Carnegie Mellon University
The Robotics Institute, School of Computer Science

Task 4: Spring Test Plan

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

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Submission Date: 13 February 2023

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Introduction

This document outlines the various tests to be performed by Team D - GetAGrip.AI for the Spring 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 Spring Validation Demonstration. By the Spring Validation Demonstration, we will have the fully-integrated autonomous green pepper harvesting robot (excluding mobility) functioning to meet all of the 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 in our designated workspace in the NSH High Bay. We have a workbench there on which we are mounting a xArm6. We are also 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.

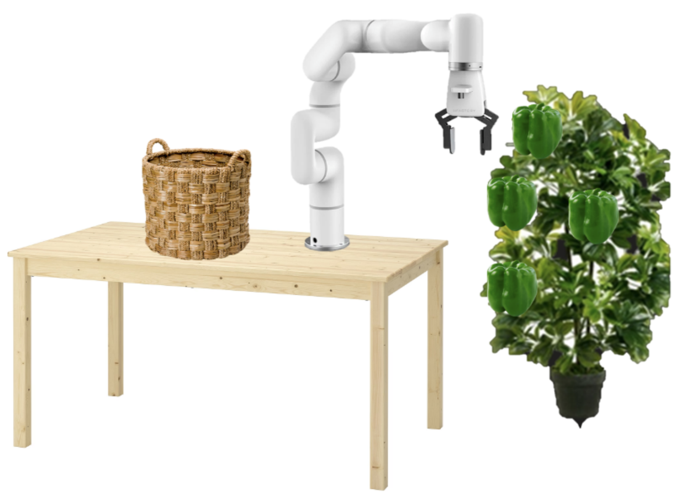

Figure 1 – Depiction of the testbed setup with the xArm 6 and a fake plant with real peppers

Schedule

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

Date	PR	Capability Milestone(s)	Test(s)	Requirements
2/16	1	● Initial gripper design ● Initial cutter prototype	-	-
3/2	2	● The perception subsystem should detect visible peppers. ● Integration of cutter & gripper ● YOLO accuracy > 80% ● End effector PCB ● Preliminary physical xArm testing	3	PR.01.1
3/23	3	● The perception subsystem should generate a point of interaction for gripping and cutting. ● PDB design and fabrication	1,4,5,6,9	PR.01.1, PR.01.2, PR.01.3
4/6	4	● Full subsystem integration ○ Cutter/Gripper final spring version fabrication ○ Perception pipeline integration ● GUI for perception pipeline ● Motion planning capable of constraint generation and enforcement	2,7,8	PR.02.1, PR.04.1, PR.05.2,
4/19	SVD	● Demonstrate the full autonomous functionality of this semester's deliverables: ○ Robot successfully harvests each accessible pepper within 5 minutes. ○ Avoid visible damage to 90% of the picked peppers (cuts/bruises). ○ 0 injuries or cases of harm to the team members.	10	SVR.01.1, SVR.02.1, SVR.03.1, SVR.03.2, SVR.04.1, SVR.05.1
4/26	SVD Encore	● Fine-tuning of system	-	-

Tests

Test 1: Trajectory Generation Test

Objective	
To test MoveIt2 to generate a trajectory from a current position to a desired position.	
Requirements	PR.03.1, PR.06.1
Equipment	xArm6, Laptop
Elements	Motion planning subsystem
Personnel	Sridevi Kaza
Location	NSH High Bay
Procedure	
1. Move the arm to an initial position. 2. Mark the current pose as the starting point. 3. Run the ROS2 script to invoke MoveIt2 to generate a trajectory for the arm to follow. 4. Execute generated trajectory. 5. Mark the end position.	
Verification Criteria	
1. Check in the simulation if the arm is moving along the generated trajectory. 2. Check through visual inspection if the physical arm is accurately following the generated trajectory. 3. Ensure that the end-effector position does not deviate from the planned trajectory by more than 1 cm (if enforceable). 4. Ensure the ability to move the end effector for pepper drop-off to within 15 cm above and within the radial bounds of a 50 cm diameter basket.	

Test 2: Constraint Generation Test

Objective	
To generate trajectories that accurately avoid a set of provided obstacles and follow any designated constraints.	
Requirements	PR.02.1
Equipment	xArm6, Laptop
Elements	Motion planning subsystem
Personnel	Sridevi Kaza
Location	NSH High Bay
Procedure	
1. Provide a set of 3D regions within the workspace of the arm, which should be avoided when generating a trajectory. a. These constraints may be hard coded for the Spring, depending on the perception team's capacity 2. Run ROS2 script to invoke MoveIt2 to generate a trajectory for the arm to move to, considering all constraints.	
Verification Criteria	
1. Check in the simulation if the generated trajectory avoids all obstacles and the arm accurately moves along the desired path. 2. Check through visual inspection that the physical arm follows the generated trajectory and accurately follows all the constraint conditions. 3. Ensure that the generated trajectory avoids 100% plant stem constraints.	

Test 3: 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 4: Peduncle POI Radial Test

Objective	
Determined peduncle point of interaction (POI) does not deviate radially from the peduncle stem by more than 3 cm.	
Requirements	PR.01.1, PR.01.2
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 with the peduncle. This is obtained from a peduncle detection algorithm. 5. Obtain ground truth by manually selecting a point on the peduncle from the 3D point cloud map of the pepper plant given by the depth camera (in RViz). This point is chosen to be close to the generated POI.	
Verification Criteria	
1. Obtain the distance of the generated POI from the ground truth point. 2. Ensure that this distance is less than 3 cm.	

Test 5: Peduncle POI Height Test

Objective	
Determined POI is within 5 cm of the top of the pepper along the peduncle.	
Requirements	PR.01.1, 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 with the peduncle. This is obtained from a peduncle detection algorithm. 5. Obtain ground truth by manually selecting a point on the top of the peduncle from the 3D point cloud map of the pepper plant given by the depth camera (in RViz).	
Verification Criteria	
The distance along the peduncle from the ground truth point to the generated POI must be less than 5 cm.	

Test 6: 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, Raspberry Pi, 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 7: 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, Raspberry Pi
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 8: Power Distribution Testing

Objective	
To ensure proper voltages and currents are supplied to each major subsystem.	
Requirements	N/A
Equipment	Fully integrated system: xArm6, end-effector, Raspberry Pi, power supply, multimeter
Elements	Manipulation, end-effector, integration
Personnel	Solomon Fenton
Location	NSH High Bay
Procedure	
1. Connect PDB input to an external power supply (battery). 2. Utilize a multimeter to measure the output voltage. a. Ensure that the measured output voltage does not drift over time. b. Ensure that each pin corresponds to the required voltage levels of the project (24V to xArm, 9V to motor, 5V to raspberryPi). 3. Connect PDB output pins to xArm, motor, and raspberryPi. a. Measure current levels and ensure they are less than 85% of operating limits listed in component datasheets. 4. Cycle power to the system and repeat voltage/current measurements. 5. Run test scripts operating the xArm6 and end effector via ROS.	
Verification Criteria	
Measured voltage and current levels never exceed 85% of operating limits listed in component datasheets.	

Test 9: Payload Verification Testing

Objective	
Verify xArm6 motion and controllability are not impacted by increasing the payload.	
Requirements	PR.03.1, PR.06.1
Equipment	xArm6, weight set
Elements	Manipulation
Personnel	Sridevi Kaza, Solomon Fenton
Location	NSH High Bay
Procedure	
1. Attach ~50% max payload, ~75% max payload. ~100% max payload. 2. Run a test script which executes a typical xArm trajectory. 3. Observe quantitative hardware behavior (unless we can report our positional data from the xArm).	
Verification Criteria	
No observed quantitative difference in behavior.	

Test 10: Spring Validation Demo (SVD)

Objective	
To perform the full functionality of this semester's deliverables.	
Requirements	SVR01.1 - SVR05.1
Equipment	Fully integrated system: xArm6, end-effector, Raspberry Pi, power supply, peppers, fake plant, RGBD camera (x2)
Elements	System-Level
Personnel	Team
Location	NSH High Bay
Procedure	
<u>Setup</u> 1. Attach six real green peppers to the fake plant setup. These peppers will be visible, easily accessible, and within the arm's workspace. 2. Place the plant within the workspace of the xArm6. 3. Ensure all team members and audience are at least 10 feet away from the arm's workspace. <u>Autonomous Operation</u> 1. Once all team members and the audience are at a safe distance 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. Once the green bell pepper has been placed in the basket, stop the timer. This will help to confirm that time requirements have been met. 5. Processes 2-4 will be performed cyclically until all peppers have been harvested. <u>End Condition</u> Once there are no recognizable peppers within the robot's workspace, the demo will conclude.	
Verification Criteria	
1. Robot successfully harvests each accessible pepper within 5 minutes. 2. Avoid visible damage to 90% 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	Capture enough environmental information to generate constraints and plan a path to pepper POI.	**PR.02.1**	Generated trajectory avoids 100% of generated plant stem constraints.
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 90% 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	TBD (To be reassessed during Spring 2023)	

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 90% 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: Spring Validation Requirements (SVRs)

SVR ID	Name	SVR Description	FR ID
SVR.01.1	Identify Peppers	Distinguish 50% of visible peppers from plants.	**FR.01**
SVR.02.1	Grip Peppers	Ensure 90% success in gripping and retrieving easily accessible peppers without dropping them.	**FR.04**
SVR.03.1	Extract Peppers	Have zero false positive actuated cuts.	**FR.05**
SVR.03.2	Extract Peppers	Succeed in cutting the peduncle 100% of the time, given proper cutting mechanism placement.	
SVR.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**
SVR.05.1	Timely Pickings	Extract each pepper in under 5 minutes.	**NPR.05.1**