Carnegie Mellon University Robotics Institute

Master of Science in Robotic Systems Development
Carnegie Mellon University Robotics Institute

16-681 MRSD Project 1
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Spring Test Plan

Team E: VADER
Vision-based Autonomous DExterous Reaper: Autonomous Bimanual Green Pepper Harvesting System

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1. Introduction

This document outlines the testing procedures to be executed by us, Team E (VADER), as part of the Spring 2025 semester. These tests are designed to demonstrate our progress towards the requirements specified during the Fall 2024 semester, and towards the completion of milestones in the development of the autonomous bell pepper harvesting system. As part of the regular Progress Reviews, as well as the Spring Validation Demonstration, we intend to demonstrate our progress towards fulfilling the system requirements through these tests.

Due to the lack of two real articulated arms, we are unable to fully demonstrate the system by the Spring Validation Demonstration. However, we expect to demonstrate the full system in simulation (with both arms), and demonstrate successful operation per each arm (gripper and cutter) separately. We intend to demonstrate successful operation with tests targeted at each individual subsystem, as well as an end-to-end demonstration of picking a single pepper autonomously in simulation.

2. Logistics

2.1. Personnel

For the spring semester tests outlined, no additional personnel besides the five project members are required for the tests.

2.2. Location and Equipment

Most in-person testing will occur at 1317 Wean Hall within our lab workspace, since the robot arm and related accessories are mounted on a stationary table within this space.

A fake pepper plant test bed or real green bell peppers will be used in several tests, for purposes of demonstrating the perception and extraction subsystems.

3. Schedule

Date	PR	Capability Milestones	Tests	Requirements Demonstrated
2/13	1	• The individual subsystems namely perception and planning are semi operational • For perception, the realsense camera can detect pepper poses and the location in 3D • For planning, the simulated dual arm system can be controlled without collision and the single arm RViz controller integrated with the real XArm 7 can reach a goal point in free space • Basic conceptual CAD enhancements for better gripper functionality	Tests 4.1; 4.2	PR.01 ; FR.01
2/27	2	• The camera is integrated with the XArm 7 and can locate a pepper placed in vicinity • The XArm can approach the pepper from any direction • Newly fabricated gripper with finger retraction mechanism	Tests 4.3; 4.4; 4.5	PR.01 ; FR.01
3/20	3	• Basic collision avoidance for different pepper orientations in sim for dual arm system working simultaneously with goal pose convergence • Grasp planning enabled for XArm7 for optimal direction of approach for gripper to grasp peppers • Perception and Planning end to end integration from detecting peppers to grasping peppers	Tests 4.6; 4.7; 4.8; 4.9	PR.03; FR.03
4/8	4	• Testing with multiple peppers to identify priority based approaches • Manufacturing spare end effectors for risk planning • Identifying bugs and employing multiple phases of testing to	Tests 4.10; 4.11; 4.12; 4.13	PR.04 ; FR.04

		ensure effective system functionality		
4/17	SVD	• Fully autonomous pepper detection, prioritization and grasping with real arm along with demonstration of the dual arm system with no collisions in simulation	Tests 4.14	PR.01; PR.02; PR.03; FR.01; FR.02; FR.03
4/24	SVD Encore	• Addressing bug fixes and improvements from SVD and fixing them.	Tests 4.14	PR.01; PR.02; PR.03; FR.01; FR.02; FR.03

4. Tests

4.1. Camera Calibration Test

Objectives	
To verify camera calibration and ensure accurate intrinsic and depth parameter estimation.	
Requirements	PR.01
Equipment	• Realsense camera • Calibration target with ArUco markers • Laptop • Calibration software • Measurement tools for ground-truth validation
Elements	Perception Subsystem/Camera Calibration
Personnel	Kshitij, Keerthi
Location	Wean Hall 1317
Procedure	
1. Set up the Realsense camera on a stable mount. 2. Position the ArUco marker calibration target within the camera's field of view. 3. Run the calibration script using the appropriate software. 4. Extract intrinsic parameters, including focal length and distortion coefficients, at a target resolution of 1280x720. 5. Compare intrinsic parameters with expected values for accuracy. 6. Calibrate the depth using known ground-truth measurements. 7. Validate depth accuracy by comparing camera depth outputs with physical	

measurements.
Verification Criteria
1. Ensure intrinsic parameter estimations (focal length, distortion coefficients) match real-world expectations. 2. Verify depth calibration accuracy within acceptable error bounds. 3. Ensure that repeated calibration tests produce consistent results.

4.2. Single Arm Sim manipulation test

Objectives	
To import XArm7 simulation URDF models into ROS and check if it can attain a desired end effector goal pose within the robot arm's workspace	
Requirements	PR.01 ; FR.01
Equipment	• PC • Monitor
Elements	Planning Subsystem,Simulation Testing
Personnel	Tom, Abhishek, Rohit
Location	Wean Hall 1317 - ROS(Virtual)
Procedure	
1. Desired Pose of the XArm is published to the MoveIt planner node. 2. The desired manipulation trajectory is planned and shown in RViz. 3. The execution command is published to the MoveIt planner node. 4. The movement is executed for the XArm7 in sim by the MoveIt controller, shown both in RViz and Gazebo.	
Verification Criteria	
1. MoveIt receives desired pose and successfully plans movement for reachable poses. 2. The simulated XArm7 moves from its current pose to its desired pose.	

4.3. Segmentation Accuracy Test

<table>
<tr><td colspan="2">Objectives</td></tr>
<tr><td colspan="2">To verify that the system can autonomously segment bell peppers in the workspace using computer pipeline techniques.</td></tr>
<tr><td>Requirements</td><td>PR.01 ; FR.01</td></tr>
<tr><td>Equipment</td><td>Realsense camera
Mounting stand (shared between tests)
USB-C cable
Laptop
Printed test images of bell peppers
Real bell peppers with varying orientations and occlusions</td></tr>
<tr><td>Elements</td><td>Perception Subsystem::Segmentation Model</td></tr>
<tr><td>Personnel</td><td>Kshitij, Keerthi</td></tr>
<tr><td>Location</td><td>Wean Hall 1317</td></tr>
<tr><td colspan="2">Procedure</td></tr>
<tr><td colspan="2">Mount the Realsense camera on the test stand.
Position real bell peppers within the camera's field of view at various distances and orientations.
Capture images and run object detection using the trained segmentation model.
Generate segmentation maps for detected bell peppers and their peduncles.
Extract confidence scores for detections.</td></tr>
<tr><td colspan="2">Verification Criteria</td></tr>
<tr><td colspan="2">Validate that the system correctly detects bell peppers and their peduncles in different scenarios.
Ensure that segmentation maps align with ground-truth annotations.
Confirm that the confidence level calculations are consistent.
The system should achieve an mAP above 0.7 and an IoU over 0.6.</td></tr>
</table>

4.4. Dual Arm Sim manipulation test

Objectives	
To import a second XArm7 simulation URDF models into the same RViz/Gazebo environment and check if both the Xarms can independently attain their desired end effector goal pose within their workspace.	
Requirements	PR.01 ; FR.01
Equipment	• PC • Monitor
Elements	Planning Subsystem,Simulation Testing
Personnel	Tom, Abhishek, Rohit
Location	Wean Hall 1317 - ROS(Virtual)
Procedure	
1. Desired Poses of both XArms are published to the MoveIt planner node. 2. The desired manipulation trajectory for each arm is planned and shown in RViz. 3. The execution command is published to the MoveIt planner node for each arm. 4. The movement is executed for each arm independently by the MoveIt controller, shown both in RViz and Gazebo.	
Verification Criteria	
1. MoveIt receives desired poses and successfully plans movement for reachable poses for both arms. 2. The planning and execution of each manipulator is independent of the other arm. 3. Both the simulated XArm7's move from their current pose to their respective desired poses in Gazebo.	

4.5. Single Arm robot manipulation test

Objectives	
To check if communication can be established between the physical XArm7 and the ROS publisher node for the Xarm to attain a desired end effector goal pose within its workspace	
Requirements	PR.01 ; FR.01
Equipment	• XArm7 with control box • PC • Monitor • Ethernet cable

Elements	Planning Subsystem::Physical Testing
Personnel	Rohit, Abhishek, Tom
Location	Wean Hall 1317
Procedure	
1. Connect power to the XArm assembly, and verify it is connected to the PC via the ethernet cable. 2. Input the desired end effector pose to the MoveIt planner node. 3. The MoveIt planner demonstrate	
Verification Criteria	
1. The physical XArm must move to the desired end effector pose. 2. Simulated and physical Xarm's joint angles must match visually.	

4.6. 3D Localization

Objectives			
To validate the accuracy of the 3D localization of bell peppers using stereo vision and to ensure that the computed 3D coordinates align with the actual position in the workspace.			
Requirements	PR.02 ; FR.02		
Equipments	Realsense D435i camera ; Camera mount ; ROS ; RealSense SDK		
Elements	Perception Subsystem:: 3D Localization		
Location	Wean Hall – Room 1317	Personnel	Keerthi ; Kshitij
Procedure			

1. Use the Intel RealSense SDK to stream both RGB and depth data in parallel from the camera. 2. Ensure that the depth and RGB frames are correctly time-synchronized to avoid mismatches between 3D coordinates and the visual representation of the bell peppers. 3. Extract the segmentation map from the detection algorithm, which defines the regions of interest (ROI). 4. For each bell pepper detected in the RGB frame, extract the corresponding depth values from the depth map. 5. Using the depth values and the camera calibration parameters (focal length, principal point), convert the 2D pixel coordinates of the bounding box into 3D world coordinates (x, y, z). 6. Compare the 3D coordinates obtained from the RealSense D345i camera with the ground truth values to assess accuracy.
Verification Criteria
1. Verify that the 2D bounding box detected in the camera feed accurately maps to 3D world coordinates. 2. Ensure that the Euclidean distance between the computed 3D positions and the ground truth for each detected pepper is within a predefined threshold (e.g., within 1–3 cm).

4.7. Pose Estimation Validation

Objectives	
To verify the accuracy of the pose estimation algorithm.	
Requirements	PR.02
Equipment	• Realsense camera • XArm7 robotic arm • Fiducial/Aruco cube for known pepper pose • Lab Computer • Pose estimation software
Elements	Perception Subsystem :: Pose Estimation
Personnel	Kshitij
Location	Wean Hall 1317

Procedure
1. Mount the Realsense camera on the XArm7 at a known position. 2. Place the fiducial/Aruco cube to represent a known bell pepper pose. 3. Run the pose estimation algorithm to generate pose estimates. 4. Transform the pose into the object's canonical frame. 5. Compute the average translation error (Etran), which is the Euclidean distance between the predicted and ground-truth center for each fruit. 6. Compute the rotation error (Erot) as the intersection angle between the z-axis of the predicted and ground-truth pose. 7. Display visualization of pose estimates and errors.
Verification Criteria
1. Ensure translation error (Etran) is within acceptable limits of 30 mm. 2. Ensure rotation error (Erot) is minimized and consistent across tests and is within 30 degrees. 3. Validate that the pose estimation remains stable across different positions and orientations. 4. Confirm transformation to the object's canonical frame is performed correctly.

4.8. Dual Arm Sim collision avoidance test

Objectives	
To implement Multi agent path finding algorithms for the dual XArm assembly, and ensure both the XArm's reach their desired end effector poses without collision.	
Requirements	PR.02 ; FR.02
Equipment	• Realsense camera • Mounting stand (shared between tests) • USB-C cable • Laptop • Printed test images of bell peppers • Real bell peppers with varying orientations and occlusions
Elements	Planning Subsystem::Simulation Testing
Personnel	Tom, Abhishek, Rohit
Location	Wean Hall 1317 - ROS(Virtual)
Procedure	
1. Desired End effector poses are input to the controller of both the arms. 2. Desired trajectories are planned and executed for both the Xarms, either serially or	

parallelly.
Verification Criteria
1. The respective controllers of the XArms receive the desired pose and successfully plan movement of both the arms for reachable poses. 2. Both the simulated XArm7's move from their current pose to their respective desired poses in Gazebo, without collision.

4.09. Pepper Prioritization

Objectives:			
To ensure that in a scene of multiple bell peppers, each of them is detected individually and the prioritization algorithm ranks the identified peppers based on their proximity to the robot arm for efficient interaction.			
Requirements	FR.02		
Equipment	Realsense D435i camera ; Camera mount ; ROS ; RealSense SDK ; RViz		
Elements	Perception Subsystem:: Prioritization		
Location	Wean Hall – Room 1317	Personnel	Kshitij ; Keerthi
Procedure			
1. Prepare the workspace with multiple bell peppers placed in various positions and orientations, ensuring some are close to the robot arm while others are farther away. 2. Begin processing the image frames through the object detection algorithm and ensure that each pepper is uniquely identified, and no bell pepper is assigned multiple bounding boxes. 3. Test if the algorithm is able to assign a unique identifier for each pepper across multiple frames to correctly track the peppers even if their positions change. 4. Ensure that the robot arm's prioritization algorithm correctly ranks peppers based on proximity to the arm such that the peppers closest to the robot arm are given higher priority for harvesting tasks.			
Verification Criteria			
1. Verify that each bell pepper must be detected and assigned a unique label, with no false positives or negatives. 2. To ensure that the system accurately prioritizes peppers based on their proximity to the robot arm.			

4.10. Grasp Planning Test

Objectives	
Ensuring Functionality of the Gripper and the Planner based on Grasp Approach from Gripper Perspective	
Requirements	PR.03 ; FR.03
Equipment	• Realsense camera • Mounting stand (shared between tests) • USB-C cable • Laptop • Printed test images of bell peppers • Real bell peppers with varying orientations and occlusions
Elements	Planning Subsystem: Gripper functionality
Personnel	Tom, Rohit, Abhishek
Location	Wean Hall - 1317
Procedure	
1. Setup the XArm 7 with ethernet cable and power supply 2. Mount the gripper on the Xarm 7 end effector firmly 3. Connect the gripper with Dynamixel and verify gripper control 4. Enable demo goal pose on RViz Control 5. Evaluate direction of approach for end effector 6. Execute the approach and make end effector reach a minimum offset away from the pepper in the right vicinity of the gripper fingers 7. Execute Dynamixel position controls and curl gripper fingers around pepper	
Verification Criteria	
1. The test will be verified based on the accuracy of angle of approach intended to be perpendicular to the axis of the pepper and in the plane of the 2. Based on whether the gripper response is in sync with the control inputs provided to it 3. Based on accuracy of gripper fingers curling correctly around the peppers about the pepper's cylindrical diameter	

4.11. End-Effector Camera Integration and Pose Refinement

Objectives:	
To verify that the initial pose estimation from the perception system correctly positions the gripper and cutter arms in 3D space relative to the target. To ensure that the cameras mounted on the gripper and cutter arms can continuously capture and refine this estimated pose and orientation to provide accurate final orientation.	
Requirements	FR.03

Equipment	Realsense D435i camera ; Camera mount ; ROS ; RealSense SDK ; RViz		
Elements	Perception Subsystem:: Pose Refinement		
Location	Wean Hall – Room 1317	Personnel	Kshitij ; Keerthi
Procedure			
1. Attach cameras to the gripper and cutter arms, ensuring proper alignment to capture the workspace around the target. 2. Utilize the table mounted camera to estimate the initial 3D positions of the gripper and cutter arms relative to the target. 3. Activate the cameras on both the gripper and the cutter arms to capture live video feed during operation. 4. Identify key points (features) to refine the pose of the gripper and cutter and adjust the 3D coordinates of the arms based on this real-time feedback. 5. Based on the recalibration, fine-tune the 3D position of the arms to match the expected target location. 6. Compare the refined 3D coordinates of the gripper and cutter arms to the actual physical target location.			
Verification Criteria			
1. Verify that the perception system's initial 3D pose estimation places both the gripper and cutter arms in the correct positions relative to the target. 2. Ensure that the errors from the initial estimation is reduced by the recalibration performed from the end-efector cameras to adjust the arm's orientation to improve precision.			

4.12. Hand-Eye Calibration Test

Objectives	
To verify the relative position and orientation of the robot-mounted RGBD camera with respect to the XArm7's end-effector in the CAD model.	
Requirements	PR.02 / PR.05 / PR.06
Equipment	• Realsense camera • XArm7 robotic arm • Fiducial/Aruco cube for known pepper pose • Lab Computer • Pose estimation software
Elements	Perception Subsystem::Integration
Personnel	Kshitij
Location	Wean Hall 1317
Procedure	
1. Place a calibration object within the camera's field of view. 2. Capture the object's position. 3. Command the robot to touch specific points on the object. 4. Repeat with different object positions to verify consistency. 5. Perform test movements and verify that the robot can accurately reach positions identified by the camera. 6. Use distinct robot poses that utilize all robot joints. 7. Ensure the calibration object remains fully visible in the camera's field of view. 8. Collect at least four calibration points, though more generally improves accuracy. 9. Move the robot arm to multiple distinct positions (10-20). 10. Capture images of the calibration object at each position. 11. Record both the robot pose and the camera's view of the calibration object. 12. Compute the transformation between the camera and robot coordinate systems.	
Verification Criteria	
1. Ensure the robot can accurately touch designated points on the calibration object. 2. Verify that computed transformations match expected values from the CAD model. 3. Confirm that calibration accuracy improves with additional data points. 4. Validate that the robot maintains precise positioning across different poses.	

4.13. Physical Integration Test

Objectives	
To verify if the single arm physical robot system can detect green peppers and grasp it sequentially, without damaging it	
Requirements	PR.04 ; ; FR.04
Equipment	• Realsense camera • USB-C cable • PC • Real bell peppers • Ethernet cable • XArm7 setup with controller • Table • End Effector Gripper • Dynamixel U2D2 controller
Elements	Perception Subsystem, Planning Subsystem
Personnel	Abhishek, Tom, Rohit, Kshitij, Keerthi
Location	Wean Hall - 1317
Procedure	
1. Place green pepper on a table. The pepper must be within the reach of the Xarm. 2. Fix end effector gripper to the XArm7 setup 3. Connect End effector to u2d2 controller, which is connected to the PC. 4. Connect the realsense camera to the PC. 5. Power the XArm7 and connect it to the PC with the ethernet cable. 6. Run the perception stack with camera feed as input to obtain pepper pose. 7. Run the ros nodes responsible for the manipulator's control, to plan and execute the path.	
Verification Criteria	
1. The pepper placed on the table must be successfully identified, and its pose should be identified accurately. 2. The identified pepper pose must be successfully communicated to the Xarm7 controller node in ros. 3. The Identified pepper must be successfully grasped by the XArm7. 4. The grasped pepper shouldn't be damaged. It is to be checked visually.	

4.14 Spring Validation Demonstration

Objectives	
System Integration and Deployment in Simulation and with Real Demo setup	
Requirements	(Based on labels put in the schedule)
Equipment	XArm7, Dextrous Gripper, Fake Peppers, Realsense Camera, RViz/Gazebo Simulation, USB C Cable, Mounts, Laptop, Ethernet Cable
Elements	Perception Subsystem, Planning Subsystem, Controls, System Integration
Personnel	Team VADER
Location	Wean Hall - 1317
Procedure	
1. Place fake pepper in a hanging branch of fake plant 2. Mount the XArm7 with control box and ethernet setup 3. Place fake plant in workspace of XArm7 4. Enable the Realsense camera on the setup 5. Start the pepper detection test 6. Enable RViz/Gazebo simulation 7. Start the pepper pose processing for RViz control and real arm control 8. Enable Single arm goal pose approach test 9. Enable grasping test	
Verification Criteria	
The verification criteria for this test will be a union of the following: 1. Verification criteria of the Perception Subsystem 2. Planning Subsystem and its End effector grasp planning 3. Controls framework combined with the overall system integration. 4. It will also involve the accuracy with which the system is able to detect (more than 70%), grasp a fake pepper in vicinity. 5. The ability of the system to minimize damage to the pepper 6. The ability of our system to autonomously	

A. Appendix

A.1. Requirements

Here is a copy of the functional, non-functional, and performance requirements as outlined in our Conceptual Design Review Report. Note that these requirements are provided for reference purposes only, and may change compared to our Spring 2025 estimations and goals.

ID	Requirement	Class	Description
FR.01	Identify Target Peppers	Mandatory	The system should be able to detect green pepper locations and pose on the plants
FR.02	Localize and Prioritize Peppers	Mandatory	Based on the location of the peppers the system should be able to deduce the proximity and prioritize the task order for them
FR.03	Plan to reach for peppers	Mandatory	After finding the pose, the arms need to plan trajectories to reach the pepper while ensuring that the two arms don't collide
FR.04	Grasp and Cut Green Peppers	Mandatory	Once the end effectors reach, they should grasp the pepper with the gripper and cut the pepper with the cutter
FR.05	Store Harvested Green Peppers in Bin	Mandatory	Once the pepper is cut, the system should transport it to the storage bin
FR.06	Adapt user inputs to Teleoperation Output Movements	Desirable	The system should produce precise outputs that correspond to the teleop inputs from the users
FR.07	Communicate with User	Desirable	The system should communicate with the user and interface the functionality while operating
FR.08	Minimize Damage to Pepper	Mandatory	The system should ensure that the peppers are undamaged and are safely extracted

Table 1: Functional Requirements

Functional Requirement	ID	Performance Requirement	Class
Identify, Localize and Prioritize Green Peppers	PR.01	Detect fully visible Peppers > 70 % of the time	Mandatory
	PR.02	Produce estimate pose of green pepper and peduncle within 3 cm of ground truth depth and within 2 cm of other coordinates and upto 30 degrees in each rotation axis	Mandatory
Plan Movements	PR.03	Plan paths that avoid collision with robot itself 95% of the time	Mandatory
	PR.04	Plan paths that deviate no more than 5cm of the target poses	Desirable
Harvest Green Pepper	PR.05	Reach target green peppers >70% of the time	Mandatory
	PR.06	Cut identified pepper peduncle successfully >60% of the time	Mandatory
Store Green Pepper	PR.07	Place harvested green pepper inside storage container successfully >80% of the time	Mandatory
Teleoperation	PR.08	Ensure compliance to user input >90% of the times	Desirable
Minimize Green Pepper Damage	PR.09	Avoids deformation and damage to 90% of picked green peppers	Desirable
Overall Success	PR.10	Avoid visible damage to harvested green pepper >90% of the time.	Desirable
	PR.11	Harvest a fully visible green pepper in testbed autonomously within 100 seconds	Desirable

Table 2: Performance Requirements

ID	Requirement	Class	Description	Performance Description
NFR.01	Range	Mandatory	Limit overall size such that platform is able to navigate between crop rows	The arm will reach green peppers 70 cm away from the robot base
NFR.02	Size	Mandatory	Fit between pepper plant rows in Iowa pepper farm	The arms will be 50 cm apart
NFR.03	Weight	Mandatory	Limit weight based on maximum payload of Amiga mobile robot base	The system will have a weight lower than 35 kg
NFR.04	Power Consumption	Mandatory	Limit power consumption based on the battery payload of Amiga mobile robot base	The system will have a maximum power consumption of 700W
NFR.05	Modularity	Mandatory	The gripper and cutters have a modular design	–
NFR.06	Cost	Desirable	Limit costs as to not exceed MRSD budget	The costs in additional parts for the system will not exceed $5,000
NFR.07	Environment	Desirable	The system will operate in weather conditions identical to pepper farms in Iowa	The system will operate in 50° - 90°F, 400 - 100,000 lux ambient daylight illumination, 50-80 % relative humidity
NFR.08	Safety	Mandatory	Be safe to operators and bystanders in the surrounding area	VADER will be safe to operators and bystanders in the surrounding area

Table 3: Non functional and corresponding performance requirements