Fall Test Plan

Autonomous Nitrate Monitoring in Cornstalks

Team D: NiMo

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I. Introduction

The purpose of this document is to provide an overview of the functional, integration, and validation tests planned for the Team D - NiMo project. The success of these tests will indicate compliance to the performance and non-functional requirements developed by Team D in the Fall 2024 semester. These tests are scheduled with the V-model methodology. For each subsystem, unit testing is completed first, followed by subsystem testing, and finally integration testing. By the Fall Validation Demonstration, we will have a fully integrated, autonomous cornstalk nitrate monitoring robot that will meet all team requirements.

II. Logistics

A. Equipment

Parts
For tests that require real corn (like sensor insertion), we will use leeks. Otherwise, fake cornstalks made out of PVC pipe will be utilized because they are reusable and we have many to test on.

Amiga Mobile Base - The mobile base to which all components will be attached.
xArm - The 6 DoF robotic arm used for manipulating the environment.
End-Effector - The mechanism attached to the end of the xArm which manipulates the cornstalk.
Nitrate Sensor - The sensor which is inserted into the cornstalk and measures the nitrate level.
External Mechanisms - The mechanisms which clean and calibrate the nitrate sensor.

B. Location

Environments
There will be two testing environments based on the needs of the test. Testing that requires navigation will be performed on Flagstaff Hill. All other tests will be performed in the FRC Highbay.

FRC Highbay - Located on the first floor of Newell-Simon Hall, this will be the primary location for tests that require the Amiga base to be stationary.

Flagstaff Hill - Located near campus in Schenley Park, this will be the primary location for tests that require the Amiga base to move.

III. Schedule

Identifier	Capabilities	Test(s)	Requirements(s)
Progress Review 7 (11 September)	- Initial plans for: testbed, UI, motion planning, navigation, perception	-	-
Progress Review 8 (25 September)	- UI complete - Testbed design complete - Navigation simulation setup	3, 4, 6	M.P.1, M.P.10
Progress Review 9 (9 October)	- Perception completed for visual servoing - Testbed fabrication complete - Navigation complete in simulation - UI Integrated with navigation	1, 2	M.P.1, M.P.2.2
Progress Review 10 (30 October)	- All subsystems complete	5, 7, 9	M.P.1, M.P.2.1, M.P.2.2
Progress Review 11 (13 November)	- All subsystems integrated and tested	8, 10	M.P.6.2, M.P.6.3

IV. Tests

TEST_NO: 1	
Objective	Test motion planning around singularities
Elements	Motion Planning Subsystem
Location	FRC Highbay
Equipment	1. xArm6 2. Team Desktop
Personnel	Tom, Shrudhi
Procedure	1. Setup the xArm6 and team desktop to receive planning commands for the robotic arm 2. Plan and execute motion for a series of waypoints that had issues with singularities using the previous planner 3. Record performance and note any concerning behavior
Verification Criteria	1. The motion planner performs better than the previous planner given the series of waypoints (fails due to singularity or not)

TEST_NO: 2	
Objective	Test UI integration with the navigation simulation
Elements	User Interface Subsystem, Navigation Subsystem
Location	FRC Highbay
Equipment	1. Team Desktop
Personnel	Sruthi, Tom, Saudamini, Shara
Procedure	1. Launch the navigation simulation and user interface on the team desktop 2. Enter a set of valid waypoints into the user interface and begin sampling 3. Watch the simulation to confirm that each waypoint is reached
Verification Criteria	1. The navigation subsystem receives the waypoints 2. The system reaches each waypoint in simulation.

<table>
<tr><th colspan="2">TEST_NO: 3</th></tr>
<tr><td>Objective</td><td>Determine whether the perception stack is functional in the anticipated FVD environment (i.e., Flagstaff Hill)</td></tr>
<tr><td>Elements</td><td>Perception & Testbed Subsystems</td></tr>
<tr><td>Location</td><td>Flagstaff Hill - grassy area near the outdoor amphitheater</td></tr>
<tr><td>Equipment</td><td>1. Pseudo-cornstalks (x3)
→ Thin metal rod, with leeks stacked to ~60 cm height.
2. NiMo End Effector assembly
→ @ minimum, with Intel D405 camera mounted inside.
3. Laptop equipped with a running NiMo Perception stack.
4. Posters of cornfield background
→ If 2 personnel are not available to execute this test: additionally a mount for the posters.
5. (Optional) Live visualization of Intel D405 camera</td></tr>
<tr><td>Personnel</td><td>Sruthi</td></tr>
<tr><td>Procedure</td><td>1. If not done already, mount the Intel D405 camera in the NiMo End Effector assembly. Make sure to do this in the Highbay before heading out to Flagstaff Hill!
2. Go to Flagstaff Hill with all required equipment.
3. Assemble the psuedo-cornstalks. Pierce the pseudo-cornstalks into the dirt at Flagstaff Hill.
4. Connect the cable of the Intel D405 camera to the laptop equipped with a running NiMo perception stack.
5. Aim the NiMo End Effector assembly, and thus the Intel D405 camera, towards one of the pseudo-cornstalks. (Optional) Confirm that the pseudo-cornstalk is in view of the camera using the live visualizer.
6. Run the stalk detection algorithm with the NiMo End Effector assembly in this location. Check the result images and see whether the pseudo-cornstalk was identified. Record the success/failure result.
7. Repeat steps 5 and 6 20 times total. Attempt a variety of pseudo-cornstalk configurations, including pseudo-cornstalks clustered together, varied lighting conditions (e.g., shady vs. not), etc.
8. Calculate the success rate.
a. If it is less than listed in the verification criteria, run steps 5-8 with the poster of the cornfield used as the image backdrop.
b. If the performance is still suboptimal with this modification, determine a mitigation plan on how to get stalk detect to work on Flagstaff Hill. Complete this test again when ready.</td></tr>
<tr><td>Verification Criteria</td><td>1. Perception stack’s stalk detection algorithm works at a 90% success</td></tr>
</table>

	rate. → Why 90%?: This is the same performance that the system was able to obtain during field testing in Iowa. 2. If the stalk detection algorithm is unable to perform with the natural lighting conditions and background of Flagstaff Hill, identify mitigation plans to improve performance. → In this case, retest the stalk detection algorithm to satisfy the above metric.

TEST_NO: 4	
Objective	Determine at which distance from the pseudo-cornstalk can stalk detection perform.
Elements	Perception Subsystem
Location	FRC Highbay
Equipment	1. xArm6 2. Team Desktop 3. Pseudo-Cornstalk → Thin metal rod, with leeks stacked to ~60 cm height. 4. NiMo End Effector → @ minimum, with Intel D405 camera mounted inside. 5. Measuring tape
Personnel	Sruthi
Procedure	1. If not done already, place the Intel D405 camera in the NiMo End Effector. Additionally, fix the NiMo End Effector to the xArm6. 2. Setup the xArm6 and team desktop to be able to run stalk detection and use the xArm6 on guide mode. 3. Mount the pseudo-cornstalk appropriately to the FRC ground. Make sure that it is mounted within the workspace of the xArm. 4. Guide the xArm6 such that the NiMo End Effector's gripper is clasping the pseudo-cornstalk. 5. Run the stalk detection algorithm. Check the results images to see whether it was successful. 6. Slightly reposition the arm such that the gripper is still around the pseudo-cornstalk. The goal is to slightly vary the image. 7. Complete steps 5 and 6 for 9 more times (10 trials total). If performance is meeting criteria, it can be confirmed that the stalk detection algorithm works when the cornstalk is within the gripper. 8. If stalk detection did not meet the verification criteria, move the cornstalk out of the gripper. Place it just outside the gripper (at the center of FOV of the camera). 9. Repeat steps 5 to 7 at this distance. If the algorithm is successful (as deemed by the verification criteria), measure and record the distance between the center of the pseudo-cornstalk to the camera. 10. If the algorithm is not successful, move the cornstalk 1 more inch away from the NiMo End Effector. Repeat step 9. Complete this process until verification criteria is satisfied.
Verification Criteria	1. Stalk detection is functioning at a minimized distance (determined through the test procedure) with a 90% success rate.

TEST_NO: 5	
Objective	Confirm that visual servoing is functional, i.e. the gripper is able to center itself along the diameter of a pseudo-cornstalk.
Elements	Perception + Motion Planning Subsystems
Location	FRC Highbay
Equipment	1. xArm6 2. Team Desktop 3. Pseudo-Cornstalk → Thin metal rod, with leeks stacked to ~60 cm height. 4. NiMo End Effector → Full assembly (with nitrate sensor attached). 5. Permanent Marker
Personnel	Tom, Shrudhi, Sruthi
Procedure	1. If not done already, place the Intel D405 camera in the NiMo End Effector. Additionally, fix the NiMo End Effector to the xArm6. 2. Setup the xArm6 and team desktop to execute perception methods and the grip + insertion processes. 3. Mount the pseudo-cornstalk appropriately to the FRC ground. Make sure that it is mounted within the workspace of the xArm. 4. Run the following service calls, in the respective order: a. Stalk detection b. Width detection c. Visual servoing (for centering) d. Hook corn e. Grip and insert nitrate sensor 5. Mark the axis perpendicular to the angle of insertion using a permanent marker. Draw this line on the top of the pseudo-cornstalk, along its "diameter." 6. Run a service call to unhook the corn. 7. Remove the pseudo-cornstalk. Take off the pierced leek. 8. Cut at the insertion location and measure the relative distance of the center of the cut with respect to the axis perpendicular to the angle of insertion. Ideally, the center of the cut should be at the center of this drawn axis. Record this measurement. 9. Repeat steps 3 to 8 for 9 more trials (total of 10 trials).
Verification Criteria	1. Visually confirm that the nitrate sensor was inserted towards the center of the cornstalk (with respect to the angle of the grip). 2. The average distance between the cut and the center of the cornstalk should be less than 5 mm.

TEST_NO: 7	
Objective	Confirm the testbed is functional for FVD/FVD Encore purposes.
Elements	Testbed Subsystem
Location	Flagstaff Hill
Equipment	1. 9x Pseudo-Cornstalks → Thin metal rod, with leeks stacked to ~60 cm height. 2. Testbed Assembly Procedure 3. Measuring Tape 4. Other supplies listed in testbed assembly procedure (TBD)
Personnel	Sruthi, Saudamini, Shara
Procedure	1. Go to Flagstaff Hill (flat area near the outdoor amphitheater). 2. Put together the testbed using the steps outlined in the assembly procedures. 3. Confirm that the testbed layout is reasonable and can satisfy FVD/FVD Encore test requirements. 4. Subject the pseudo-cornstalks to possible environmental conditions for FVD/FVD encore. This can include subjecting the pseudo-cornstalks to considerable lateral and axial forces to mimic wind and/or forces from the xArm6, etc.. 5. Confirm that the pseudo-cornstalks are able to return to a relatively upright position post-perturbations. “Relatively upright” can be qualified as mimicking similar behavior to an actual cornstalk, which can be compliant.
Verification Criteria	1. Testbed is able to withstand all expected conditions for FVD/FVD Encore.

TEST_NO: 8	
Objective	Perform and verify that the amiga robot can take delta steps while exploring the waypoint region to find a suitable cornstalk
Elements	Navigation subsystem
Location	Flagstaff Hill
Equipment	1. Amiga robot 2. GPS RTK base station 3. Pseudo-Cornstalk 4. Team Desktop 5. NiMo End-Effector
Personnel	Shara, Saudamini
Procedure	1. Transport the amiga robot and GPS equipment to the flagstaff 2. Set up the GPS base station at a fixed and stable location. 3. Collect GPS coordinates from the base station 4. Provide waypoints to the UI 5. Select waypoints from the UI 6. Place at least one cornstalk which is not suitable for insertion in a waypoint region 7. Perception subsystem detects the first unsuitable pseudo-cornstalk 8. Perception subsystem detects a suitable pseudo-cornstalk 9. The robot takes a delta step towards the suitable pseudo-cornstalk in the same waypoint region 10. Gripper grasps the suitable pseudo-cornstalk
Verification Criteria	1. The amiga robot is able to detect one unsuitable and one suitable pseudo-cornstalk in a waypoint region 2. The delta step is performed as verified by the end effector being able to grab the suitable pseudo-cornstalk

TEST_NO: 9	
Objective	Perform and verify that the amiga robot can navigate to the desired waypoints
Elements	Navigation subsystem
Location	Flagstaff Hill
Equipment	6. Amiga robot 7. GPS RTK base station 8. Pseudo-Cornstalk 9. Team Desktop
Personnel	Shara, Saudamini
Procedure	11. Transport the amiga robot and GPS equipment to the flagstaff 12. Set up the GPS base station at a fixed and stable location. 13. Collect GPS coordinates from the base station 14. Provide waypoints to the UI 15. Select waypoints from the UI 16. Observe the robots movement and measure the deviations noticed in the actual path vs the desired path
Verification Criteria	1. The amiga robot reaches the desired waypoint with < 15 cm lateral error.

TEST_NO: 10	
Objective	Constraint Testing
Elements	Motion Planning subsystem
Location	HighBay
Equipment	1. xArm6 2. Amiga Base 3. End-Effector
Personnel	Shrudhi, Tom
Procedure	1. xArm will be mounted on the Amiga Base as it would be for FVD 2. Create a points of interest, near the Amiga Base, as a pseudo-cornstalk position and pass it to the system 3. Create and plan trajectories for each functionality, carried out with respect to the pseudo-cornstalk position 4. Ensure 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 position of the pseudo cornstalk is outside its workspace 6. For 20 pseudo-cornstalk positions, repeat steps 2 to 5
Verification Criteria	1. The generated trajectories should avoid all collisions with the ground and amiga base.

TEST_NO: 11	
Objective	FVD Test
Elements	Motion Planning, Navigation, Perception, User Interface, Testbed
Location	Flagstaff Hill
Equipment	1. Amiga mobile base with x-arm mounted on it 2. Mock-up corn field
Personnel	Tom, Sruthi, Shara, Shrudhi, Saudamini
Procedure	1. Move the amiga mobile base facing toward the mock-up corn field 2. User inputs three predetermined waypoints into user interface 3. Amiga mobile base moves to the first waypoint in the corn field 4. Start the procedure of autonomous nitrate insertion which consists of the following tasks - A. Locate the nearest cornstalk in the waypoint B. Move the x-arm to find a suitable cornstalk C. Perform the procedure of Cleaning and Calibrating the Nitrate Sensor D. Check if the sensor readings are within a specified range E. Insert Nitrate sensor into the cornstalk if suitable F. Remove Nitrate sensor from the cornstalk G. Perform the procedure of Cleaning the sensor H. Locate the next nearest cornstalk if either the cornstalk was not suitable or the Nitrate sensor was removed and repeat from step B 5. Amiga Base moves to the next waypoint in the corn field and repeat from step 4 until all waypoints in the map are exhausted
Verification Criteria	1. The robot successfully finds a nearest suitable cornstalk at all three waypoints 2. The sensor is successfully cleaned and calibrated at all three waypoints 3. The sensor is successfully inserted into the cornstalk and removed from the cornstalk at all three waypoints

V. Appendix

Table 1: Mandatory Performance Requirements

Functional Requirements	Performance Requirements	Description
[F1] Receive a list of testing locations from the user.	**[M.P.1]** Receive testing location within 5 minutes.	The robot follows a trajectory in the cornfield based on the GPS waypoints.
[F2] Drive along a row of corn to testing locations.	**[M.P.2.1]** Maintain a lateral path error less than 15 cm over 10 m. **[M.P.2.2]** Reach testing locations within 2.5 m.	The robot visits each waypoint in the same row of corn.
[F3] Identify cornstalk of suitable width.	**[M.P.3]*** Identify suitable cornstalk 50% of the time	The nitrate sensor should be inserted into the cornstalk such that the side perpendicular to the insertion angle should have a smaller axis (parallel to the longer side).
[F4] Clean the surface of the nitrate sensor.	**[M.P.4.1]*** Clean 75% of the sensor surface. **[M.P.4.2]** Success rate is 75%.	After every insertion process, the nitrate sensor needs to be cleaned to make sure the residue from the insertion does not affect the nitrate readings for the next insertion.
[F5] Calibrate the nitrate sensor.	**[M.P.5]*** Success rate is 80%.	Same as above.
[F6] Grip the selected cornstalk of suitable width	**[M.P.6.1]*** Success rate is 75%. **[M.P.6.2]** Grip within 10 cm of the ground. **[M.P.6.3]*** Success rate of gripping within 10 cm is 80%.	For inserting the nitrate sensor, the end-effector needs to grip the cornstalk within the given range.
[F7] Insert the nitrate sensor into the cornstalk of suitable width.	**[M.P.7]*** Success rate is 50%.	
[F8] Record readings from	**[M.P.8]** Filter out of range	To check if the sensor is

the nitrate sensor.	nitrate readings 90% of the time.	accurate, we are just checking if the readings are in range. Checking physical damage on the sensor is not in our scope.
[F9] Remove the nitrate sensor from the cornstalk.	**[M.P.9]** Success rate is 90%.	
[F10] Provide the user with nitrate readings.	**[M.P.10]** Return nitrate readings within 5 minutes of completion.	

* : This requirement has been specified based on the performance of the previous system implementation and discussions with the sponsor.

Table 2: Mandatory Non-Functional Requirements

[M.N.1] Will have a clearance height of more than 0.6 m.
[M.N.2] Will be transportable via a trailer.
[M.N.3] Will be robust to sensor and behavior failures.
[M.N.4] Will operate for 1.5 hrs before power loss.