CraterGrader:

Autonomous Lunar Sitework Robot

Team A

Fall 2022 Test Plan

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Introduction

This document outlines the various tests that Team A (CraterGrader) will conduct during the semester (Fall 2022) to verify that we are progressing towards meeting desired performance and non-functional requirements for the project. The tests verify technical progression towards the FVD of demonstrating fully autonomous grading of a lunar simulant worksite. An overview of this semester's milestones is shown below (see Schedule).

Logistics

The majority of tests will take place in the Planetary Robotics Lab sandbox on the basement floor of GHC, the same location in which the SVD was performed last semester. The FVD will be live, while all other tests will be run by appropriate team personnel with the results and/or recordings presented during the corresponding Progress Reviews. Everyone will be participating in the FVD, but only the necessary personnel need to be present for other tests.

Schedule

Date	Identifier	Capability Milestone(s)	Associated Test(s)	Associated System Requirements
Sep. 21	PR8a	Hardware Freeze	Test F01	R06, R07, R08, R09, R10
Sep. 25	PR8b	Planner, Mapping Implemented	Test F02 Test F03	R03, R05, R13
Oct. 2	PR9a	Full Functionality	Test F04 Test F05	R03, R05, R06, R07, R08, R11, R12, R13
Oct. 9	PR9b	Autonomous Testing	Test F06 Test F07	R03, R05, R13
Oct. 30	PR10	System Freeze	Test F08 Test F09 Test F10	All
Nov. 15	PR11	Dry Run Demo	--	All
Nov. 21	FVD (PR12)	FVD	--	All

Date	Identifier	Test	Primary Subsystem(s)	Primary System Requirements
Sep. 17	Test F01	Autograder with Upgraded Blade	Mechanical, Motion Control	R06, R07, R08, R09
Sep. 18	Test F02	Mapping Test with Static Terrain	Mapping, Sensing, Localization	R03
Sep. 24	Test F03	Global Path Planning	Planning	R05
Sep. 24	Test F04	State accuracy first test	Localization	R03, R05
Oct. 1	Test F05	State accuracy final test	Localization	R03, R05
Oct. 2	Test F06	Mapping test w/ changing terrain	Mapping, Localization	R03
Oct. 7	Test F07	Global trajectory following	Planning, Localization, Motion Control	R05
Oct. 9	Test F08	Autonomous mapping	All (excl. blade)	R03, R05, R11, R12, R13
Oct. 14	Test F09	Autonomous single crater	All	All
Oct. 21	Test F10	Autonomous multi-crater	All	All

Tests

Test F01: Autograder with Upgraded blade

Test Name	Autograder with Upgraded Blade	**Test Number**	Test F01
Objective			
Verify autograder blade control functionality with upgraded blade			
Elements	Primary: mechanical, motion control		
Location	GHC Sandbox		
Equipment	CraterGrader worksystem, teleop controller, GHC sandbox infrastructure		
Personnel	3 persons: 1 teleoperator, 1 e-stop operator/tether, 1 videographer		
Procedure			
1. The robot is placed in the worksite and powered on following the Power Up/Down Procedure. 2. The tool auto-homing is verified on startup.			

3. The following subsystem is launched (according to Software Launch List)
    a. Motion control (verify tool is auto-homed before launching)
4. In TELEOP mode, the teleop controller verifies tool can be raised and lowered by:
    a. Manually setting tool to autograder design height
    b. Updating autograder params to use that design height
5. The teleop controller zeros tool position
6. The motion control system is placed in autograder mode
7. The robot is driven forward and backward to assess autograder functionality

Verification Criteria

1. Tool auto-homes on startup
2. Tool can be raised and lowered with full teleop mode
3. In autograder mode
    a. When reversing, the tool is raised to a fixed stow height
    b. At all other times, the tool kept at a fixed design height

Test F02: Mapping Test with Static Terrain

Test Name	Mapping Test with Static Terrain	**Test Number**	Test F02

Objective

Quantitatively observe live mapping performance in the sandbox.

Map is going to rely heavily on localization performance, which will improve over the semester therefore committing to numerical requirements is unnecessary

Map comparison of FARO vs. cg-mapping will serve as a first pass of what is feasible with regards to map quality and will be targeted for improvement as localization continues to improve

Elements	Primary: mapping, sensing; Secondary: localization
Location	GHC Sandbox
Equipment	CraterGrader worksystem, teleop controller, GHC sandbox infrastructure, FARO scanner
Personnel	3 persons: 1 teleoperator, 1 e-stop operator/tether, 1 videographer

Procedure

1. Personnel create interesting static terrain in the worksite
2. The robot is placed in the worksite and powered on following the Power Up/Down Procedure.
3. The following subsystems are launched (following the Software Launch List).

    a. Motion Control → Full teleop ONLY (and idle)
    b. Sensing
    c. Localization
    d. Mapping
    e. Visualization
4. The robot is driven around the worksite, building up map until all cells are filled,
5. The robot is removed from the worksite,
6. The FARO scans the worksite and CloudAnalysis is performed on the point cloud.

Verification Criteria

1. Map generated by worksystem closely resembles map obtained from FARO scan, after post-processing through CloudAnalysis

Test F03: Global Path Planning

Test Name	Global Path Planning	**Test Number**	Test F03

Objective

The objective of Test F03 is to verify ROS2 implementation of the “full” planner, including the transport planner and the A* lattice planner to be followed by the mobility system.

This will happen with a pre-canned map and does not require the vehicle, it can happen on any development machine. The output lattice plan will be visualized using RVIZ

Elements	Planning ROS2 Launch File, Pre-canned Map
Location	Not relevant
Equipment	Personal Development Laptop
Personnel	3 persons: 1 ROS2 operator/videographer, 1 note taker, 1 test director

Procedure

1. A ROS2 node publishing a known, constant map and a vehicle pose is launched
2. A unit-testable ROS2 planning node subscribes to the map and runs a callback to generate the following
    a. Transport Planner Map
    b. Lattice Planner
3. The transport plan and lattice plan are visualized in RViz
4. The expected output from the prototype script is compared to both outputs for identicality or high similarity.

Verification Criteria

1. The transport plan in ROS2 looks almost identical to the Python prototype when using the same map.
2. The lattice planner outputs a similar plan to the Python script when both start at the same location, for the same or similar transport plan.
3. RViz screenshots shall be taken, and the overall ROS2 topic Hz will be recorded for planner publishing.

Test F04: State accuracy first test

Test Name	State accuracy first test	**Test Number**	Test F04
Objective			
Test updated all updated elements of the localization subsystem, with an early pass at covariance tuning.			
Elements	Localization, sensing		
Location	GHC Sandbox		
Equipment	CraterGrader worksystem, teleop controller, GHC sandbox infrastructure		
Personnel	3 persons: 1 teleoperator, 1 e-stop/tether operator, 1 videographer		
Procedure			

1. The robot is placed in the center of the worksite facing one of the walls, and powered on following the Power Up/Down Procedure. This includes all external infrastructure preparation, including the UWB beacons and the Leica TS16 total station.
2. The motion control, sensing, and localization subsystems are launched (following the Software Launch List).
3. Plotjuggler is run to display live robot state variables (x, y, z, roll, pitch, yaw, vx, vy, vz) over time, and a screen recording is initiated.
4. The following tests are run with the robot in various state configurations. After each step, the Plotjuggler data are exported to a CSV file:
    a. State information is captured with the robot idle at the center of the worksite
    b. A marking is placed one meter ahead of the robot using a measuring tape. The robot is driven forward one meter and then backward one meter.
    c. The robot is driven up an incline with a reasonable change in z position.
    d. The robot is driven along a quarter-circle arc such that it faces a new wall.
    e. The robot is placed on an incline with a reasonable slope causing a non-zero pitch.
    f. The robot is placed on an incline with a reasonable slope causing a non-zero roll.
    g. The e-stop operator holds the robot in place by the rear handle while the teleoperator commands forward motion, forcing the vehicle to slip. The e-stop operator must inform the teleoperator to stop if the vehicle becomes too

entrapped or if drive motors begin to stall. The e-stop operator must hit the onboard e-stop if the teleoperator does not stop in a timely manner.

5. If verification criteria (as detailed below) are failing at any point, fine-tune covariance matrices and repeat the relevant steps.

Verification Criteria

1. The time-varying signals for all robot state variables are observed to correspond to the actual robot state for all tests being run.
2. The EKF is clearly able to effectively incorporate input from all elements, including newly added modalities.
3. Clear differentiation between map and odom frame velocities can be observed during the slip test.

Test F05: State accuracy final test

Test Name	State accuracy final test	**Test Number**	Test F05

Objective

Finalize covariance matrices for all elements of the EKF in the localization subsystem. Obtain quantitative results for state estimation performance.

Elements	Localization, sensing
Location	GHC Sandbox
Equipment	CraterGrader worksystem, teleop controller, GHC sandbox infrastructure, measuring tape
Personnel	3 persons: 1 teleoperator, 1 e-stop/tether operator, 1 videographer

Procedure

1. The robot is placed in the center of the worksite facing one of the walls and powered on following the Power Up/Down Procedure.
2. The motion control, sensing, and localization subsystems are launched (following the Software Launch List).
3. Plotjuggler is run to display live robot state variables (x, y, z, roll, pitch, yaw, vx, vy, vz) over time, and a screen recording is initiated.
4. The following tests are run with the robot in various state configurations. After each step, the Plotjuggler data are exported to a CSV file:
    a. State information is captured with the robot idle at the center of the worksite
    b. A marking is placed one meter ahead of the robot using a measuring tape. The robot is driven forward one meter and then backward one meter.
    c. The robot is driven up an incline with a reasonable change in z position.

d. The robot is driven along a quarter-circle arc such that it faces a new wall. e. The robot is placed on an incline with a reasonable slope causing a non-zero pitch. f. The robot is placed on an incline with a reasonable slope causing a non-zero roll. g. The e-stop operator holds the robot in place by the rear handle while the teleoperator commands forward motion, forcing the vehicle to slip. The e-stop operator must inform the teleoperator to stop if the vehicle becomes too entrapped or if drive motors begin to stall. The e-stop operator must hit the onboard e-stop if the teleoperator does not stop in a timely manner. 5. If verification criteria (as detailed below) are failing at any point, fine-tune covariance matrices and repeat the relevant steps.
Verification Criteria
1. The time-varying signals for all robot state variables are observed to correspond to the actual robot state for all tests being run. 2. The RMS noise for all robot state variables is determined to be no worse (ideally better) than the results from Test 04. 3. Clear differentiation between map and odom frame velocities can be observed during the slip test.

Test F06: Mapping test w/ changing terrain

Test Name	Mapping test w/ changing terrain	**Test Number**	Test F06
Objective			
Confirm the mapping architecture’s capability to handle dynamically changing terrain (assuming reasonable localization) with the usage of the grading blade.			
Elements	Primary: mapping; Secondary: localization		
Location	GHC Sandbox		
Equipment	CraderGrader robot, GHC Sandbox infrastructure, Shovel, FARO scanner		
Personnel	3 persons: 1 teleoperator, 1 e-stop/tether operator, 1 videographer		
Procedure			
1. The sandbox worksite is set up with varying topographical features, including craters of varying sizes, bumps, pits, and strips of positive and negative displacements. 2. A FARO prescan is taken and saved.			

3. The robot is placed in the worksite and powered on following the Power Up/Down Procedure.
4. The motion control with full teleop (and idle), sensing, localization, mapping, and visualization subsystems are launched (following the Software Launch List).
5. Diagnostic checks through Foxglove are done.
6. Begin recording the video of the testing process.
7. Use `ros2 bag record -a` to record the dynamically generated map.
8. The teleoperator enters the worksite and uses a shovel to dig a pit in front of the robot, putting the displaced material next to the pit while the robot is stationary. The teleoperator leaves the worksite afterwards.
9. The teleoperator commands the blade to the highest position (retracted).
10. The CraterGrader worksystem is driven around the worksite to get an initial map of the worksite (filling all cells) combining the localization, perception, and mapping subsystems.
11. Change the CraterGrader work system into autograder mode.
12. The robot is driven around the worksite, grading craters, spreading positives, and digging out minor negative topological features while running the mapping subsystem.
13. Stop recording the test.
14. Power down the robot following the Power Up/Down Procedure.
15. Remove the robot from the worksite.
16. A scan of the worksite is taken and cloudAnalysis is used to analyze the scan for V&V.

Verification Criteria

1. Qualitatively, observe the continuously updated map as the terrain is dynamically updated, ensuring that it appears accurate. This includes both the initial negative/positive displacement created with a shovel and the grading done by the robot.
2. Relative to the robot speed, the map is updated sufficiently quickly when observing mismatched topographical features.
3. The final map from the vehicle is compared to the FARO scan for an idea of the underlying final map performance.

Test F07: Global trajectory following

Test Name	Global trajectory following	**Test Number**	Test F07
Objective			
Integrate planning and mobility control subsystems for fully autonomous path following (drive and steer).			
Elements	Primary: planning, mobility control; Secondary: localization, sensing		

Location	GHC Sandbox
Equipment	CraterGrader worksystem, GHC sandbox infrastructure
Personnel	3 persons: 1 vehicle operator, 1 e-stop/tether operator, 1 videographer

Procedure

1. The robot is placed in the worksite and powered on following the Power Up/Down Procedure.
2. The motion control, planning, sensing, and localization subsystems are launched (following the Software Launch List).
3. The planner is provided with a mock terrain map containing a single crater, from which it can generate a kinematically feasible path to fill this hypothetical crater.
4. Planned paths and control messages are recorded using `ros2 bag record -a`
5. The robot mode is switched to autonomous mode.
6. The mobility controller executes the appropriate drive velocity and steering commands to follow the designated path.

Verification Criteria

1. The robot's position as reported by the localization subsystem tracks the path generated by the planner.
2. The robot is able to reach all intermediate waypoints along the path that make up in-and-out crater-filling primitives.

Test F08: Autonomous mapping

Test Name	Autonomous mapping	**Test Number**	Test F08

Objective

The first attempt at autonomously mapping the worksite, starting only with a designated coverage area to map. The worksystem will need to perform a coverage plan to map the entire worksite, and then follow that generated trajectory.

The mapping system will need to use both the localization and perception systems to effectively build the sitewide map. This information will be used to both recognize progress made towards full site mapping as well as potential obstacles to avoid throughout the mapping process.

The completion of this task will result in a cohesive sitewide map that matches previously measured ground truth, while avoiding entrapment throughout the process.

Elements	Perception, Localization, Mobility, Mapping
Location	GHC Sandbox
Equipment	CraderGrader robot, GHC Sandbox infrastructure, FARO scanner
Personnel	3 persons: 1 autonomy operator, 1 e-stop/tether operator, 1 videographer

Procedure

1. The sandbox will be set up with multiple craters within specs driven by requirements.
2. Designated mapping task parameters are configured.
3. A ground-truth scan of the worksite will be taken using the FARO scanner.
4. The robot is placed in the worksite and powered on following the Power Up/Down Procedure.
5. All subsystems are launched (following the Software Launch List).
6. System verification checks are performed via Foxglove system monitoring module
7. Robot is switched to autonomous mode.
8. Robot is commanded to conduct site mapping
9. Power down the robot following the Power Up/Down Procedure.

Verification Criteria

1. The produced map data output from the robot is quantitatively similar to a similarly processed map generated from the FARO laser prescan.
2. The robot is able to avoid entrapment and does not require human intervention throughout operation.
3. Map coverage is complete relative to the assigned map area.

Test F09: Autonomous Single Crater Test

Test Name	Autonomous Single Crater Test	**Test Number**	Test F09

Objective

The first attempt at a fully autonomous test with no human intervention tests all subsystems integrated together. A single crater is created in the sandbox to be graded.

Perception’s ability to see the height of the site and craters; Localization’s ability to accurately position the robot relative to the worksite, infrastructure, and crater; Mapping’s ability to map the flat worksite and the crater as a set of highs (sources) and lows (sinks); Planning’s ability to assign grading directionality to the sources and sinks, generate waypoints, and create paths; Control’s ability to follow those generated paths through actuator commands.

Qualitatively: Completion of worksite grading task + corresponding efficiency, determining root causes of potential inefficiencies. Quantitatively: Flatness requirements will be measured but full compliance is not required to pass the test. Comparison between map between Mapping and as measured by total station.	
Elements	Perception, Mapping, Planning, Control, and Localization
Location	GHC Sandbox
Equipment	CraderGrader robot, GHC Sandbox infrastructure, FARO scanner
Personnel	3 persons: 1 autonomy operator, 1 e-stop/tether operator, 1 videographer
Procedure	
1. The sandbox worksite is set up with a single crater. 2. A prescan is taken and saved using the FARO scanner. 3. The robot is placed in the worksite and powered on following the Power Up/Down Procedure. 4. All subsystems are launched (following the Software Launch List). 5. All necessary nodes are launched. 6. Go-no checks through Foxglove are done. 7. The robot is switched to autonomous mode. 8. The robot conducts mapping pass autonomy when given a start command. 9. The robot proceeds to do a full grade of the worksite. 10. Power down the robot following the Power Up/Down Procedure. 11. Remove the robot from the worksite. 12. A scan of the worksite is taken and cloudAnalysis is used to analyze the point cloud for V&V.	
Verification Criteria	
1. The planner is visually verified to act “intelligently” while grading the single crater. 2. The robot does not get stuck or require human intervention. 3. The worksite looks visually flat and graded. 4. The final map performance from the vehicle is quantitatively compared to the FARO scan by analyzing the FARO scan using cloudAnalysis.	

Test F10: Pre-FVD Multi-Crater Test

Test Name	Pre-FVD Multi-Crater Test	**Test Number**	Test F10
Objective			

Test F10, Pre-FVD Multi-Crater Test, is functionally the same as Test F09, except with more challenging terrain for the planner. Specifically, this test addresses the ability of the planner and control to navigate multiple claustrophobic craters.

The planner's ability to select good waypoints, and controller's ability to keep the vehicle on track will be tested while traversing the worksite.

Qualitatively we will observe the efficiency of the total system, including behavior and speed. Flatness requirements will be measured but full compliance is not required to pass the test (added site geotechnic requirements would be a full FVD).

Elements	Mapping, Perception, Planning, Control, and Localization
Location	GHC Sandbox
Equipment	CraderGrader worksystem, GHC Sandbox Infrastructure, FARO scanner
Personnel	3 persons: 1 autonomy operator, 1 e-stop/tether operator, 1 videographer

Procedure

1. The sandbox worksite is set up with a crater topography.
2. A FARO prescan is taken and saved.
3. The CraterGrader robot is powered on in the sandbox.
4. All necessary nodes are launched.
5. Diagnostic checks through Foxglove are done.
6. Robot conducts mapping pass autonomy when given a start command.
7. Robot proceeds to do full grade of worksite
8. FARO scan of worksite is taken and pumped through CloudAnalysis scripting for V&V

Verification Criteria

1. Planner is visually verified to act "intelligently" while managing multiple craters in close proximity.
2. Vehicle does not get stuck nor requires human intervention.
3. The final map from the vehicle is compared to the FARO scan for an idea of underlying final map performance, which may be difficult to interpret due to flatness.
4. The worksite looks visually flat and graded. The FARO scan is analyzed using CloudAnalysis to confirm quantitatively.