Team D: NiMO

Autonomous Nitrate Monitoring in Cornstalks

Team D: Critical Design Review Report

Thomas Detlefsen
Saudamini Ghatge
Shara Lawande
Sruthi Mukkamala
Shrudhi Ramesh Shanthi

Sponsors: Dr. Oliver Kroemer, Dr. George Kantor

May 2, 2024

Abstract

Nitrogen plays a crucial role in plant growth, particularly in cornstalks during their V3 to VT stages, where they require significant nitrogen levels for optimal growth. Therefore, farmers tend to use excessive amounts of fertilizers without any feedback on the actual amount required by the cornstalks. However, excessive nitrogen fertilizer usage by corn farmers can lead to runoff, posing environmental and health risks in farming communities. To address this challenge, we are proposing a solution that involves autonomous nitrate monitoring in cornstalks. Our robot, NiMo, is equipped with a manipulator housing a nitrate sensor in its gripper. With this technology, the robot navigates through the cornfield, inserts and removes the nitrate sensor into/from cornstalks, and logs nitrate data. By optimizing nitrogen usage and protecting community health, NiMo seeks to enable farmers to maximize profits while minimizing environmental impacts.

Contents

1 Project Description

Nitrogen is an essential plant nutrient that creates chlorophyll, which is required for photosynthesis and thus all plant growth [2]. Such a requirement for nitrogen also applies to cornstalks. Specifically, cornstalks require a significant amount of nitrogen in their V3 to VT stages, which are the middle-to-end of their vegetative stages (i.e. growth of leaves, stems, and roots) [7][8]. During these periods, corn farmers typically use nitrogen-based fertilizers to maximize their yield of healthy corn crops [7].

However, to protect the returns on their crops, corn farmers tend to overshoot on the amount of nitrogen-based fertilizer to supplement. Any fertilizer that is not absorbed by the soil typically ends up in water runoff, which has been linked to adverse effects on community health in U.S.-based, corn-farming regions [4]. Within such communities, there have been significant upticks in cancer diagnoses, sudden and mass deaths in cattle and other livestock, and city lawsuits against farms due to increased water filtering costs [6][5][3].

Thus, the goal is to enable farmers to optimize their profits while protecting the community's health. Today, this ideal scenario is being prevented by the lack of quick and consistent feedback on how much nitrogen is being absorbed by the corn. NiMo is an autonomous nitrate monitoring robot **Figure 1** that aims to fill this gap in the market. Equipped with a mobile manipulator and base, NiMo will provide rich insights to map nitrate levels in a cornfield based on soil map regions. NiMo will be improving on past attempts of a robotic solution by incorporating the ability to autonomously clean & calibrate the nitrate sensor and monitor the quality of the autonomous nitrate testing process [1].

2 Use Case

Farmer Joe owns a 500-acre cornfield in northwest Illinois. After visually inspecting a few cornstalks, Farmer Joe has determined that his cornfield has reached V3 maturity. The V3 phase marks the onset of a period where cornstalks require more nitrogen for growth (often via fertilizer supplementation). Thus, Farmer Joe plans to use NiMo, a new CMU robot that can autonomously sample cornstalks for nitrate values, to determine how much additional nitrate to provide via fertilization. The robot was designed to conduct sampling along one row of cornstalks. With NiMo, he can abandon his past practice of naively and often overly supplementing his cornfield with nitrate fertilizer.

Having unpacked NiMo from the crate, Farmer Joe charges the robot base to full battery overnight (often takes 4-5 hours). The next day, he confirms it is a good day to employ the robot because there is no rain in the weather forecast. Farmer Joe now inputs GPS coordinates into NiMo's interface marking the boundaries of his cornfield. He also identifies a row of cornstalks with a high diversity of soil types, along which nitrate sampling will be conducted. Soil types vary based on soil composition, soil moisture, environmental conditions, etc. Equipped with details on soil types along a chosen row, Farmer Joe inputs one GPS coordinate that identifies each unique soil type. With all this data provided, Farmer Joe utilizes the joystick control interface to maneuver the robotic base to the start of the specified test row. From here, he starts NiMo's program to autonomously sample the cornstalks for nitrate. In the meanwhile, Farmer Joe can step away from the fields and eat some breakfast with his family. Knowing that the battery life of the robot is about 1.5 hours, he'll return to the fields to check on progress in an hour.

NiMo is shown in its environment in **Figure 1**. NiMo autonomously navigates to the first GPS coordinate that Farmer Joe inputted (i.e. associated with the first soil region) by driving above the row of corn. After reaching this location, NiMo utilizes its cameras and robotic arm to identify a nearby cornstalk that is of appropriate width and height for sampling. These width and height constraints are solely dependent on the geometry of the robot. Yay! NiMo has found a suitable cornstalk. The robot cleans and calibrates the in-arm nitrate sensor with on-board deionized water and nitrate solutions. Then, using its end effector on the robotic arm, NiMo grips onto a cornstalk, inserts the in-arm nitrate sensor into the cornstalk, takes a nitrate reading, retracts the nitrate sensor, and lets go of the cornstalk. After cleaning the in-arm nitrate sensor with deionized water again, the robot navigates to the next GPS coordinate that Farmer Joe inputted and repeats the same process.

About half an hour after embarking on its journey, NiMo completes its sampling. It halts at the end of the specified row. Once Farmer Joe returns to the fields and sees that the robot has completed its autonomous operation, he utilizes the joystick control interface to maneuver the robotic base back to the barn. After plugging in the robot base for charge, Farmer Joe pulls up the survey log on nitrate assessment. Each line of data records (1) the exact GPS coordinate of the nitrate sample, (2) Farmer Joe's inputted GPS coordinate that this reading is associated with, and (3) whether the nitrate sensor insertion was valid or invalid. With this information, Farmer Joe is now ready to develop an educated fertilizer plan for his cornfield.

Figure 1: NiMo Robot

3 System Level Requirements

The requirements listed in **Table 1** and **Table 2** were created after research and discussions with meetings with stakeholders. This system is a continuation of previous work from members of the Intelligent Autonomous Manipulation (IAM) laboratory at CMU and as such, some requirements were based off of lessons learned from previous iterations. Every performance requirement is motivated by the stakeholders, previous system metrics, or field requirements (requirements necessary for the system to be deployed on a farm).

Requirement **M.P.4** originally had a component ”Clean 75% of the sensor surface.” This requirement has been removed since we have found that a more effective method of determining whether the sensor has been cleaned is by checking the sensor readings to see if it reacts to the cleaning solution. Instead of visual inspection, we use this method.

Table 1: Mandatory Functional and Performance Requirements

Functional	Performance	Description
M.F.1 Receive a list of testing locations from the user	**M.P.1** Receive testing locations within 5 minutes	The robot follows a trajectory in the cornfield based on the GPS waypoints
M.F.2 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
M.F.3 Identify cornstalks of suitable width	**M.P.3** 50% of suitable stalks detected	Cornstalks that are within the workspace of the arm and within the width range of the end-effector should be detected
M.F.4 Clean the surface of the nitrate sensor	**M.P.4** 75% success rate	The cleaning solution should make contact with the sensor so that the readings of the sensor change
M.F.5 Calibrate the nitrate sensor	**M.P.5** 80% success rate	The calibration solution should make contact with the sensor so that the readings of the sensor change
M.F.6 Grip the selected cornstalk of suitable width	**M.P.6.1** 75% success rate **M.P.6.2** Grip within 10 cm of the ground **M.P.6.3** 80% success rate for gripping within 10 cm	For inserting the nitrate sensor the end-effector needs to grip the cornstalk within the given range
M.F.7 Insert the nitrate sensor into the cornstalk of suitable width	**M.P.7** 50% success rate	
M.F.8 Record readings from the nitrate sensor	**M.P.8** Filter out of range nitrate readings 90% of the time	To check if the sensor is accurate, the system needs to check if the readings are in range. Checking physical damage is not in scope
M.F.9 Remove the nitrate sensor from the cornstalk.	**M.P.9** 90% success rate	
M.F.10 Provide user with nitrate readings.	**M.P.10** Return nitrate readings within 5 minutes of completion	

Table 2: Mandatory Non Functional Requirements

Requirements	
M.N.1	Have a clearance height of more than 0.6 m
M.N.2	Be transportable via a trailer
M.N.3	Be robust to sensor and behavior failures
M.N.4	Operate for 1.5 hours before power loss

4 Functional Architecture

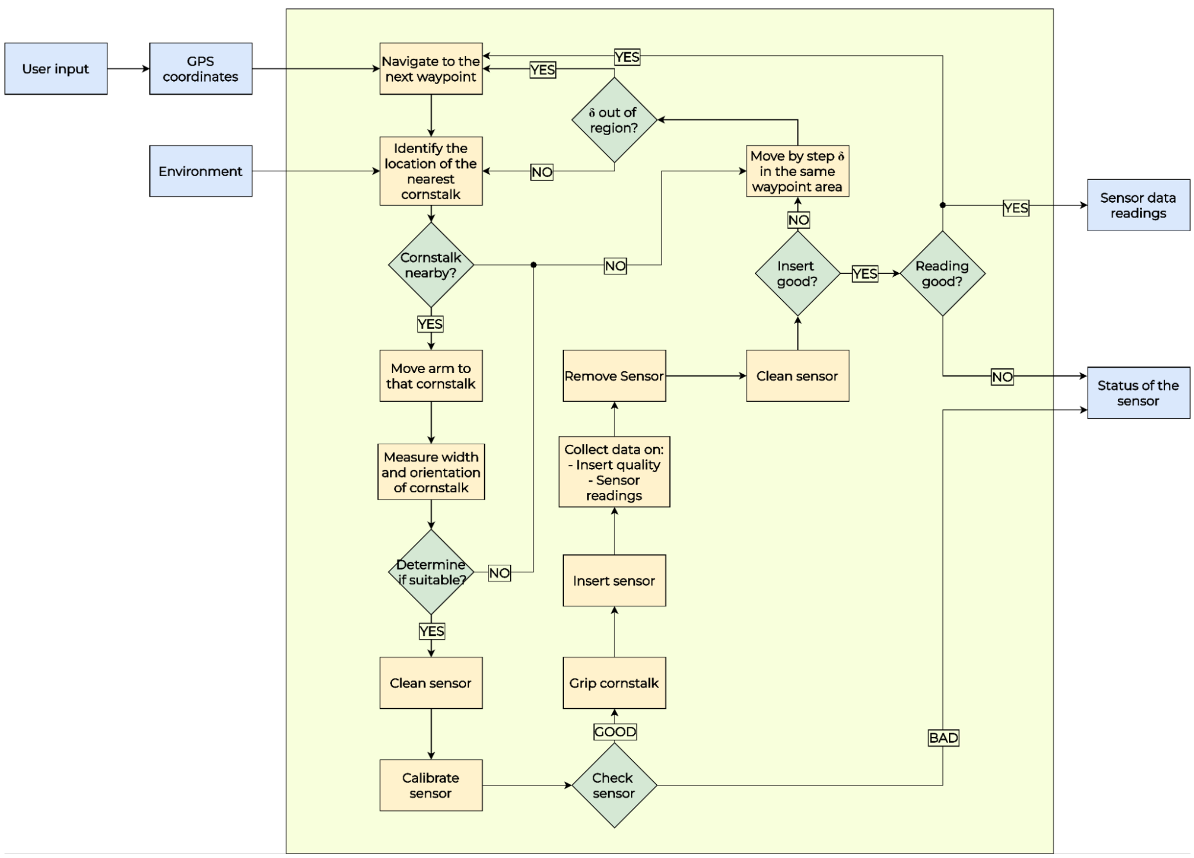

Figure 2: Functional Architecture

The high level actions performed by the system are shown in the functional architecture **Figure 2**. The system takes GPS coordinates, provided by the user, to navigate to specific waypoints. Upon reaching a waypoint, the system checks for the presence of cornstalks in the vicinity by utilizing the visual data captured from the environment. If a cornstalk is nearby, the system moves the arm to that specific cornstalk and measures the stalk's width and orientation. If the cornstalk is deemed suitable based on these measurements, the system proceeds to a cleaning and calibration routine for the sensor. If there are no cornstalks nearby or the cornstalks are not of desired width and orientation, the system moves by a step δ in the same waypoint region to further analyze the next nearest cornstalk.

The system proceeds to clean and calibrate the sensor. Then the sensor is inserted into the cornstalk to collect data, which includes the quality of the insertion and the sensor readings. With a good insertion, the system then evaluates the quality of the reading; if the readings are good the system sends out the logged sensor data readings as output to the user. If the reading is not good, i.e. is out of the acceptable range of nitrate levels, it raises the sensor status flag for the sensor to be replaced externally. Upon utilizing a feedback mechanism to evaluate sensor insertion, in the case the insertion of the sensor is not good, the robot moves by a step δ in the same waypoint region. In all cases, if movement by step δ is exhausted, the system proceeds to move to the next waypoint region. after cleaning the sensor.

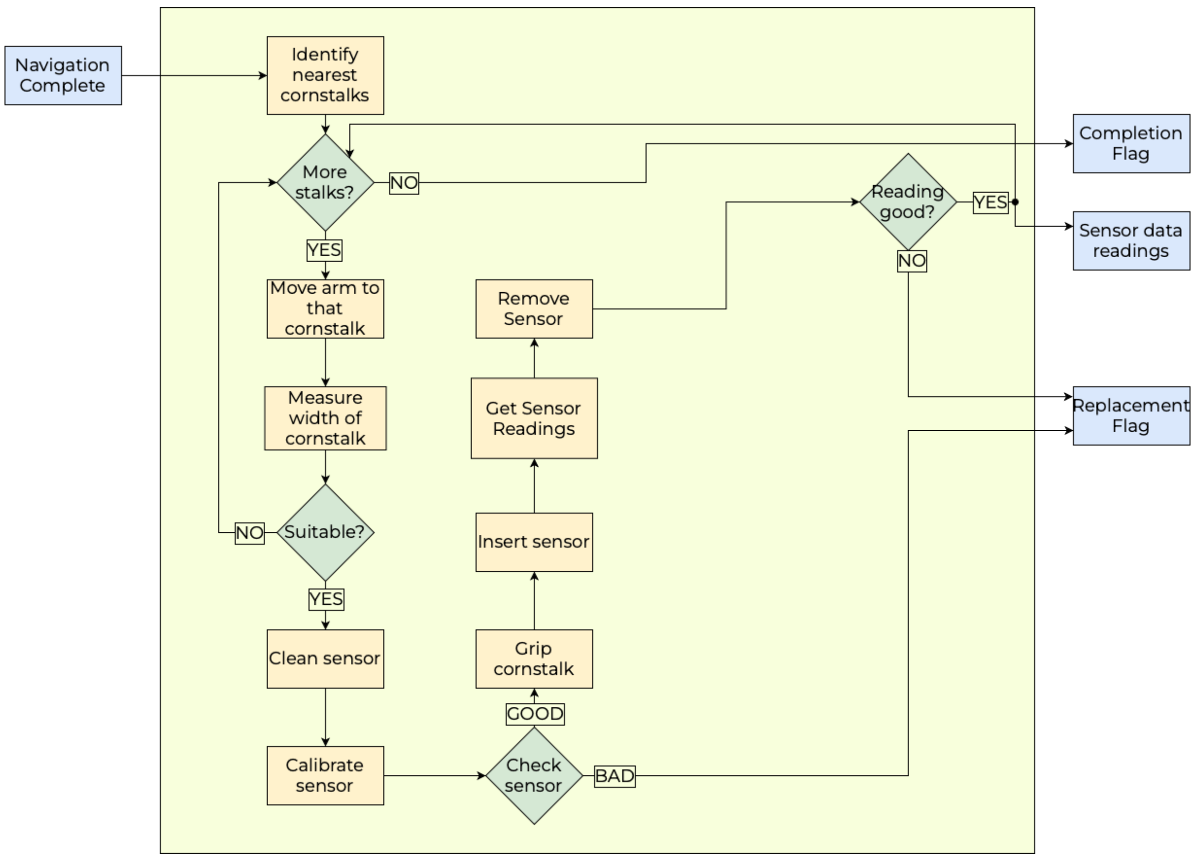

Figure 3: Functional Architecture implemented to date

Figure 3 shows the functional architecture implemented so far and the system that will be used for summer testing. The main differences are that this architecture does not include navigation and instead waits for the signal that navigation has been completed. Also, the current implementation does not have feedback on the quality of insertion and instead only checks the reading of the nitrate sensor.

5 Cyberphysical Architecture

The cyberphysical architecture depicted in **Figure 4** shows the overall flow of the system developed from the Functional Architecture in the previous section. Each of the arrows is color-coded based on the type of information or energy that flows between the blocks: electrical is green, sequential is black, information is blue, and mechanical is red.

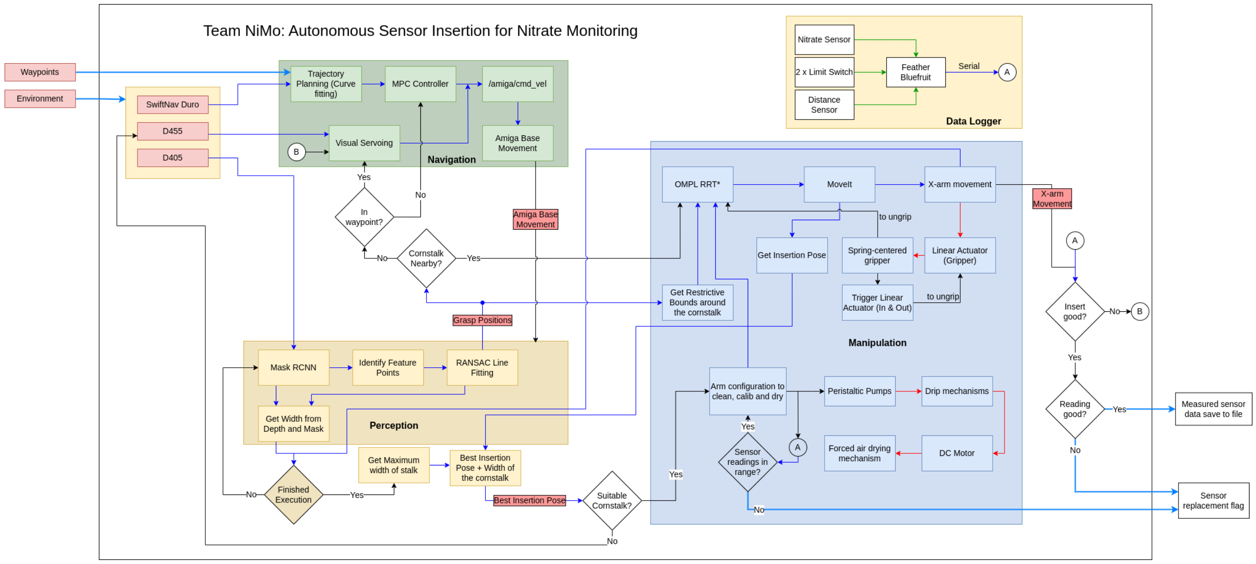

Figure 4: Cyberphysical architecture

The flow of the cyber-physical architecture begins at both the Trajectory Planning within Navigation block and the SwiftNav Duro in the Sensing block.

After the user feeds in the GPS coordinates of the waypoints of different soil regions, where the nitrate levels need to be tested, the navigation stack navigates the robot to the first waypoint. The navigation stack uses the SwiftNav Duro GPS and the D455 camera to get feedback on the location of the Amiga mobile base as it moves to each waypoint.

Using the D405 camera facing the corn row, the Perception stack identifies the cornstalks in the area and the grasp position relative to the world frame through MaskRCNN and RANSAC Line Fitting.

With the nearest cornstalk's grasp position identified, the xArm orbits around the grasp position of the cornstalk at a fixed radius. The width of the cornstalk is identified at each angle of the orbit, using which the Perception stack can return the angle with the maximum width at which the sensor can be inserted. The angle of insertion is passed on to the Manipulation stack.

Before proceeding with insertion, the Manipulation stack moves the xArm, with the sensor extended within the gripper, to the Cleaning and Calibration mechanism. This mechanism consists of a dripping mechanism, using peristaltic pumps, that has the xArm move to the first nozzle for cleaning of the sensor with deionized water. The xArm further moves to the second and third nozzles for calibration with low nitrate concentration and high nitrate concentration solutions respectively. The xArm is brought back to the first nozzle for cleaning again, before the sensor is dried using a force air drying mechanism.

With the sensor calibrated, it is ready to measure the nitrate content in the cornstalk. The xArm approaches and hooks the cornstalk by making use of the grasp position, such that the cornstalk is within the gripper of the End-Effector. The arm rotates itself, with the cornstalk in the gripper, to move to the best angle of insertion. The End-Effector inserts the sensor into the cornstalk, with the nitrate levels of the cornstalk being recorded. Once the nitrate level is recorded, the sensor is removed from the cornstalk and the range of the nitrate readings are evaluated if they are within the expected range.

If there are any issues, the navigation stack moves the base forward to test another cornstalk within the same waypoint. If there are no issues, the navigation stack moves the base to the next waypoint and the process continues until all waypoints are exhausted. Finally, the nitrate readings are returned to the user.

6 Current System Status

6.1 Targeted Requirements

For the Spring Semester, our team successfully achieved all the targeted requirements as outlined in table 3.

Here are the results from conducting 20 trials on our system.

Table 3: Targeted Requirements

M.P.#	M.P. Description	Desired	Actual
M.P.3	Identify suitable cornstalk 50% of the time	50%	85%
M.P.3	Identify maximum width insertion angle 50% of the time	50%	65%
M.P.4.1	Clean 75% of the sensor surface.	75%	Metric is not being measured.
M.P.4.2	Success rate is 75%.	75%	95%
M.P.5	Calibrate the nitrate sensor 80% of the times	80%	95%
M.P.6.1	Grip the selected cornstalk of suitable width 75% of the time	75%	95%
M.P.6.2 & M.P.6.3	Grip within 10 cm of the ground 80% of the time	80%	95%
M.P.7	Insert the nitrate sensor 9mm into the cornstalk of suitable width 50% of the time	50%	80%
M.P.9	Success rate of removing the nitrate sensor from the cornstalk is 90%	90%	95%

6.2 Overall System Depiction

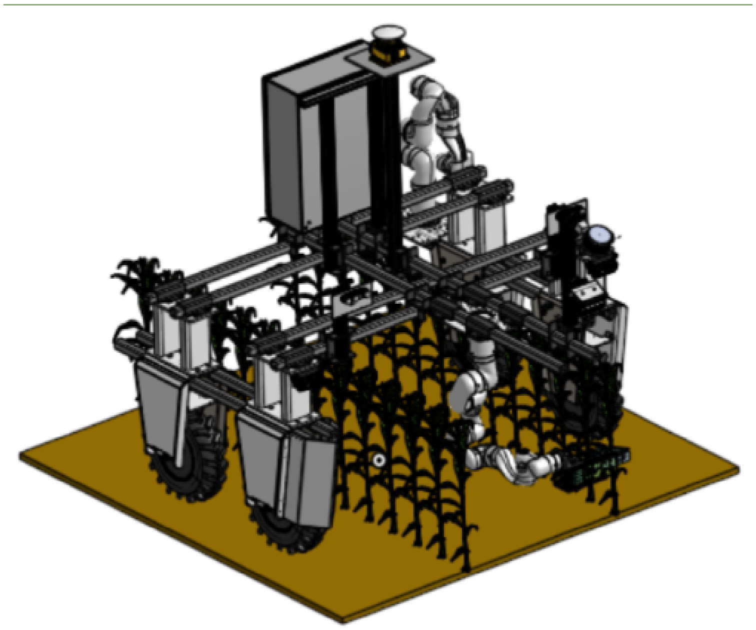

Figure 5: Conceptual System Depiction

Figure 6: Overall System Depiction

The overall system consists of the subsystems integrated on the Amiga Base with the testbad setup within the base vicinity. **Figure 5** shows the conceptual depiction of the entire system before development. In **Figure 6**, the overall system consists of the UFactory xArm6 arm for the Manipulation subsystem. The custom End-Effector has been attached to the arm, which houses the nitrate sensor, the Intel Realsense D405i camera, and other key electronics to support its mechanism. The External Mechanisms subsystem is mounted on the Amiga base that houses the dripping mechanism for the cleaning and calibration routine for the nitrate sensor, with a custom PCB to enable its functionality.

The system can currently identify, move to and insert the nitrate sensor into the nearest cornstalks within a corn row. In addition, it can successfully clean and calibrate the nitrate sensor before each insertion. For our testing, we had made use of leeks as our pseudo-cornstalks, placed on our custom test bed that mimics a row of cornstalks. This semester we did not tackle mobile navigation to move along a corn row, leading our test-bed's location to be fixed with respect to the base. On the Amiga base, we have the on-board compute that interlinks functionality between each subsystem through our system FSM. Under ideal conditions, the system is currently capable of successfully inserting and calibrating a sensor under 8 minutes for a cornstalk.

6.3 Subsystem Descriptions

6.3.1 Finite State Machine

To implement the functionality of our system, we have utilized a Finite State Machine that appropriately loops through each state, adhering to the functional architecture we laid out.
We identified three main states for our system **Figure 7**:

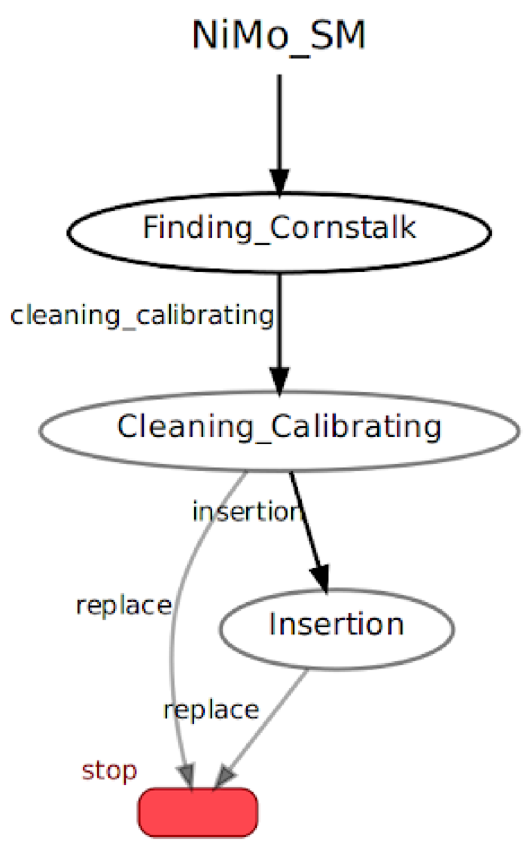

Figure 7: Finite State Machine

- **Finding Cornstalk** - Detecting cornstalks in the area and selecting one to determine the optimal insertion side
- **Cleaning & Calibrating** - Cleaning and Calibrating the nitrate sensor to calibrate and check its functionality
- **Insertion** - Grasping the cornstalk, inserting the nitrate sensor, and logging nitrate sensor readings
- **Replace** - Replacing the nitrate sensor manually

6.3.2 Perception

There are two purposes for perception subsystem:

- **Localize Cornstalks** - Get the location of all visible suitable cornstalks in the world frame.
- **Get Cornstalk Width** - Get the width of the closest cornstalk in mm.

An example of the cornstalk localization can be seen in the **figures 8** and **9**. In **figure ??** the masks are shown on the leeks with white diamonds running through the middle representing the chosen feature points. **Figure 9** shows the prediction of the stalk location on the depth cloud using a green line. The grasp point is represented by a pink sphere. The depth cloud is upside-down because the arm is mounted opposite it's normal configuration

Figure 8: Image of leeks with masks from perception

6.3.3 End Effector

The primary functionalities of the end effector subsystem are to (1) grip the cornstalk and (2) insert and remove the nitrate sensor from the cornstalk. Additional secondary functionalities include:

- Appropriately expose the nitrate sensor for clean and calibrate processes.
- House data logger for nitrate sensor.
- House D405 in-arm camera, used for cornstalk width detection.

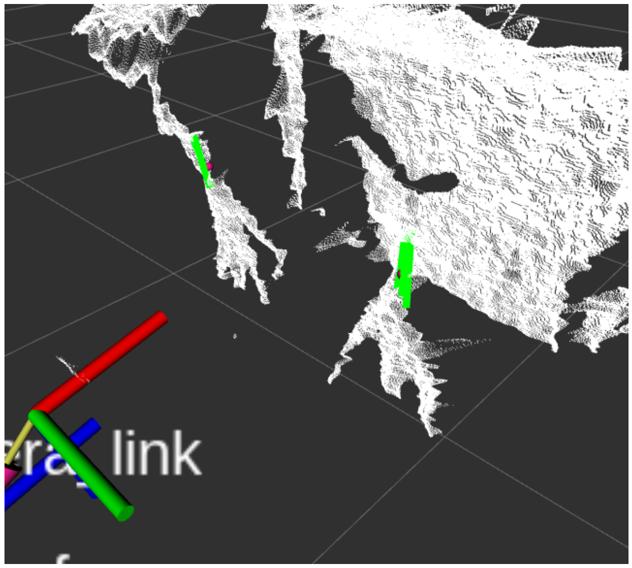

Figure 9: Estimate of leek position and grasp point on depth cloud

Figure 10: NiMo End Effector on xArm

- Protect all end-effector electronics from clean and calibrate processes (i.e. liquids).

As of this semester, the design, fabrication, testing, and integration of the end effector subsystem has been completed. The final end effector assembly, as integrated with the xArm, is shown in Figure 10. The end effector gripping a pseudo-cornstalk is visualized in Figure 11.

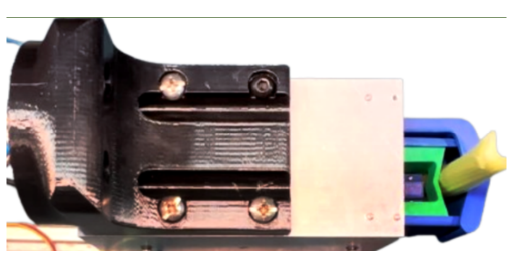

Figure 11: NiMo End Effector, gripping pseudo-cornstalk

6.3.4 Manipulation

The Manipulation subsystem have the following major functionalities:

- Orbit around a cornstalk to identify the best width
- Move the sensor to each nozzle of the External Mechanisms subsystem
- Hook and Unhook the cornstalk for insertion

The goal of the manipulation subsystem is to facilitate the maintenance of sensors for successful insertions within cornstalks. The subsystem provides the connection between the perception, external mechanisms, and end-effector subsystems.

In view of the fact that we are using the UFactory xArm6, we have decided to leverage the capabilities of the xArm API. In addition to allowing for easy and robust planning, the xArm API also allowed for faster planning.

The xArm goes through a series of trajectories while being heavily integrated into the system Finite State Machine (FSM). The xArm first moves to the home position with the gripper facing the row of cornstalks, to identify the nearest cornstalk for insertion. Upon identification and retrieving the cornstalk's grasp points, the xArm performs Arc Motion around the cornstalk to identify the best angle for a suitable insertion. Further, the system allows for the sensor to interface with the External Mechanisms subsystem for cleaning calibration. The xArm then moves to the pre-grasp position to the cornstalk, before hooking and adjusting to the angle of insertion required. Once insertion has been completed, the arm moves to the External Mechanisms for cleaning before identifying the next nearest cornstalk.

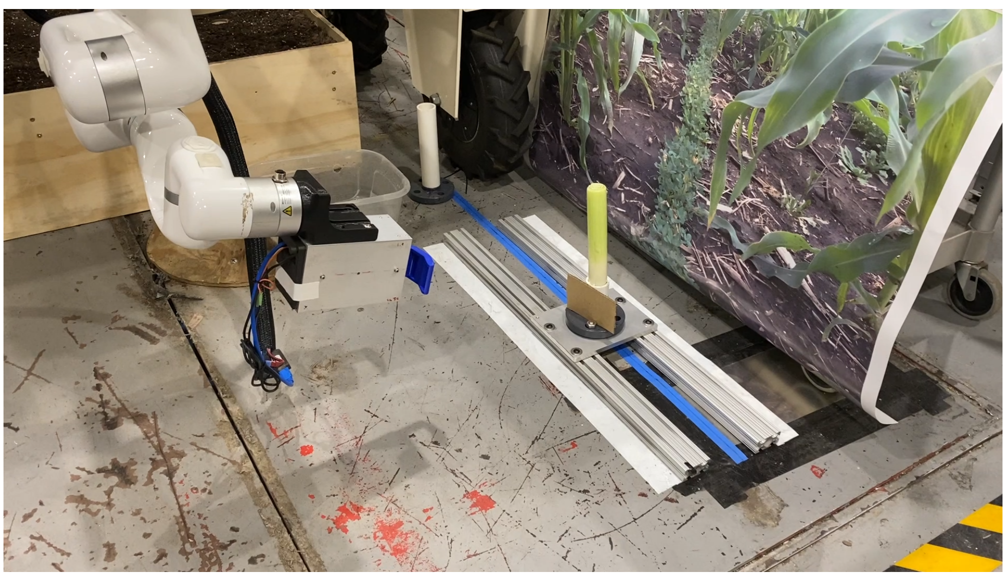

Figure 12: xArm Looking at Cornstalk Row

Figure 13: xArm orbit pose around Cornstalk

Figure 14: xArm at External Mechanisms

Figure 15: xArm hooking Cornstalk at an angle

6.3.5 External Mechanisms

The Main functionality of the external mechanisms subsystem is to clean and calibrate the sensor before inserting into cornstalk, such that the readings we obtain from the sensor are more reliable.

As of this semester, the choice and testing of the mechanism, design, fabrication and assembly of the mechanism have been completed. The final external mechanisms assembly, as mounted on the amiga robot base is shown in figure 16.

Figure 16: External Mechanisms Mounted on Amiga

6.4 Modelling, Analysis and Testing

To analyze the performance of various subsystems in meeting the desired requirements, we performed several tests throughout the course of the semester. The results of these tests can be split up with respect to each subsystem.

6.4.1 Perception

Since the width detection was a novel component for this system, it was tested rigorously according to **table 4**.

For the horizontal movement, image distortion led to greater differences in width. Camera calibration was attempted to correct this distortion, but it did not make a difference. The disparity in widths is low enough that it does not matter.

For high roll angles, the stalk is not detected. This is acceptable because a cornstalk with a high roll angle would be unhealthy and should not be tested in the first place.

For cornstalks occluded by leaves, the leaves were still detected, but at a much lower confidence than the stalks themselves meaning that the false positives could be filtered.

Table 4: Perception Width Testing

Test	Metric	Conclusion
Depth Movement	$\pm$0.45mm	Consistent width >10 cm depth
Horizontal Movement	$\pm$3.65mm	Differences due to image distortion
Yaw Angle	$\pm$1.20mm	Performed as expected
Roll Angle	N/A	Stalk not detected at higher angles
Width	$\pm$1mm	Performed as expected
Ovular Measurement	N/A	Performed as expected
Occlusion	N/A	Occlusions detected with low conf.

6.4.2 End Effector

Table 5: End Effector Unit Testing Results

Test	Description	Result
Repeatability Test	Verify grip and full sensor insertion on the same cornstalk	- 100% success rate - No. of Trials: 8
Varying Diameter Test	Verify grip and full sensor insertion in designed operating range of major diameter between 15 - 45 mm	- 100% success rate - No. of Trials: 8 - Redefined min. to 17 mm (failed at complete insertion @ 15 mm)
Varying Orientation Test	Verify grip and full sensor insertion for rotated cornstalk of ovular cross-section (i.e., can insert along both major and minor axes)	- 100% success rate - No. of Trials: 7

Varying Y-Offset Test	Verify grip and full sensor insertion when cornstalk is displaced away from gripper (i.e., not touching the gripper at all)	- 100% success rate - No. of Trials: 4
Varying X-Offset Test	Verify grip and full sensor insertion when cornstalk is touching gripper, but not at its center.	- 0% success rate w.r.t. full insertion - 100% puncture rate - No. of Trials: 4
Boundary Conditions Test	Confirm performance for completely rigid to completely flexible cornstalk.	System can succeed regardless of applied boundary condition.

6.4.3 Manipulation

The following tests were conducted to understand how compliant the Manipulation subsystem is with different positions of the Corn rows and subsequent Cornstalks positions with respect to the Amiga base. We were able to conclude that with cornstalks closer to the arm and Amiga base, we are encountering singularities in the path planned. We aim to mitigate this by setting intermediate joint poses, before having the arm move in the Cartesian space to the cornstalk.

Table 6: Manipulation Testing Results

Test Performed	# of Tests	Grasp Region (m)	% Success	Conclusion
Approach Cornstalks and Sweep motion around Cornstalks	20	y > 0.6: x > 0.2 x <= 0.2	100%	xArm performed as expected
Approach Cornstalks and Sweep motion around Cornstalks	10	y < 0.6: x > 0.2 x <= 0.2	80% 20%	xArm workspace is very limited with corn rows closer to base. Singularities faced in planning.
Hook Cornstalks	20	y > 0.6: x > 0.2 x <= 0.2	90%	xArm performed as expected
Hook Cornstalks	10	y < 0.6: x > 0.2 x <= 0.2	90% 0%	xArm workspace is very limited with corn rows closer to base. Singularities faced in planning.

6.4.4 External Mechanisms

We conducted some rigorous testing to concur the reliability of the nitrate sensor, the choice of mechanism and the reliability of the electronic components being used.

Sensor verification Testing: We conducted sensor verification tests to examine how the sensor responds when exposed to clean and calibration solutions. Our aim was to determine whether the sensor's behavior followed a consistent pattern that could be generalized across different levels of nitrate in the solutions. The results confirmed a consistent pattern: the sensor reliably converged to lower readings as the nitrate concentration in the solution increased.

Choice of Mechanism: To clean and calibrate the sensor, the following mechanisms were considered:

- Dripping
- Spraying
- Dipping
- Jetting

We found that the sensor's response time and reliability varied significantly with different application methods. When sprayed, the sensor took longer to stabilize at a reading and performed unreliably in simulated windy conditions. Dipping the sensor resulted in slow convergence and contamination of the solutions after several tests. Jetting the sensor at high flow rates also led to unreliable performance, likely due to the high pressure of the fluid impact. In contrast, the dripping method allowed the sensor to converge quickly and consistently, demonstrating it as the most effective technique.

Table 7: External Mechanisms Testing

Test	# of test	% Success	Conclusion
Sensor verification	10	80%	Nitrate sensor follows a specific pattern on exposure to different solutions
Choice of Mechanism	15	25%	The dripping mechanism is the fastest and most reliable
Reliability of The Electronics	20	50%	The relays we are working with are not reliable

6.5 SVD Performance Evaluation

The aim of this demo was to showcase a successful run through of our system, during which the perception stack would detect the pseudo-cornstalk, the arm would perform a sweep motion around the detected cornstalk to understand how to grip it, followed by cleaning and calibrating the sensor, and finally insert the sensor into the cornstalk perpendicular to the maximum width.

The required equipment of the demo included the amiga robot base, xArm, the end-effector housing the realsense D405i camera and the nitrate sensor, external mechanisms subsystem, and our testbed setup. The demo took place at the field robotics center.

Our system functioned flawlessly, meeting all the predefined criteria set out for the SVD. The set of system capabilities that were demonstrated in the SVD and SVD Encore are shown in Table 8.

Table 8: SVD Results

M.P. Description	Desired Outcome	Actual Result

At least 50% of suitable cornstalks within the workspace of the xArm are detected	50%	100%
The cleaning and calibration solutions make contact with the sensor for 15 seconds.	15s	15s
The robot grips the cornstalk within 10 cm of the ground	<10cm	«10cm
The nitrate sensor is inserted properly at least 50% of the time.	50%	83%, 72%

6.6 Strong/ Weak Points

Our progress through the semester led to a successful demonstration during SVD and SVD Encore. While there are several strong areas of our system, there are also areas that need improvement. The strong and weak points of our system are highlighted below:

Strengths:

- Robust and Durable End-Effector
- Modular System
- Accurate Perception
- Reliable Cleaning and Calibration mechanism
- Performance repeatability

Weaknesses:

- Unpredictable sensor behaviour
- Unrealistic testing platform
- Workspace limits for cornstalks closer to arm
- Lack of feedback mechanisms for error handling
- Increased time of functionality
- Reliability of PCB

7 Project Management

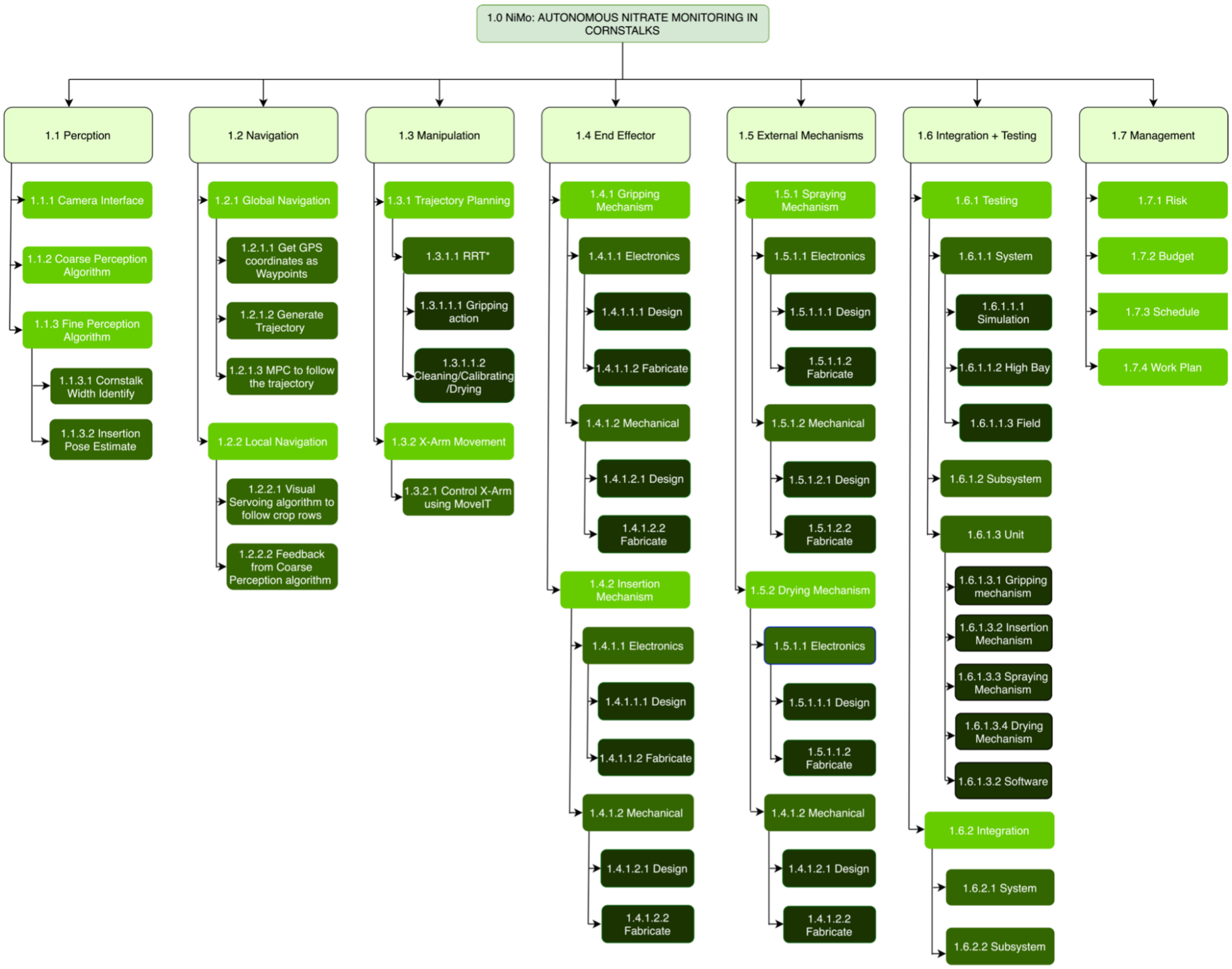

Figure 17: Work Breakdown Structure

7.1 Work Breakdown Structure explained

The Work Breakdown Structure (WBS) shown in **Figure 17** is split into seven subsystems and project activities. The structure is arranged as a mix of product and process-oriented WBS in order to emphasize subsystems and project activities that will take significant effort. These groups are: Perception, Navigation, Manipulation, End Effector, External Mechanisms, Integration and Testing, and Project Management. The third level of the WBS lists the deliverables for each of the subsystems and project activities. The fourth and fifth levels describe specific work packages that can be assigned to individual group members.

7.2 Schedule

As of the end of the spring semester we have completed all of our milestones on time. This means that we are well prepared for the fall semester which we describe in the bi-weekly schedule below.

Similar to the spring semester, we set milestones for designing, testing, and integrating each new component. The new components we plan to complete are:

- Integration with an alternate end-effector (developed by IAM Lab)
- Local and Global Navigation
- Drying Mechanism Completed

Bi-Weekly 1 In the first two weeks we will analyze the results from summer testing and reassess our plan based on this information. From there we will begin to research the individual components mentioned above and any other improvements motivated by summer testing.

Bi-Weekly 2 In the next bi-weekly period, we will begin the development of these components and at the same time perform initial testing on the components. This would be CAD modeling for the drying mechanism, starting navigation in simulation and beginning to work on integration for the alternate end-effector.

Bi-Weekly 3 At the end of the third period, the individual subsystem development and testing will be completed and integration of the subsystems will begin. This will be on track to show significant progress for the System Development Review.

Bi-Weekly 4 During the fourth period we will focus entirely on subsystem development and testing. We will also begin to focus on the testing environment for the FVD in more detail so that we have time to make arrangements and alterations.

Bi-Weekly 5 By the end of the fifth bi-weekly period, integration between the subsystems will be completed. This means that all new components are integrated on the system in an initial form, but not fully tested.

Bi-Weekly 6 During this period we will fully test the completed system and make more refinements as we move to the FVD setup.

Bi-Weekly 7 For the final bi-weekly period, we will make final changes to the system before freezing the software so the system can be tested and all unexpected behaviors can be understood.

7.3 Test Plan

For the newly proposed components each will have unique testing:

- **Integration Testing** - The IAM Lab gripper will be tested with the current stack and the same demonstration performed at SVD will be performed with the alternate gripper. The success criteria will be the same as SVD.
- **Simulation** - The first verification of navigation will be the system's performance in simulation. Success criteria will be based on the ability to track waypoints and move along a row without disturbing corn.
- **Field Testing** - The second verification of navigation will be the system's performance in a real environment. The success criteria will be the same, but will marked areas to represent the rows of corn.
- **System Integration** - The drying mechanism will be tested by integration with the nitrate sensor in the cleaning and calibration process. The success criteria will be a properly calibrated sensor in a shorter amount of time compared to air drying.

7.3.1 Fall Semester Capability Milestones

The fall semester progress reviews will roughly align with the bi-weekly schedule shown above. The detailed capabilities aligned with progress reviews is shown in **Table 11** below.

Table 9: Fall Capability Milestone

Progress Review	System Capabilities
PR 7	The first period will be used to reflect on summer testing and begin research and development on the improvements for the fall semester. No technical improvements will be demonstrated, but plans will be shown.
PR 8	The preliminary CAD design for the drying mechanism and the initial navigation system in simulation will be demonstrated.
PR 9	A full demonstration of the integrated alternate end-effector will be shown similar to the spring validation demonstration.
PR 10	An initial functional prototype of the drying mechanism will be demonstrated alone. Initial field testing for navigation will have been performed and videos and data from these tests will be shown
PR 11	Partial integration of the drying mechanism, navigation, and alternate gripper will be shown modeling the fall validation demonstration.
PR 12	An initial version of the fall validation demonstration will be shown. This will have every subsystem integrated, but may still have some issues.

7.3.2 Fall Validation Demonstration

The test conditions are as follows:

- **Location**: NSH B-Level
- **Equipment**: Farm-ng Amiga mobile base, Mock cornfield setup

The Fall Demonstration procedure can be found in Table **10**. An image of the setup can be seen in figure **18**

Table 10: Fall Demo Procedure

Steps	Procedure	Success Criteria	Requirements
1	The operator starts the robot and inputs the waypoint coordinates	The testing locations are processed within 5 minutes	**M.P.1**
2	The robot advances to the mockup cornfield	A lateral path error of 15 cm is maintained The testing location is reached within 2.5m	**M.P.2.1**, **M.P.2.2**
3	In the mockup cornfield, the arm orbits the cornstalk and identifies whether is is suitable.	50% of suitable stalks are detected	**M.P.3**
4	The arm moves to clean the nitrate sensor.	75% success rate	**M.P.4**
5	The arm waits temporarily while the sensor is dried by the external drying mechanism.	75% success rate	**M.P.4**
6	The arm moves to calibrate the nitrate sensor.	80% success rate	**M.P.5**
7	The end effector grips the cornstalk at the proper height.	The end-effector grips within 10 cm of the ground	**M.P.6.1**, **M.P.6.2**, **M.P.6.3**
8	The gripper inserts the nitrate sensor into the cornstalk.	50% success rate	**M.P.7**
9	The nitrate sensor records the readings.	Out of range readings are filtered 90% of the time	**M.P.8**
10	The arm removes the nitrate sensor from the cornstalk.	The nitrate sensor is removed without visible damage	**M.P.9**
11	The system repeats the process for other cornstalks in the area then returns the nitrate readings.	Readings are returned within 5 minutes of completion	**M.P.10**

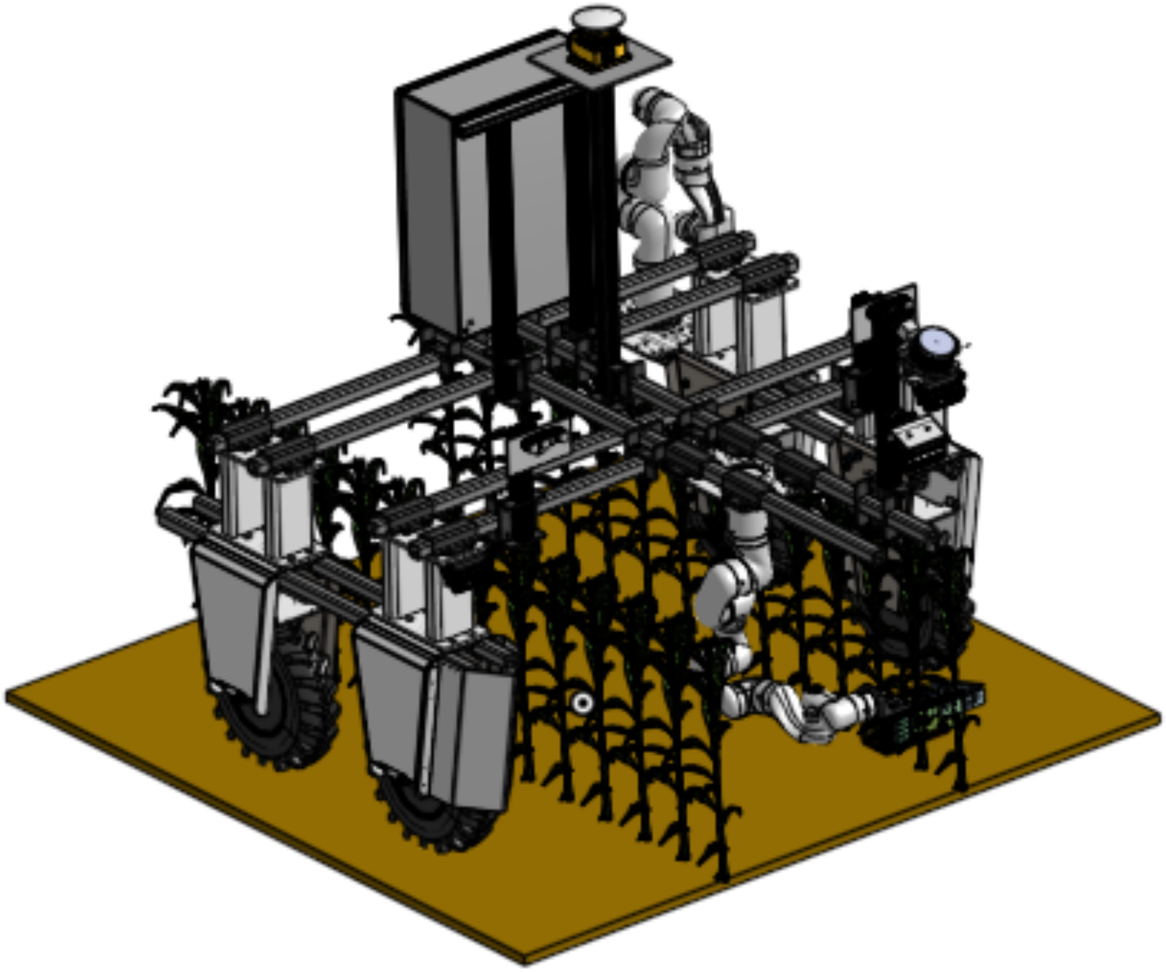

Figure 18: Fall Validation Demonstration Setup

7.4 Budget

The total budget provided for the MRSD capstone project is $5000. At the conclusion of the spring semester, we have spent $435, which is approximately 9% of our budget. The biggest ticket items are as follows:

- **Linear Actuator (x2)**: $170
- **Peristaltic Pumps (x3)**: $74.85
- **Right Angle USB**: $35

Table 11: Expenditures at end of Spring Semester

Line No.	Qty.	Part Name	Total Price
1	2	Micro Linear Actuator	$170.00
2	3	Peristaltic Liquid Pump	$74.85
3	1	6061 Aluminum Rectangular Tube	$40.47
4	1	Right Angle Cable	$34.79
5	3	Liquid Containers	$24.84
6	1	Rasberry Pi Zero	$16.00
7	1	Compression Springs	$11.87
8	1	Press-Fit Nut, 1/4" (Plastic)	$10.67
9	1	Press-Fit Nut, 1/4" (Metal)	$10.49
10	1	Acrylic Sheet	$9.70
11	1	Anti-Static Foam	8.98
12	1	USB Cable	$7.79
13	1	Motor Driver Breakout Board	$7.50
14	1	Press-Fit Nut, M3	$7.37
15	1	Microcontroller Case	$6.28
16	1	Press-Fit Nut, M2	$6.16
17	1	JST Cable Matching	4.46
18	1	6061 Aluminum 90 Degree Angle	$2.40
19	1	Cable Tie, Metal	$0.93

7.5 Risk Management

By the preliminary design review, we identified five major risks. Since then, we have identified an additional two. These risks are: (1) manufacturing concerns, (2) integration bottlenecks, (3) undesirable performance of inherited perception stack, (4) poor reliability of nitrate sensor, (5) version conflicts, (6) manipulation edge cases and singularities, and (7) poor hardware performance and reliability (non-COTS). NOTE: For the full risk management table, please refer to appendix.

[R1] Manufacturing concerns

The risks that come with manufacturing are multipronged: variations in build vs. test, subpar tolerances/clearances of 3D printed components, and scheduling concerns for machining and 3D printing. During this semester, we faced all of these subrisks and successfully mitigated them as well. Some of the steps taken towards mitigation include iterating, integrating, and failing quickly; generating test 3D-prints for interface testing with low infill; and identifying alternative routes and personnel to curb scheduling roadblocks.

[R2] Integration bottlenecks

We identified that the main bottleneck for integration will be progress on the manipulation subsystem, for which only one individual was identified as system owner. System implementation of all other subsystems (i.e. perception, end effector, manipulation) was dependent on the manipulation stack being complete. Thus, we identified and executed a mitigation plan of having an alternate system owner for manipulation. This individual was trained on how the manipulation stack worked and even helped with development of some functionalities. From these actions, there was no longer system dependence on a select individual and progress was faster (which tagged well with progress of other subsystems).

[R3] Undesirable performance of inherited perception stack

There was concern on how the inherited perception stack would work for difficult scenarios such as occlusions and false positives. The executed mitigation plan was to test these behaviors quickly and robustly. Through this process, we were able to confirm steady behavior for both edge cases.

[R4] Poor reliability of nitrate sensor

The nitrate sensor behaves unknowingly, and there isn't openly accessible and documented information regarding its expected behavior. This causes risk to the performance and validity of our entire system, since if the sensor does not work appropriately, our whole robotic solution is rendered meaningless. Since our team identified this risk ahead of time, we decided to test the sensor as robustly as possible at an early point. We were able to identify general trends in behavior which guided us with classifying a "good" vs. "bad" sensor. Additionally, we communicated these performance issues with our sponsor consistently in order to maintain visibility on this risk. From these conversations, we were able to conclude that we should quantify success of our product independently from the sensor, i.e., our system performance would not be held responsible for the sensor's performance.

[R5] Version conflicts

The risk of version conflicts played out in two scenarios: (1) variations in the setup of the team desktop vs. the amiga system and (2) variations in our team's perception stack libraries and the past version's perception stack libraries. We have yet to mitigate the first scenario, which we plan to do by using docker. The second scenario we mitigated by cross checking the versions and libraries between the two systems and modifying our code (which was yet to be tested) to work with the past perception implementation (which has worked successfully on the cornfields).

[R6] Manipulation edge cases and singularities

This risk is new to the latter half of the spring semester. When cornstalks are closer to the xArm, we observed that the arm's motion was hitting singularities. We plan to solve this risk of arm singularities by thoroughly testing the workspace, dividing the arm's motion into zones, and developing intermediate poses for each zone that can prevent such behavior.

[R7] Poor hardware performance and reliability (non-COTS)

This risk has also been newly identified in the latter half of the spring semester. The reliability of some of our electronic boards is already poor in stagnant conditions. With movement in cornfields, the performance is expected to be even worse. Thus, we plan to mitigate the risk of poor electronic performance on the field by rethinking the circuits and making them more robust.

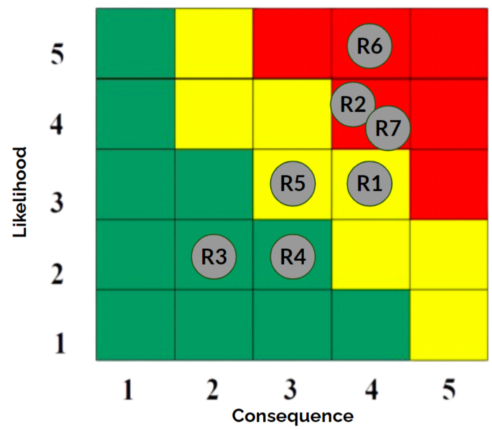

Figure 19: Likelihood-Consequence Table

8 Conclusions

8.1 Lessons Learned

System integration and testing will have unforeseen delays. Plan for it.

Our team anticipated that integration would require a large portion of our time, which is why we aimed to complete subsystem build, testing, and validation by the end of spring break. However, irrespective of the leeway we incorporated into our schedule, system integration was still pushed back by about 2-3 weeks due to unforeseen issues with end effector design, delays in finalizing an external mechanisms methodology, and increased needs with manipulation functionalities. Through this experience, our team understood the importance of being real with ourselves with respect to how long tasks will actually take. Additionally, it is important to include some time padding to account for extreme cases of rework or revisiting particular tasks.

Communicating with the sponsor consistently throughout every stage of development is critical to prevent deviation in progress.

Throughout the semester, our team had a high frequency of communication with our sponsor. We would interact with our sponsor and/or the sponsor's lab twice a week - once to only provide updates on an MRSD level and another time to provide context on our system with respect to the larger context of the AIRAA-CMU project.

Because of this high level of dialogue, our team received a large amount of feedback on our progress and whether our proposed system would line up with the anticipated environment in the cornfields. For example, we were relayed input that the cornstalks would not actually be V3-V5 in stage when summer testing in IA State. In reality, they could be upwards of V10 to R1 in stage, which means that they are much taller and thicker than previously anticipated (i.e., larger cross-sectional area). This allowed for us to quickly modify the end effector's gripping range to be larger by changing the design. Additionally, we were able to change the hard-coded arm motion for the clean and calibration processes to account for increased height of the cornstalks (so the arm would not hit anything in these higher planes).

Similarly, we received feedback on the location of the cornstalks with respect to the Amiga base when driving down a row of corn. This will guide any motion modifications in the progress to come, specifically to accommodate for larger range of motion along the x-axis (i.e., along the axis drawn from the center of the Amiga to the wheel).

Daily standups are vital for team success! More communication is better than no communication.
Towards the beginning of the semester, our team noticed that there was lack of transparency amongst individuals and subsystems with respect to progress. For example, some blocking work for the manipulation subsystem would be completed for days, but not communicated to this subsystem's lead. Additionally, there was a lack of accountability for assigned work. Many times, we would think "it's okay, we can do that task tomorrow or later this week," when in reality that task was critical and a dependency for others' work. Such a mentality was causing a slip in project progress and the project schedule.

Thus, the team decided to try and implement daily standups to address these concerns. These standups were not intended to last more than 10 to 15 minutes, where the team would share their progress over the last 24 hours and what the immediate next steps are for the next day. The standups were at fixed times (i.e., right after our shared morning classes) to promote accountability and dependability from the team.

After implementing these processes, the communication, transparency, and project progress amongst our team significantly improved. We will be the first to admit that sometimes the standup meetings were redundant and unnecessary. But, we realized that a routinely set check-in sets high team expectations and even brings the team dynamics even closer. Overall, more communication is always better than no communication!

8.2 Key Fall Activities

As our team enters fall semester in anticipation of the Fall Validation Demo (FVD) and wrapping up our capstone project, we predict these key projected fall activities:

- Revisiting and modifying our functional architecture, subsystem progress, and integration procedures developed for the Spring Validation Demo (SVD) to reflect findings from Iowa summer testing (in the cornfields).
- Develop and integrate navigation capabilities with Amiga base. Both global navigation (along cornrows) and local navigation (to identify a suitable cornstalk for sensor insertion).
- Improve reliability checks and feedback on whole process (e.g., ultrasonic sensor to verify insertion height from ground). Overall, make system more closed loop.

References

[1] Towards autonomous crop monitoring: Inserting sensors in cluttered environments. https://kantor-lab.github.io/cornbot/index.html, n.d. Accessed: 2023-05-01.

[2] D. Buchholz. Nitrogen in the plant. https://extension.missouri.edu/publications/wq259, 2022. Accessed: 2023-05-01.

[3] D. Charles. Iowa's largest city sues over farm fertilizer runoff in rivers. https://www.npr.org/sections/thesalt/2015/01/12/376139473/iowas-largest-city-sues-over-farm-fertilizer-runoff-in-rivers, 2015. Accessed: 2023-05-01.

[4] M. Keena. Environmental implications of excess fertilizer and manure on water quality. https://www.ndsu.edu/agriculture/extension/publications/environmental-implications-excess-fertilizer-and-manure-water-quality, 2017. Accessed: 2023-05-01.

[5] K. News. Experts warn of dangerous high-nitrate content in cattle feed. https://www.kttn.com/experts-warn-of-dangerous-high-nitrate-content-in-cattle-feed/, 2023. Accessed: 2023-12-14.

[6] K. Schneider. On "cancer road," a group of southeastern minnesota families ask if nitrate exposure is to blame. https://www.minnpost.com/other-nonprofit-media/2023/09/on-cancer-road-a-group-of-southeastern-minnesota-families-ask-if-nitrate-exposure-is-to-blame/, 2023. Accessed: 2023-05-01.

[7] A. Struffert and F. Fernández. Corn fertigation: How much and when? https://blog-crop-news.extension.umn.edu/2018/05/corn-fertigation-how-much-and-when.html, 2018. Accessed: 2023-05-01.

[8] K. Temme. Revolutionary self-fertilizing corn enables better agriculture productivity. https://www.pivotbio.com/blog/revolutionary-self-fertilizing-corn-enables-better-agriculture-productivity, 2018. Accessed: 2023-05-01.

A Appendix

Risk ID	Risk	Reqt	Type	Cause	Mitigation	Likelihood	Consequence
R1	Manufacturing Concerns	F4 F5 F6 F7 F9	Technical	Variability in design vs. build	- Iterate, fail, and update quickly - Model fasteners	3	4
				3D-printing: bad tolerances	- Test prints with low infill - Interface testing	4	3
			Programmatic Schedule	Coordinating machining & 3D-printing	- Discuss early and ID alternate personnel	2	4
R2	Integration Bottlenecks	F3 F4 F5 F6	Schedule	1 system owner for manipulation; external mechanisms delay	- ID alternate owners - Integrate ext. mech. last	4	4
R3	Performance of Inherited Perception Stack	F3 MN3	Technical	Behavior w/ Occlusions	- Confirm performance with past owner - Targeted testing on exceptions	2	2
				Behavior w/ False Positives		2	1
R4	Nitrate Sensor Reliability	F4 F5 F8 MN3	Programmatic Technical	3rd party research org. (IA State) is sensor supplier. Tech. details are proprietary.	- (V1/2) Conduct independent testing on sensor - Maintain communication w/ IA State	3	2
R5	Version Conflicts	F2 F3 MN2	Programmatic Technical	Amiga system vs. Team Desktop	- Work with Docker	3	3
				Perception Library Diffcs.	- Check library "fit" ASAP	1	2
R6	Handling edge-cases in Manipulation	F3 F6 F7 F9	Technical	Hitting singularities when cornstalks are closer to the x-arm	- Feed intermediate joint states before hitting singularities	5	4
R7	Hardware bottlenecks	F4 F5	Technical	Failure of electronic components (external mechanisms)	- Design of a more robust circuit	4	4

Figure 20: Spring 2024 Risk Management Table