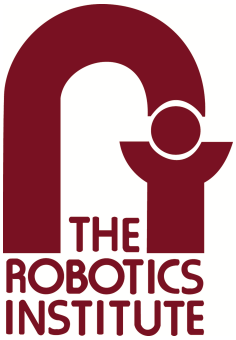
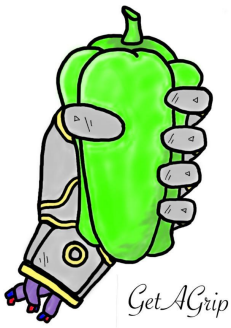


Carnegie Mellon University
The Robotics Institute, School of Computer Science

Task 4: Fall Test Plan



The Autonomous Harvest of Green Peppers
Team D: GetAGrip.AI

Teammates: Solomon Fenton, Jiyoon Park, Shri Ishwaryaa SV, Sridevi Kaza, Alec Trela

Submission Date: 20 September 2023

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Introduction

This document outlines the various tests by Team D - GetAGrip.AI for the Fall 2023 semester. These tests are designed to verify that the requirements for the system formed in the Fall 2022 semester are met through different stages of the sprints. Team D will report the results of these tasks through the progress reviews and the Fall Validation Demonstration. By the Fall Validation Demonstration, we will have the fully integrated autonomous green pepper harvesting robot (including mobility) functioning to meet all requirements specified in Appendix A.

Logistics

Personnel

No additional personnel other than the five team members are required for testing.

Location / Equipment

Team D will conduct most of our testing with the manipulator in our designated workspace in the NSH High Bay. We have a workbench there on which we are mounting a xArm6. The mobility testing will be conducted at the B level of NSH. We are building a testbed there, which includes a fake plant with real peppers attached to it. Below is a depiction of what our testbed setup would look like.

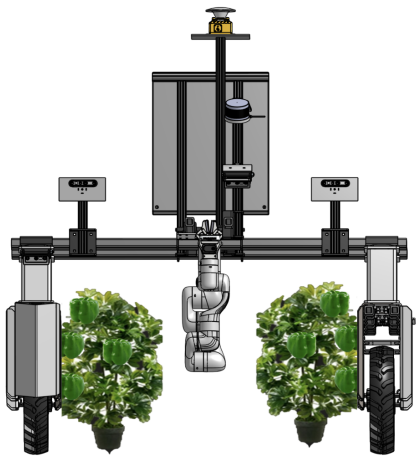

Figure 1 – Depiction of the testbed setup with the Amiga, xArm 6, and fake plants with real peppers on it

Schedule

This table contains the following information for each of the remaining Progress Reviews and the FVD:

Date	PR	Capability Milestone(s)	Test(s)	Requirements
9/10	9	• End-effector final testing + freeze • End-effector spare copies made • Initial P/MP/M integration testing (teleoperated mobile platform) • Pre-Iowa software architectural revamp complete • Code version checkpoint	Test 4, Test 11, Test 12	PR.04.1, PR.05.2
9/25	10	• Iowa trip / mid-semester end-to-end testing • Constraint avoidance tested • YOLO retrained with new datasets and freeze model • Code Version Checkpoint	Test 1, Test 2, Test 4, Test 5, Test 6, Test 11, Test 12	PR.01.1, PR.01.2, PR.01.3 PR.03.1, PR.04.1, PR.05.2, PR.06.1
10/9	11	• Final software architecture implemented • Manipulation testing • Full system integration • Code version checkpoint	Test 3, Test 4, Test 5, Test 9, Test 10	PR.01.1, PR.03.1, PR.06.1
10/23	12	• GUI for the system is ready for deployment • Perception orientation test • Full system code release	Test 6, Test 7, Test 8, Test 4	PR.01.1, PR.01.2, PR.01.3, PR.02.1
11/6	13	• End to End testing & Troubleshooting	All tests	All PRs
11/20	FVD, FVD Encore	• Fine-tuning of system	Test 11	All FVRs

Tests

Test 1: Linkage Analysis Test

Objective	
As a post-hoc quantification for end-effector capabilities, we will look to quantify our mechanism's capabilities through simulation and compare that to necessary forces required to cut peduncles under similar circumstances.	
Requirements	PR.03.1, PR.04.1
Equipment	Solidworks, 15 Green Bell Peppers
Elements	End-Effector Subsystem
Personnel	Alec Trela
Location	NSH High Bay
Procedure	
1. Harvest 15 peppers from while in Iowa. Harvest the first 5 three days before the rest and allow them to dehydrate. Harvest the second 5 three days before and hydrate them in the fridge overnight. The last five can be harvested on the day of the test. 2. Assemble a testing rig with a simple lever and a weight set. 3. Each of the 15 peppers should be cut at least 5 times, noting their category and the required force to cut the pepper 4. This should be compared to a linkage analysis performed in Solidworks, noting the derived factor of safety and if it differs for any one type of pepper.	
Verification Criteria	
1. As per Abhisesh Siwal in the FRC, the factor of safety is typically, at minimum, 4 for cutting-related tasks in agriculture. 2. If we do not witness a factor of safety of at least 4 we will need to make design changes.	

Test 2: Mechanical Failure Tests

Objective	
In order to maximize the use of end-effector motors & reduce the effects of variance in peduncle condition in successful stem cuts, we would like to baseline the stress limits of 3D printed parts. Given the price point of the motors, we would like to use them to their maximum potential. However, we understand that estimating the 3D-printed components can be hard to simulate. Here, if we can figure out if the linkages will fail under max load, it will be critical for a systems-based approach to design.	
Requirements	PR.04.1, PR.05.2, PR.06.1
Equipment	End-Effector, 3x Sets of Spare Links, M6 Screw, Vise
Elements	End-Effector Subsystem
Personnel	Solomon Fenton (or Alec Trela)
Location	NSH B506
Procedure	
• Obtain an End-Effector & multiple sets of spare linkages • Stabilize the End-Effector with the Vise such that the End-Effector can be operated at safe distance • Iterate P-Gains of the motors of the End-Effector through the following ranges (0, 5) – or until the current draw is more than 4A • If any part of the End-Effector fails, repeat the process for redundancy noting points of failure • If you can max out the current draw to the motors without failure, repeat the process ten times for redundancy	
Verification Criteria	
• If we can reach maximum current draw of the motors without part failure we have no concerns of part failure during the FVD procedure	

Test 3: Pepper Carrying Tests

Objective

After successful extraction, it is crucial that the peppers are delivered properly. As such, we will need to know if there are any concerns with carrying the pepper to the basket while undergoing expected movement patterns at expected speeds.	
Requirements	PR.06.1
Equipment	xArm 6, End-Effector, One Green Bell Pepper
Elements	End-Effector & Manipulation Subsystems
Personnel	Alec Trela/Solomon Fenton & Sridevi Kaza
Location	NSH High Bay
Procedure	
• Allow the End-Effector to grasp the pepper by placing its peduncle within the paddles of the gripping mechanism • Using another helper script, generate 5-way points to plan to, ensuring at least three results in a full rotation of the end-effector link • Repeat this process ten times	
Verification Criteria	
• Pepper is dropped at most one time during the testing procedure	

Test 4: Code Checkpoint Acceptance Testing

Objective	
In order to better manage the versioning of our software, we have numerous code checkpoints identified by which we are to conduct testing and tag the current version prior to continuing development work. During this checkpoint, we will conduct a test similar to that of our spring validation demo, verifying and validating that the added hardware/software does not compromise system functionality.	
Requirements	FVR01.1 - FVR05.1
Equipment	xArm 6, end-effector, testbed setup, workbench/Amiga, associated electronics
Elements	All subsystems

Personnel	(minimum) Alec Trela, Solomon Fenton
Location	NSH High Bay / NSH B Level
Procedure	
• Set up test plants with green peppers • Run full autonomous procedure • Record results for each subsystem in code checkpoint spreadsheet • Increment code versioning	
Verification Criteria	
See code checkpoint spreadsheet	

Test 5: Pepper Identification (Long-Range) Test

Objective	
To distinguish 75% of visible peppers at a distance of 80 cm from the plant.	
Requirements	PR.01.1
Equipment	xArm6, RealSense depth camera D435i, laptop
Elements	Pepper detection unit from perception subsystem
Personnel	Jiyoon Park, Shri Ishwaryaa S V
Location	NSH High Bay
Procedure	
1. Hang real peppers on fake plants in different locations and orientations. 2. Place one depth camera on a table such that the plant lies in the camera view (at a distance of 80 cm) and in the manipulator's workspace. 3. Count the number of visible peppers detected (true positives) by the object detection algorithm. A bounding box should be placed around a pepper to be considered a visible, detected pepper. 4. Obtain ground truth and compare it with the algorithm's output through visual inspection.	
Verification Criteria	

Ensure that the number of visible peppers detected (true positives) by the algorithm is more than 75% visible peppers in the image.

Test 6: Peduncle POI Test

Objective	
Determined peduncle point of interaction (POI) does not deviate radially from the peduncle stem by more than 3 cm and is within 5 cm from the top of the pepper.	
Requirements	PR.01.1, PR.01.2, PR.01.3
Equipment	xArm6, RealSense depth camera D435i, laptop
Elements	Peduncle detection unit from perception subsystem
Personnel	Jiyoon Park, Shri Ishwaryaa S V
Location	NSH High Bay
Procedure	
1. Hang real peppers on fake plants in different locations and orientations. 2. Place a RealSense depth camera D435i on the xArm6. 3. Move the arm close to the plant so that a single pepper lies in the camera image. 4. Generate a 3D position vector with respect to the arm camera that indicates the POI on the peduncle. This is obtained from a peduncle detection algorithm. 5. Draw a cylindrical visualization marker in RViz at the generated POI with a cylinder radius of 3 cm and height of 5 cm.	
Verification Criteria	
1. Ensure that the marker intersects the peduncle radially to verify that the POI does not deviate radially from the peduncle by more than 3 cm. 2. Ensure that the marker intersects the top of the pepper to verify that the POI is within 5 cm from the top of the pepper.	

Test 7: Pepper Orientation Test

Objective

To obtain accurate peduncle orientation for the manipulator to align the end-effector for cutting.	
Requirements	N/A
Equipment	xArm6, RealSense depth camera D435i, laptop
Elements	Pepper and peduncle detection unit from the perception subsystem
Personnel	Jiyoon Park, Shri Ishwaryaa S V
Location	NSH High Bay / NSH Level B
Procedure	
1. Hang real peppers on fake plants in different locations and orientations. 2. Place a RealSense depth camera D435i on the xArm6. 3. Move the arm close to the plant so that a single pepper lies in the camera image. 4. Generate a 3D orientation vector with respect to the arm camera that indicates the orientation of the peduncle. This is obtained from the pepper & peduncle detection algorithm. 5. Visualize the point cloud from the RealSense D435i camera in RViz. 6. Visualize the orientation vector by displaying it in RViz and manually inspect it to see if it aligns with ground truth in the displayed point cloud.	
Verification Criteria	
The visualization of the orientation vector should intersect with the actual peduncle orientation.	

Test 8: Constraint Testing

Objective	
To ensure that the xArm does not collide with the ground or amiga base.	
Requirements	PR.02.1
Equipment	xArm6, end-effector, amiga
Elements	Manipulation
Personnel	Sridevi

Location	NSH High Bay
Procedure	
1. Set up the xArm mounted on the amiga as it would be for the FVD. 2. Create a randomized POI pose where a pepper could potentially be placed. 3. Plan and execute a trajectory to the POI pose. Take into account virtual walls for the ground and amiga base. 4. Ensure that the arm does not collide with any obstacles in the workspace or with itself. 5. Ensure that the arm does not move if the planner fails to generate a trajectory or if the POI is outside the arm's reachability map. 6. Repeat sets 2-5 for at least 20 POI poses.	
Verification Criteria	
The generated trajectories should avoid all collisions with the ground and amiga base	

Test 9: Manipulation POI Pose Testing

Objective	
To ensure that the xArm is able to accurately move to the desired POI poses	
Requirements	PR.03.1
Equipment	xArm6, end-effector, amiga
Elements	Manipulation
Personnel	Sridevi Kaza
Location	NSH High Bay
Procedure	
1. Set up the xArm mounted on the amiga as it would be for the FVD. 2. Create a randomized POI pose where a pepper could potentially be placed. 3. Plan and execute a trajectory to the POI pose. 4. Document the final position of the end-effector and calculate the error to the desired POI. 5. Ensure that the arm does not move if the planner fails to generate a trajectory or if the POI is outside the arm's reachability map. 6. Repeat sets 2-5 for at least 20 POI poses.	

Verification Criteria
End-effector pose should not deviate from the desired POI pose by more than 1 cm (if the POI is within the reachable xArm workspace)

Test 10: Manipulation Basket Drop Testing

Objective	
To ensure proper drop-off of peppers into the basket with minimal damage to the peppers.	
Requirements	PR.06.1
Equipment	xArm6, end-effector, amiga
Elements	Manipulation
Personnel	Sridevi Kaza
Location	NSH High Bay

Procedure

7. Set up xArm mounted on the amiga as it would be for the FVD.
8. Place the basket in the proper location that it will be in for FVD.
9. Set up one fake plant with peppers and keep the amiga base stationary.
10. Place one cut pepper in the end-effector grippers at a potential POI pose.
11. Plan and execute a trajectory to the predefined basket drop pose.
12. Release the gripper.
13. Ensure that the pepper falls into the basket and that the drop-off pose is within 15 cm above the basket height and within the radial bounds the basket diameter.
14. Repeat steps 6-9 for at least 10 peppers and document the results.

Verification Criteria

1. Pepper drop-off position should be within 15 cm above the basket and within the radial bounds of a 50 cm diameter basket.
2. Peppers should all land in the basket.

Test 11: Cutting Fidelity Test

Objective

Ensure that the cutting mechanism can properly sever a peduncle under varied conditions.	
Requirements	PR.05.2
Equipment	End-effector, table-top power supply, green bell peppers (20)
Elements	Cutting mechanism unit from end-effector subsystem
Personnel	Alec Trela
Location	NSH B506
Procedure	
1. Properly connect the power supply to motors and microcontroller. 2. Place the peduncle at the approximate center of the gripping plates, within 5 cm of the top of the pepper. 3. Actuate the end-effector to ensure gripping and subsequent cutting of the peduncle. 4. Repeat steps 1-3 20 times.	
Verification Criteria	
The end-effector was able to cut through the entirety of all peduncle stems successfully.	

Test 12: End-Effector Error Handling Test

Objective	
To determine an acceptable range of error for the gripping/cutting location.	
Requirements	PR.04.1, PR.05.2
Equipment	xArm6, end-effector, table-top power supply
Elements	End-effector subsystem
Personnel	Solomon Fenton, Alec Trela, Sridevi Kaza
Location	NSH High Bay
Procedure	
1. Hang real peppers on fake plants hanging straight down. 2. Manually place the end effector at an ideal gripping location for the peduncle.	

a. Teleoperate using the xArm6, handhold the end effector, or build a temporary mounting mechanism.
3. Initiate grasping and cutting sequence from various starting positions:
   a. Vary positional error
      i. Along the plane of the gripper pad - testing grip integrity at tip, middle, and base.
      ii. Perpendicular to the plane of the gripper pad +/- 3cm deviation from the ideal.
   b. Vary orientation error
      i. +/- 50 degrees roll error (or up to failure) from aligned with stem.
4. Record qualitative performance statements of each test case.

Verification Criteria

1. Each positional error test case met performance requirements for cutting and gripping.
2. Ensure orientation error can be handled for up to +/- 30 degrees.

Test 13: Fall Validation Demo (FVD)

Objective	
To perform the full functionality of this semester's deliverables.	
Requirements	FVR01.1 - FVR05.1
Equipment	Fully integrated system: xArm6, Amiga, end-effector, power supply, peppers, four fake plants, RGBD camera (x2)
Elements	System-Level
Personnel	Team
Location	NSH Level B

Procedure

Setup

1. Have four fake pepper plants and at least one real green bell pepper on each plant. These peppers will be visible, easily accessible, and within the arm's workspace.
2. Tele-operate the Amiga base to have a plant in the xArm workspace.
3. Ensure all team members and audience members are at least 10 feet away from the xArm's workspace.

Autonomous Operation

1. Once all team members and the audience are safe from the robot, one team member will initiate the system.
2. Another team member will start a timer once the system begins its recognition procedure.
3. Let the autonomous pepper harvesting process run.
4. Lap the timer once a green bell pepper has been placed in the basket. This will help to confirm that time requirements have been met.
5. Tele-operate the Amiga to move to the next location once the pepper(s) have been picked from the current plant.
6. Repeat processes 2-5 to be performed cyclically until all peppers have been harvested.

End Condition

Once the Amiga reaches the end of the pepper plant row, the demo will conclude.

Verification Criteria

1. Robot successfully harvests each accessible pepper within 5 minutes.
2. Avoid visible damage to 75% of the picked peppers (cuts/bruises).
3. 0 injuries or cases of harm to the team members.

Appendix A: Requirements

Table 1: Functional Requirements

ID	Name	Class	Description	PR ID	PR Description
FR.01	Identify Peppers	Mandatory	Distinguish peppers from the plant and initiate an ordering scheme. Estimate peduncle pose and POI.	**PR.01.1**	Distinguish 75% of visible peppers from plant
				PR.01.2	Determined POI does not deviate radially from the peduncle centroid by more than 3 cm.
				PR.01.3	Determined POI is within 5 cm of the top of the pepper.
FR.02	Plan Path to Peppers	Mandatory	Plan a path to pepper POI while avoiding collisions with obstacles in the workspace of the arm.	**PR.02.1**	Generated trajectory avoids 100% of collisions with the ground and the amiga mobile base.
FR.03	Reach Peppers	Mandatory	Actuate robot manipulator to execute planned path.	**PR.03.1**	End effector position does not deviate from planned trajectory by more than 1 cm (if enforceable)
FR.04	Grip Peppers	Mandatory	Grasp pepper for extraction and retrieval	**PR.04.1**	Ensure 75% success in gripping and retrieving peppers without dropping them.
FR.05	Extract Peppers	Mandatory	Sever the peduncle, removing any connection between the pepper and plant	**PR.05.1**	Have zero false positive actuated cuts
				PR.05.2	Succeed in cutting the peduncle 100% of the time, given proper cutting mechanism placement.
FR.06	Place Peppers	Mandatory	Retrieve the detached pepper, placing it safely in container	**PR.06.1**	Move end effector for pepper drop-off to within 15 cm above and within the radial bounds of a 50 cm diameter basket.
FR.07	Navigate to New Plant	Desirable	Navigate to additional crops once the current plant no longer has accessible peppers	**PR.07.1**	Can teleoperate the Amiga to 100% of the plants.

Table 2: Non-Functional Requirements

ID	Name	Class	Description	NPR ID	PR Description
NFR.01	Damage	Mandatory	Limit damage to pepper and surrounding crop	**NPR.01.1**	Avoid visible damage to 75% of the picked peppers (cuts/bruises)
NFR.02	Size	Mandatory	Limit overall size such that platform is able to navigate between crop rows	**NPR.02.1**	Be able to fit and navigate within a 0.6m path width (distance between pepper crop rows).
NFR.03	Cost	Desirable	Limit costs as not to exceed MRSD budget	**NPR.03.1**	Manage finances to stay within $5000 budget for augmentation to the provided hardware platforms
NFR.04	Safety	Desirable	Encourage safe practices and procedures through strict no injuries requirement	**NPR.04.1**	0 injuries or cases of harm to the team members
NFR.05	Speed	Mandatory	Complete core system level functionalities (FR0.1-FR0.06) in reasonable amount of time	**NPR.05.1**	Pick any reasonable (pre-identified as such) pepper in under 5 minutes.

Table 3: Fall Validation Requirements (FVRs)

FVR ID	Name	FVR Description	FR ID
FVR.01.1	Identify Peppers	Distinguish 50% of visible peppers from plants.	**FR.01**
FVR.02.1	Grip Peppers	Ensure 75% success in gripping and retrieving easily accessible peppers without dropping them.	**FR.04**
FVR.03.1	Extract Peppers	Have zero false positive actuated cuts.	**FR.05**
FVR.03.2	Extract Peppers	Succeed in cutting the peduncle 100% of the time, given proper cutting mechanism placement.	
FVR.04.1	Place Peppers	Move the end effector for pepper drop-off to within 15 cm above and within the radial bounds of a 50 cm diameter basket.	**FR.06**
FVR.05.1	Timely Pickings	Extract each pepper in under 5 minutes.	**NPR.05.1**