Precisely Weeding Tree Nurseries Autonomously

Task 4: Spring Project Test Plan

Team F: **ZAAPP**

Zihan Wan

Amaar Quadri

Adrian Walker

Parth Shah

Philip Koch

Sponsor: moss© Robotics Inc.

16-661: MRSD Project I

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Carnegie Mellon University
Robotics Institute

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1 Introduction

This document outlines the tests to be executed by us, Team F (ZAAPP), as part of the 2024 Spring semester. These tests have been designed to measure our progress towards meeting the requirements laid out in the 2023 Fall semester, and to establish milestones in the development of our robotic system. We intend to demonstrate our progress via these tests during our regular progress reviews, and eventually during the Spring Validation demonstration. We do not expect to have a fully integrated system by the Spring Validation demonstration. However, we intend to demonstrate most of the functionality listed in our Requirements with tests targeted at individual subsystems.

2 Logistics

2.1 Personnel

No personnel beside the five team members are required for these tests, except for the Full-power Laser Validation Test (11) and the Eye-safe Laser System Validation Test (12), which will be carried out by moss© personnel.

2.2 Location and Equipment

Most testing will occur in and around Newell-Simon Hall (NSH), with the exception of the Full-power Laser Validation Test.

An adjustable test frame with height markings will be constructed and used in several tests (4, 2, 6, 12, 11). We intend to use moss©'s Husky base (which is currently located in NSH FRC) in the Manipulation Construction & Mounting Test (7) and Manipulation System Accuracy Test (8), as well as our SVD.

3 Schedule

Date	PR	Capability Milestone(s)	Test(s)	Require-ments
02/15/24	1	• Initial Manipulation CAD design • Initial Actuation CAD design • Initial vision model	-	-
02/29/24	2	• Forward Facing Localization Test • Achieve sub-optimal accuracy for downward facing detection	4.1,	M.P.3
03/21/24	3	• Manipulator – **Build manipulator** • Actuator – **Build actuator** • Sprayer – **Test Sprayer Construction and leak** • Perception – **Test Forward Facing Detection** – **Implement downward facing detection** • Eye-safe laser functional	4.3, 4.5, 4.6, 4.8, 4.11,	M.P.1, M.P.2, M.P.4, M.P.8, M.N.4, D.N.4,
04/04/24	4	• Manipulator: – **Manipulation System Accuracy test** • Sprayer: – **Sprayer actuation and repeatability test** • Localization Implementation – **Forward Facing Tracking Test** • Functional laser system prototypes – **Test eye safe laser** – **Test full power laser prototypes**	4.2, 4.4, 4.7, 4.9, 4.10	M.P.4, M.P.3, M.P.6, M.P.8, M.N.4,
04/18/24	SVD	• Independent Subsystem Demo – **Downward Facing Detection and Relative Localization Test** – **Manipulation System Accuracy Test** – **Sprayer Actuation and Repeatability Test** – **Eye-safe Laser System Validation Test**	4.2, 4.4, 4.7, 4.9, 4.10, 4.12,	M.P.1, M.P.2, M.P.3, M.P.4,
04/25/24	SVD Encore	Independent Subsystem Fine-tune	-	-

4 Tests

4.1 Forward Facing Localization Test

Objectives	
To verify that we can convert weed detections to robot-relative (or, in this test, camera-relative) 3D point clouds.	
Requirements	M.P.3
Equipment	Realsense D435i camera, test frame (shared between tests), USB-C cable, laptop, 4 distinct printed April tags with cardboard backing
Elements	Localization System
Personnel	Phil and Parth
Location	The bay outside the MRSD lab in NSH
Procedure	
1. Construct grid of tape on the ground in front of the camera at fixed increments. 2. Mount D435i on the ZAAPP test frame. 3. Place test frame on tape grid. 4. Position April tags on the grid in front of the camera such that the tags' face is roughly parallel to the camera's image plane. 5. Run off-the-shelf April tag detection. 6. Run in-house localization against April tag detections, D435i depth map, and known camera extrinsics. 7. Display localization visualization.	
Verification Criteria	
1. Compare ground-truth position of each April tag in stand-relative coordinates to calculated position. The error should be within the M.P.3 specifications.	

4.2 Forward Facing Tracking Test

Objectives	
To verify that we can correlate weed detections as the system moves through its environment.	
Requirements	M.P.3
Equipment	D435i, mounting stand (shared between tests), mobile cart, USB-C cable, laptop, 4 non-distinct printed April tags with cardboard backing
Elements	Localization System
Personnel	Phil and Parth
Location	The bay outside the MRSD lab in NSH
Procedure	
1. Mount D435i on the ZAAPP test stand. 2. Mount test stand on mobile cart. 3. Position April tags in front of the camera such that the tag's face will be roughly parallel to the camera's image plane as the cart moves forward. 4. Move the cart linearly through the environment. 5. Run off-the-shelf April tag detection. 6. Run in-house localization against April tag detections, D435i depth map, and known camera extrinsics, as well as detection correlation pipeline. 7. Display localization visualization, including internal representation ID of each detection.	
Verification Criteria	
1. Check that the internal representation ID of each detection remains consistent throughout system movement. In other words, a given April tag should maintain the same detection ID between camera frames.	

4.3 Forward Facing Detection Test

Objectives	
To verify that we can detect weeds in a dataset that is the best approximation we have of our target use case.	
Requirements	M.P.1, M.P.2
Equipment	Laptop, pre-trained model, annotated "Jason's farm"[1] RGB image data
Elements	Perception System
Personnel	Phil and Parth
Location	The bay outside the MRSD lab in NSH
Procedure	
1. Run a pre-trained model on the annotated test set[2]. 2. Calculate weed IoU for each example[3]. 2. Calculate the mean IoU over the test set. 3. Display a subset of samples and detections for visual verification.	
Verification Criteria	
1. Visually verify detected segmentations line up with weeds. 2. Verify mean IoU over test set weed segmentations is at least 60%.	

[1]This is a dataset that we collected during Fall 2023 at a tree nursery outside Pittsburgh. It consists of forward-facing images of nursery trees and weeds, captured at a height of roughly 600mm.

[2]This data was hand-annotated by our team.

[3]IoU is defined here as the intersection of detected weed pixels and annotated weed pixels over the union of these two sets.

4.4 Downward Facing Detection Validation Test

Objectives	
To validate the weed detection model's performance with an off-the-shelf dataset (with downward camera orientation) and ensure segmentation accuracy meets specified criteria.	
Requirements	M.P.1, M.P.2
Equipment	Laptop, pre-trained model, Sugar Beets Dataset 2016[4]
Elements	Perception System
Personnel	Parth and Phil
Location	The bay outside the MRSD lab in NSH
Procedure	
1. Randomly select 10 images from the test set[5] of the Sugar Beets 2016 dataset. 2. Run a pre-trained model on the selected images to obtain segmentation masks. 3. Compare the predicted segmentations with the ground-truth annotations and calculate weed IoU for each image. 4. Calculate the mean IoU over the selected images. 5. Display the samples and detections for visual verification.	
Verification Criteria	
1. Verify mean IoU[6] over test set weed segmentations is at least 60%.	

[4]Chebrolu, N., Lottes, P., Schaefer, A., Winterhalter, W., Burgard, W., & Stachniss, C. (2017). Agricultural robot dataset for plant classification, localization and mapping on sugar beet fields. *The International Journal of Robotics Research*. doi: 10.1177/0278364917720510

[5]The dataset underwent prior division into training and testing sets before model training, ensuring exclusion of the latter from the training process.

[6]IoU is defined here as the intersection of detected weed pixels and annotated weed pixels over the union of these two sets.

4.5 Downward Facing Detection and Relative Localisation Test

Objectives	
To verify weed detection and localization in a real-world setting with top-down camera configuration.	
Requirements	M.P.3
Equipment	D435i, mounting stand, fake weeds setup[7], measuring tape
Elements	Perception System
Personnel	Parth and Phil
Location	The bay outside the MRSD lab in NSH
Procedure	
1. Mount D435i on the ZAAPP test stand. 2. Mount test stand on mobile cart. 3. Ensure the fake weeds setup is properly arranged and positioned. 4. Position the cart beside the fakeweeds setup with the camera right above it. 5. Run the weed detection module on the D435i to detect weeds. 7. Count the total number of weeds detected by the weed detection module. 6. Localize the detected weeds relative to the camera and find their relative positions. 8. Compare the relative position obtained with the ground truth positions.	
Verification Criteria	
1. Verify visually that the detection module has Precision $> 50\ \%$ and Recall $> 50\%$. 2. Verify that the distance between the localized position of detected weeds and their ground truth position is within 10 cm.	

[7]The setup comprises a 1m x 1m tarp covered with soil, featuring artificial weeds planted on its surface.

4.6 Manipulation Construction & Mounting Test

Objectives	
Evaluate the structural integrity and assembly quality of the manipulator system.	
Requirements	D.N.4
Equipment	Husky base, manipulation hardware component, 80/20 aluminum, stepper motor, servo motor, Arduino, breadboard, wiring, and push button
Elements	Manipulation Subsystem
Personnel	Amaar Quadri, Zihan Wan
Location	NSH FRC
Procedure	
1. Assemble the manipulator subsystem ensuring no components are missing. 2. Securely attach the manipulation subsystem to the Husky base. 3. Subject the manipulation subsystem to endurance tests such as shaking and pushing. 4. Following the test, carefully remove the manipulation subsystem.	
Verification Criteria	
1. Confirm the subsystem's secure attachment to the Husky base. 2. Assess the subsystem's stability and retention on the base under stress tests. 3. Ensure the subsystem can be detached without causing damage to any components.	

4.7 Manipulation System Accuracy Test

Objectives	
Evaluate the precision of the manipulation subsystem in reaching specified target positions.	
Requirements	M.P.4.
Equipment	Husky base, manipulation hardware component from Manipulation Construction & Mounting Test, 0.5mW laser pointer
Elements	Manipulation Subsystem
Personnel	Amaar Quadri, Zihan Wan
Location	NSH FRC
Procedure	
1. Attach the 0.5-mW low power laser pointer to the end of the manipulator to indicate its aiming point. 2. Use UI interface to command the the servo and stepper motor through the Arduino 3. For accuracy testing, execute the following commands three times each: • Direct the stepper motor to a predetermined position. • Adjust the tilt axis to a specific angle. • Position the manipulator to a chosen location and document the laser pointer's accuracy.	
Verification Criteria	
1. The stepper motor's ability to reach the commanded position within a tolerance of +/- 50 mm. 2. The tilt axis's capacity to achieve the commanded position within a tolerance of +/- 5 degrees.	

4.8 Sprayer Construction and Leak Test

Objectives	
To verify that the parts procured for the sprayer system fit together and that the resulting system does not have any liquid leaks.	
Requirements	M.N.4
Equipment	All of components of the sprayer system, PVC tape, soap and water
Elements	Sprayer Subsystem
Personnel	Amaar and Zihan
Location	Outside of NSH B level
Procedure	
1. Wrap all of the male threads of the pipe fittings in PVC tape. 2. Construct all components of the sprayer system as designed. 3. Coat all connection points in soapy water. 4. Fill up the tank with water to pressurize the system. 5. Visually inspect the connection points for bubbles caused by leaks.	
Verification Criteria	
1. Visually inspect the constructed system to ensure that all components fit together. 2. Visually inspect the connection points covered in soapy water to look for bubbles caused by leaks.	

4.9 Sprayer Actuation and Repeatability Test

Objectives	
To verify that the peristaltic pump can be actuated to expel a desired amount of fluid from the atomizing nozzle.	
Requirements	M.N.4
Equipment	Fully constructed sprayer system, peristaltic pump, 24V Battery, DC motor driver, Arduino, breadboard, wiring, and push button, water, beaker
Elements	The Sprayer Subsystem, peristaltic pump, and DC motor driver will be tested
Personnel	Amaar and Adrian
Location	Outside of NSH B level
Procedure	
1. Feed the tubing of the sprayer subsystem into the peristaltic pump. 2. Fill the tank with water. 3. Place the atomizing nozzle inside the beaker. 4. Press the push button which will trigger the Arduino to rotate the peristaltic pump by a set amount. 5. Record the amount of water in the beaker. 6. Empty the beaker. 7. Return to step 3 and repeat 3 times.	
Verification Criteria	
1. Visually verify that pressing the push button causes the peristaltic pump to rotate, and causes water to be expelled from the atomizing nozzle. 2. The quantity of water in the beaker across the 3 tests is consistent to within 20% of the mean.	

4.10 Full-power Laser Validation Test

Objectives	
To verify that the designed laser system is both functional and capable of damaging weeds at the correct distance from the weed.	
Requirements	M.P.8, M.N.4
Equipment	The laser subsystem, a benchtop power supply, protective laser goggles, test frame with height markings and beam backstop, green plant/weed leaf specimens, timing device (stopwatch), video recording device (preferably with tripod), fire extinguisher, laser safety procedure (written by ZAAPP).
Elements	Full-power Laser System
Personnel	moss personnel
Location	moss's facilities
Procedure	
1. Mount the laser system to the test frame, set to the lowest height. 2. Prepare the benchtop power supply. 3. Place a test specimen on the target mark. 4. Set up a video recording device. 5. Prepare the timing device. 6. Ensure the area is secure such that no person can accidentally walk in. 7. Don the laser goggles. 8. Connect the power supply. 9. Start video recording. 10. Enable the laser and start the time.r 11. Run the laser for 5 seconds. 12. Disconnect the power supply. 13. Stop the video recording. 14. Inspect the weed specimen for damage. 15. Take a picture of the specimen. 16. Repeat steps 8 through 15 for 1 second less. 17. After completing the 1-second recording, repeat steps 8 through 16 at each marked height.	
Verification Criteria	
1. Visually verify that the specimen has been damaged after each lasing run. 2. The ultimate verification goal is for the laser to damage the specimen at the final system's mounting height.	

4.11 Eye-safe Laser System Validation Test

Objectives	
To verify that the designed laser system is both functional and is a suitable visual replica of the full-power laser system and is thus a suitable substitute, as well as to confirm the designed optical power is safe.	
Requirements	M.P.6, M.P.8, M.N.4
Equipment	The eye-safe laser subsystem, a benchtop power supply, test frame with height markings, protective laser goggles, multimeter, green plant/weed leaf specimens, video recording device (preferably with tripod), fire extinguisher, laser safety procedure (written by ZAAPP)
Elements	Eye-safe Laser Subsystem
Personnel	moss personnel
Location	MRSD Lab
Procedure	
1. Mount the laser system to the test frame, set to the application height. 2. Connect the multimeter to measure the current supplied to the laser diode. 3. Prepare the benchtop power supply. 4. Place a test specimen on the target mark. 5. Set up a video recording device. 6. Ensure the area is secure such that no person can accidentally walk in. 7. Don the laser goggles. 8. Connect the power supply. 9. Start video recording. 10. Enable the laser. 11. Record the current measurement. 12. Disconnect the power supply. 13. Inspect the weed specimen for damage. 14. Take a picture of the specimen if it is damaged .	
Verification Criteria	
1. The current measured matches the desired current output from the laser diode datasheet that corresponds to an optical power output of < 5 mW (strictly less due to safety restrictions). 2. The laser point is visible and stable.	

4.12 Spring Validation Demo

Objectives	
Demonstrate the independent functionality of the components that will comprise our system as well as the mechanical integration of our system.	
Requirements	M.P.1, M.P.2, M.P.4, M.N.4, M.P.6, M.P.8, M.N.4
Equipment	moss' Husky, manipulator system, sprayer system and a beaker, ESP-32, a laptop, a tablet, a 1m × 1m tarp, soil, fake weeds, Intel Realsense camera, eye-safe laser prototype, real laser prototype and its mounting fixture, broom and dustpan, USB-C Cable
Elements	Perception System, Localization System, Manipulation Subsystem, Sprayer Subsystem, Full-power Laser System, Eye-safe Laser Subsystem
Personnel	Zihan, Adrian, Amaar, Parth, Phil
Location	Outside of NSH B Level
Procedure	
1. Place the tarp on the floor, cover it in a thin layer of soil, and place the Husky and fake weeds on it. 2. Mount the Realsense camera and the manipulator system onto the Husky in accordance with the CAD. 3. Mount the eye-safe laser prototype on the manipulator system in accordance with the CAD. 4. Mount the full power laser on its mounting fixture on the desk. Do not power it. 5. Connect the manipulator system, sprayer system, and eye-safe laser system to the ESP-32 and the laptop. 6. Connect the Realsense camera to the laptop and start the downward facing detection and relative localization test. 7. Start the manipulator system accuracy test. 8. Start the sprayer actuation and repeatability test. 9. Start the eye-safe laser system validation test. 10. Show a video of the full power laser validation test on the tablet.	
Verification Criteria	
The verification criteria for this test will be a union of the verification criteria of the Downward Facing Detection and Relative Localization Test (6), Manipulation System Accuracy Test (8), Sprayer Actuation and Repeatability Test (10), and Eye-safe Laser System Validation Test (12).	

5 Appendix

5.1 Requirements

Note that these requirements are sourced directly from our CDPR, are provided for reference purposes only, and have not been updated to match our Spring 2024 estimations.

→ **M.F.1** Detect Weeds
The system shall detect weeds in its environment and path.

- **M.P.1** Precision $> 60\ \%$
  Precision is defined as $Precision = \frac{TP}{TP+FP}$, where TP stands for True Positive (correct weed detections) and FP stands for False Positive (incorrectly identified as weeds).

- **M.P.2** Recall $> 60\ \%$
  Recall is defined as $Recall = \frac{TP}{TP+FN}$, where TP also stands for True Positive (correct weed detections) and FN stands for False Negative (weeds that were not detected).

→ **M.F.2** Localize Weeds
The system shall localize detected weeds in the world frame.

- **M.P.3** Localization RMSE $< 100\, mm$
  $localization\_RMSE = \sqrt{\frac{1}{N}\sum \|localized\_weed\_position - gt\_weed\_positions\|_2^2}$

→ **M.F.3** Position Tool
The system shall position the tool to target the desired location.

- **M.P.4** Manipulator Positioning RMSE $< 50\, mm$
  $manipulator\_positioning\_RMSE = \sqrt{\frac{1}{N}\sum \|commanded\_tool\_position - final\_tool\_position\|_2^2}$

→ **M.F.4** Eliminate Weeds
The system shall eliminate the weeds within the area of operation.

- **M.P.5** Targeting RMSE $< 50\, mm$
  $targeting\_RMSE = \sqrt{\frac{1}{N}\sum \|affected\_area\_centers - gt\_weed\_positions\|_2^2}$

- **M.P.6** Efficacy of Elimination $> 70\ \%$
  At least 70% of $ZAAPP'd$ weeds should show visible[1] damage within 24 hours.

→ System Level Performance

- **M.P.7** Throughput $> 100\ m^2/hr$
  The system shall cover an area of 100 meters squared every hour in conditions where weed-density is less than 2 weeds per meter squared.

[1] Visible damage is defined as the leaves of the weeds either wilting to some degree or tuning brown.

– **M.P.8** Effectiveness $> 50\,\%$

The system should be able to *ZAAPP* 50 % of the targeted weeds.

5.1.1 Non-Functional Requirements

Table 14 defines the mandatory non-functional requirements, their names, and sources.

Table 14: Mandatory Non-Functional Requirements

ID	Requirement	Description	Source
M.N.1	Appropriate Size	The system must fit between tree rows.	Farmer
M.N.2	Viable Cost	The system must make economical sense to replace human workers.	Farmer
M.N.3	Minimal Weight	The system's weight must be within the carrying capacity of the base.	moss©
M.N.4	Eco-Friendly	The system must be less harmful to the environment than traditional methods.	moss©

5.2 Desirable Requirements

5.2.1 Functional and Performance Requirements

→ **D.F.1** Human Proximity Safety Protocol

The system shall cease weed neutralization activities when humans are detected in its vicinity.

5.2.2 Non-Functional Requirements

Table 15 defines the desirable non-functional requirements, their names, and sources.

Table 15: Desirable Non-Functional Requirements

ID	Requirement	Description	Source
D.N.1	Safety	The system should not pose a danger to humans in its vicinity.	Farmer
D.N.2	Weather Resistant	The system should be able to operate in most weather conditions.	Farmer
D.N.3	Battery Life	The system should have very high uptime.	Farmer
D.N.4	Durablity	The system should be resistant to daily wear and tear.	Farmer
D.N.5	Color	The system should be visible in the farm.	*ZAAPP*