Searching while **Mo**deling the Environment for Time-critical **Res**cues

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Table of Contents

1. Introduction

This document details the testing procedures that Team G (Smores) will carry out during the Spring 2025 term. These procedures will track progress toward fulfilling the system objectives established in the Fall 2024 term at the regularly scheduled Progress Reviews, culminating in the Spring Validation Demonstration. Furthermore, they serve as critical checkpoints in developing our robotic platform - a drone that can map indoor environments through smoke. It is important to note that we will not be delivering a fully integrated system by the end of this semester. Instead, our goals in Spring 2025 will focus on demonstrating the most complex challenges of this problem: dense depth estimation and odometry through perceptually degraded environments like smoke.

2. Logistics

To ensure that we have a perceptually degraded environment to adequately test our system, most tests will take place at Allegheny Fire Academy or the NREC drone cage, depending on the locations' availability. We have secured permissions to test at both of these locations as of January 2025. Allegheny Fire Academy is an indoor space where it is possible to deploy smoke and as such is the preferred location for our system testing. In cases where Fire Academy may not be available, the NREC drone cage is a backup option. The NREC drone cage is an outdoor cage where we have installed closed canopy tents with a fog machine to mimic an indoor smoked environment.

3. Schedule

Date	P.R.	Capability Milestones	Test(s)	Requirements
02/13	1	• Preliminary odometry outputs • Preliminary dense depth outputs • Initial CAD model		
02/27	2	• Successful sesnor calibrations • Acquired flight licenses • Validation of odometry as per requirements • Validation of dense depth as per requirements	4.1 4.3	PR.M.1 PR.M.2 PR.M.3
03/20	3	• Flight with new sensor mount and Nvidia Orin • Time Synchronization between sensors • Onboard odometry working • Onboard Depth Estimation working • Integration validated with field tests	4.2 4.4 4.5 4.6	FR.D.1
04/08	4	• Improving GUI and real-time communication	4.7	PR.M.6 PR.M.7
04/17	SVD	• Integrated demonstration of perception and mapping stack with teleoperated drone	4.8	PR.D.2
04/24	SVD Encore	• Fine-tuning algorithms	4.9	

4. Tests

<table>
<tr><td>Test Title</td><td colspan="2">4.1 Validating Intrinsics and Extrinsics Calibration</td></tr>
<tr><td>Objective</td><td colspan="2">Validate the calibration of the drone sensors</td></tr>
<tr><td>Elements</td><td colspan="2">Drone hardware</td></tr>
<tr><td>Location</td><td colspan="2">AirLab</td></tr>
<tr><td>Equipment</td><td colspan="2">Drone, Heated Checkerboard, Laptop with ROS</td></tr>
<tr><td>Personnel</td><td colspan="2">Aayush Fadia Ranai Srivastav</td></tr>
<tr><td colspan="3">Procedure</td></tr>
<tr><td colspan="3">- Heat the checkerboard
- Collect rosbags that consist of thermal, RGB, and IMU data from the respective sensors
- Use calculated intrinsics to calculate the pixel space location of features and compare with actual (reprojection error)
- Visually verify that the image is not distorted</td></tr>
<tr><td colspan="2">Verification Criteria</td><td>Requirements Satisfied</td></tr>
<tr><td colspan="2">- Reprojection error <= 2 pixels
- Straight lines are not curved in the rectified image
- Epipolar lines are horizontal and parallel</td><td>- PR.M.1
- PR.M.2</td></tr>
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<table>
<tr><td>Test Title</td><td colspan="2">4.2 Hardware integration test</td></tr>
<tr><td>Objective</td><td colspan="2">Ensure system integration of new hardware and software</td></tr>
<tr><td>Elements</td><td colspan="2">System Integration</td></tr>
<tr><td>Location</td><td colspan="2">Fire academy or NREC</td></tr>
<tr><td>Equipment</td><td colspan="2">Pheonix Pro with Orin, Stereo Thermal, Stereo RGB, IMU</td></tr>
<tr><td>Personnel</td><td colspan="2">Amy Jiang Abhishek Iyer</td></tr>
<tr><td colspan="3">Procedure</td></tr>
<tr><td colspan="3">- Connect drone to LiPo battery
- Deploy smoke using the smoke machine
- Arm drone, connect to drone software interface, launch necessary scripts
- Collect rosbag of perceptually degraded environment</td></tr>
<tr><td colspan="2">Verification Criteria</td><td>Requirements Satisfied</td></tr>
<tr><td colspan="2">- Drone powers on and supplies adequate power to motors, Orin, sensors
- Can connect with drone while drone is armed and ready to fly anywhere within a 25m radius
- OPTIONAL: Drone flies</td><td>- PR.M.1
- FR.D.2</td></tr>
</table>

Test Title	**4.3 Metric Dense Depth**
Objective	To verify if we can recover metric dense depth through smoke
Elements	Perception and depth subsystem
Location	Fire Academy
Equipment	Phoenix Pro, heated and room temperature objects, smoke bombs or the fog machine, Lidar, Smoke Masks, Eye protection
Personnel	Abhishek Iyer Swastik Mahapatra

Procedure
- We will place heated and unheated objects a known distance away from the Phoenix Pro. - The known distance can be measured by hand or through a lidar, it will be measured along the ray that connects the camera to the object. - The Phoenix Pro will run the metric dense depth algorithm and output a depth image with the intensities of the image measuring the metric depth of the image (resolving for scale and shift ambiguities). - We will verify our known distances with the metric depth estimation pipeline.

Verification Criteria	**Requirements Satisfied**
- We can achieve metric depth between 30cm and 1 metre reliably. - The recovered depth is between ±50% of the ground truth.	- PR.M.1 - PR.M.2

Test Title	**4.4 Real-time metric dense depth**
Objective	To validate if metric dense depth can be achieved in real-time
Elements	Perception and depth subsystem
Location	Fire Academy
Equipment	Phoenix Pro, heated objects, smoke bombs or the fog machine, Smoke Masks, Eye protection
Personnel	Abhishek Iyer Swastik Mahapatra

Procedure
- We will initiate the depth estimation pipeline onboard the Phoenix Pro. - We will check the number of frames the pipeline can output over the time of the flight. - This will be a predetermined flight path where we would have collected data earlier using Lidar (sparse depth) and SLAM (dense depth) without using smoke. - We will compare our accuracy and real-time performance with said ground truth.

Verification Criteria	**Requirements Satisfied**
- The average accuracy of depth prediction is between ±50% of true depth - The average number of frames processed in a second throughout the flight should exceed 5 frames.	- FR.D.2 - NR.M.2

Test Title	**4.5 Odometry Subsystem**
Objective	To evaluate if we can localize ourselves in smoke
Elements	Localization and Odometry subsystems
Location	NREC or Fire Academy
Equipment	Phoenix Pro, Smoke bombs or fog machines, Smoke Masks, Eye protection
Personnel	Ranai Srivastav, Amy Jiang, Aayush Fadia

Procedure

- Plan out a test path by taping it on the floor.
- Use a cart to move drone along planned path in the presence of smoke.
- Run the odometry algorithm onboard and transmit then visualize odometry to the base station.
- Compare with trajectory obtained from VINS while following the same path without smoke.

Verification Criteria	**Requirements Satisfied**
- *Endpoint error < 2m* - *Absolute Pose Error < 5m* - Able to localize ourselves at any given time *within 2 meters* - Odometry runs at or *greater than 10 Hz*	- PR.M.1 - FR.D.2 - FR.M.2

Test Title	**4.6 Sensor Signal Time Sync**	
Objective	Validate sensor outputs are time-synced	
Elements	System Integration	
Location	AirLab	
Equipment	PhoenixPro, Laptop with Smores software stack	
Personnel	Aayush Fadia, Swastik Mahapatra, Ranai Srivastav	
Procedure		
- Deploy time sync code to the drone platform - Collect relevant sensor streams		
Verification Criteria		**Requirements Satisfied**
- *Visually estimate* if all sensor streams on time-synced topics are arriving at the same time via rqt_bag - Estimate the time delta between any sensor streams is less than *0.1 seconds*		- FR.M.1 - NR.M.3

<table>
<tr><td>Test Title</td><td colspan="2">4.7 Subsystem Integration Test</td></tr>
<tr><td>Objective</td><td colspan="2">To validate if the localization, dense depth, and time synchronization, all work in unison</td></tr>
<tr><td>Elements</td><td colspan="2">System</td></tr>
<tr><td>Location</td><td colspan="2">Fire Academy</td></tr>
<tr><td>Equipment</td><td colspan="2">Phoenix Pro, Lidar, Smoke bombs or fog machine, Smoke masks, Eye protection gear</td></tr>
<tr><td>Personnel</td><td colspan="2">Aayush Fadia Abhishek Iyer Amy Jiang Ranai Srivastav Swastik Mahapatra</td></tr>
<tr><td colspan="3">Procedure</td></tr>
<tr><td colspan="3">- Set up peripherals, and launch necessary drone software.
- Ensure verification criteria while the drone is stationary.
- Ensure verification criteria while the drone is flying.</td></tr>
<tr><td colspan="2">Verification Criteria</td><td>Requirements Satisfied</td></tr>
<tr><td colspan="2">- Drone should report live sensor feed to Ground Control Station (GCS)
- Drone should pass specifications for Odometry Subsystem test mentioned above (4.5)
- The drone should pass the specification listed for the Real-time Dense Depth Recovery test plan (4.4)</td><td>- NR.M.3</td></tr>
</table>

<table>
<tr><td>Test Title</td><td colspan="2">4.8 Spring Validation Demo</td></tr>
<tr><td>Objective</td><td colspan="2">To demonstrate the capability of localizing and estimating depth through perceptual degradation</td></tr>
<tr><td>Elements</td><td colspan="2">System</td></tr>
<tr><td>Location</td><td colspan="2">Fire Academy or NREC</td></tr>
<tr><td>Equipment</td><td colspan="2">Phoenix Pro, Lidar, Smoke bombs or fog machine, Smoke masks, Eye protection gear, Laptop with Smores software stack, heaters, power supply, test-setup items</td></tr>
<tr><td>Personnel</td><td colspan="2">Aayush Fadia Abhishek Iyer Amy Jiang Ranai Srivastav Swastik Mahapatra</td></tr>
<tr><td colspan="3">Procedure</td></tr>
<tr><td colspan="3">- Setup the test environment including power supply, smoke machine, drone platform, and audience visualization aids.
    - The test environment will be enclosed and smoke will be released until the desired environment is reached.
    - The test environment will have heaters and other objects placed throughout the testing area
- The drone will proceed moving through the environment while mapping the environment and reporting dense depth
- The drone will circle back to where it started from</td></tr>
<tr><td colspan="2">Verification Criteria</td><td>Requirements Satisfied</td></tr>
<tr><td colspan="2">- The audience can see live (latency < 200ms)of the sensor feeds through appropriate visualizations
- Endpoint error < 5m
- Dense depth reconstruction is visually similar to true environment</td><td>- PR.M.1
- PR.M.2
- PR.M.3
- FR.D.2
- FR.M.1
- FR.M.2
- NR.M.2</td></tr>
</table>

<table>
<tr><td>Test Title</td><td colspan="2">4.9 Spring Validation Demo - Encore</td></tr>
<tr><td>Objective</td><td colspan="2">To demonstrate the capability of localizing and estimating depth through perceptual degradation, allowing drone teleoperation</td></tr>
<tr><td>Elements</td><td colspan="2">System</td></tr>
<tr><td>Location</td><td colspan="2">Fire Academy or NREC</td></tr>
<tr><td>Equipment</td><td colspan="2">Phoenix Pro, Lidar, Smoke bombs or fog machine, Smoke masks, Eye protection gear, Laptop with Smores software stack, heaters, power supply, test-setup items</td></tr>
<tr><td>Personnel</td><td colspan="2">Aayush Fadia, Abhishek Iyer, Amy Jiang, Ranai Srivastav, Swastik Mahapatra</td></tr>
<tr><td colspan="3">Procedure</td></tr>
<tr><td colspan="3">- Setup the test environment including power supply, smoke machine, drone platform, audience visualization aids
    - The test environment will have heaters and other objects placed throughout the testing area
- The drone will proceed moving through the environment while mapping the environment and reporting dense depth
- The drone will circle back to where it started from</td></tr>
<tr><td colspan="2">Verification Criteria</td><td>Requirements Satisfied</td></tr>
<tr><td colspan="2">- The audience can see live (latency < 200ms)of the sensor feeds through appropriate visualizations
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- Dense depth reconstruction is visually similar to true environment</td><td>- PR.M.1
- PR.M.2
- PR.M.3
- FR.D.2
- FR.M.1
- FR.M.2
- NR.M.2
- NR.M.3</td></tr>
</table>

5. Appendix

Table 1. Mandatory Functional Requirements

ID	Requirement	Description	Origin
FR.M.1	Sense the environment	The drone senses the environment through perceptual degradation.	TR
FR.M.2	Localize itself	The drone develops an internal representation of the environment and localizes itself on it.	TR
FR.M.3	Detect Points of Interest (PoI)	The drone helps firefighters detect and locate POIs.	SR
FR.M.4	Plan a path	The drone will plan the trajectory when given waypoints.	TR
FR.M.5	Navigate via Waypoints	The drone will be controllable through teleoperated commands or Waypoint navigation	SR
FR.M.6	Visualize the environment	Firefighters will be able to interact with visualizations depicting necessary information	SR
FR.M.7	Communicate with an operator	Firefighters will be able to communicate with the drone, control it, and stop it if necessary	TR

Table 2. Mandatory Non-Functional Requirements

ID	Requirement	Description	Origin
NR.M.1	Weigh less	To ensure ease of transport and long battery life	SR
NR.M.2	Be fast	To ensure timely information	SR
NR.M.3	Be robust	To ensure longevity of the system and less downtime	SR

Table 3. Mandatory Performance Requirements

ID	Requirement	Description	Origin
PR.M.1	Sense the environment farther than 30cm away from itself	Leads to incorrect disparity and depth	TR
PR.M.2	Sense the environment closer than 1m away from itself	Leads to incorrect depth given perceptual degradation	TR
PR.M.3	Localize itself within 2m of true position in perceptual degradation	To provide accurate location estimates for drone, POIs	TR

PR.M.4	Detect at least 2 classes for POI: humans and open doors	Important POIs while responding to fires	SR
PR.M.5	Detect POI with accuracy greater than 80% when 80% visible	To balance precision vs. recall for detection	DD
PR.M.6	Communicate with an operator with a maximum latency of 200ms	Low latency for tele-op and timely information from sensors	TR
PR.M.7	Communicate with an operator within 25m	The system needs to operate through various building materials	TR

Table 4. Desirable Functional Requirements

ID	Requirement	Description	Origin
FR.D.1	Store sensor information	The visualizations will be saved for future retrieval and analysis	SR
FR.D.2	Detect Obstacles	The drone will detect static obstacles through perceptual degradation	TR
FR.D.3	Avoid Obstacles	The drone will avoid detected obstacles through perceptual degradation	TR

Table 5. Desirable Non-functional Requirements

ID	Requirement	Description	Origin
NR.D.1	Be easy to use	To provide more natural control for the user and reduce training	SR
NR.D.2	Be modular	To ensure the portability of the system to various environments	DD

Table 6. Desirable Performance Requirements

ID	Requirement	Description	Origin
PR.D.1	Localize POI within 5m of the true position	Crucial information in large spaces	DD
PR.D.2	Navigate the environment at a speed of 10 cm/s	Balances exploration speed with safety	DD
PR.D.3	Communicate with an operator within 25m	The system needs to operate through various building materials	TR