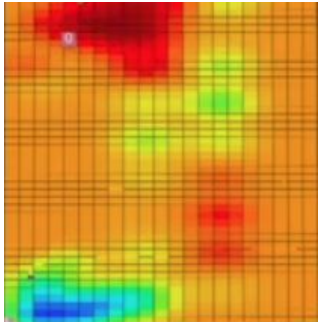

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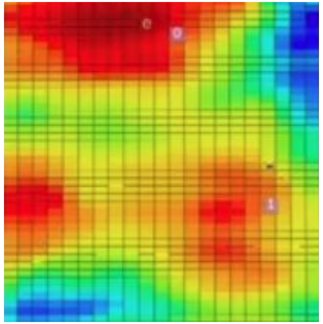

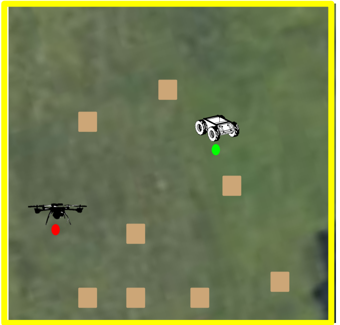

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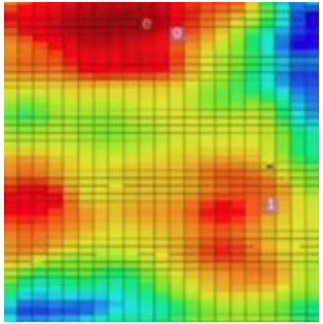

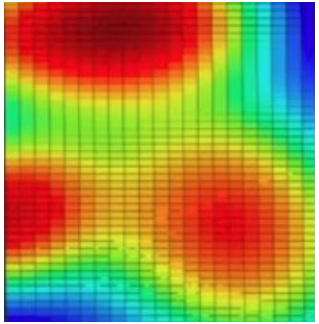

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Budget

Part Name	Quantity	Unit Price	Total Price
Ground Truth Temperature Sensor	12	$49.99	$599.88
Ground Truth Temperature Sensor WiFi Gateway	1	$99.95	$99.95
Heat Source	2	$16	$32
Battery Monitor	1	$9.89	$9.89
On-board Temperature Sensor	4	$13.99	$55.96
Temperature Sensor Extension Cable	4	$6.99	$27.96
RTK-GPS Set (2 Rovers and 1 base)	1	$2,000	$2,000
		Total:	**$2,865.64**

Budget

- Total Budget: $2,865.14
- Current Spent: $2,366.51(82.58%)

- No anticipated big-ticket items to purchase in fall.
- Items to purchase:
  - Groundtruth temperature sensors
  - Heatsource: Heat Blankets
  - Spare components

Risk Management

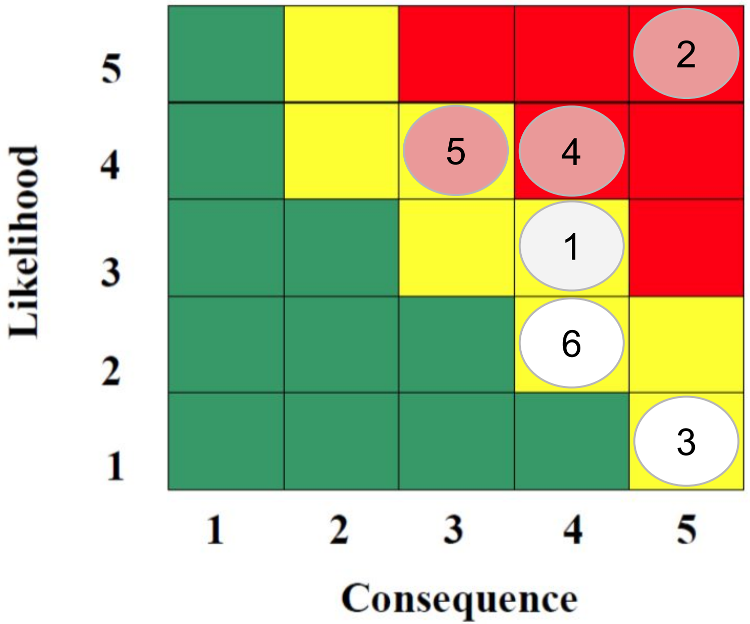
ID	Risk	Type	Description	Likelihood	Consequence	Risk Reduction Plan
1	Electric System Failure	Technical	The battery or electric system fails due to incorrect operation.	2 (-1)	4	• Add reverse voltage and overvoltage protection. • Document and regulate operation.
2	Work Delay	Schedule	Heavy workload puts the team behind the schedule	4 (-1)	5	• Optimize the WBS to break down the workload into manageable pieces.
3	Run Out of Budget	Financial	Run out of funds purchasing parts and repairing robots.	2 (+1)	5	• Make purchasing decision carefully after trade study.
4	Latency for Real-time Operation	Technical	Communication latency between master computer and UGV fails real-time operation.	4 (0)	4	• Shut down unnecessary sensor publications. • Use a higher speed router.
5	Poor Weather for Validation Tests	Schedule	Poor weather prevents/delays the system from outdoor experiments.	1 (-3)	3	• Monitor upcoming weather. • Schedule tests beforehand.

Risk Management

ID	Risk	Type	Description	Likelihood	Consequence	Risk Reduction Plan
6	Even Temperature Distribution	Technical	Temperate difference in the test field is close to or smaller than sensor noise.	1 (-1)	4	• Use sensors with higher sensitivities based on previous experiment results. • Add heat sources to the test field to increase temperature variance.
7	Poor Localization Accuracy	Technical	Localization accuracy is not high enough considering the size of the test field.	1 (-3)	5	• Use RTK GPS instead of built-in GPS.
8	Slow Temperature Convergence	Technical	Temperature converges too slow for ground truth and onboard sensors to meet the time requirement.	4	5	• Use temperature sensors with faster response time.

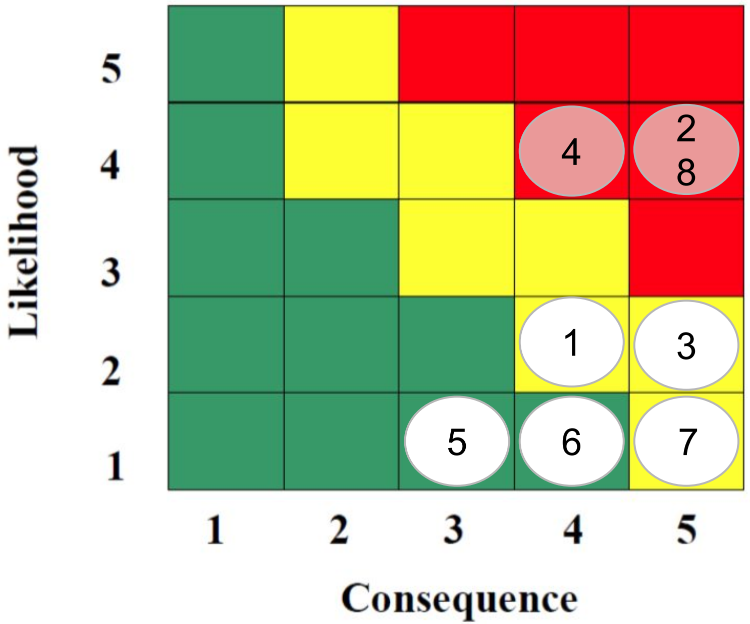
Original Risk Management

1. Electric System Failure
2. Work Delay
3. Run Out of Budget
4. Latency for Real-time Operation
5. Poor Weather for Validation Tests
6. Even Temperature Distribution
7. Poor Localization Accuracy



Updated Risk Management

1. Electric System Failure
2. Work Delay
3. Run Out of Budget
4. Latency for Real-time Operation
5. Poor Weather for Validation Tests
6. Even Temperature Distribution
7. Poor Localization Accuracy
8. Slow Temperature Convergence



Conclusions

- Key Lesson Learned:
  - Clear documentation can save a lot of time
  - System robustness is important
  - Plan outdoor tests beforehand
  - Safety check before piloting robots
  - Time management for validation test
- Resultant Key Activities:
  - Use Git and keep documenting developed subsystems
  - Conduct multiple tests for subsystems
  - Conduct safety check before each robot deployment
  - Carefully design the flow and carefully allocate time for the validation test

Q&A