

Design, development, testing, and validation of robotic liquid application systems for precision agricultural applications

by

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Abstract

The agricultural production system faces two major environmental issues: the overuse of pesticides and the accumulation of plastic waste. Traditional methods employ large self-propelled sprayers for applying herbicides, insecticides, and fungicides without adequate knowledge of the spatial variability of pests within the field, leading to overuse of pesticides. However, recent advancements in control strategies, including pulse width modulation (PWM) technology combined with artificial intelligence and robotics, enable precise spraying, thereby reducing pesticide use. Also, shifting from plastic mulch to sprayable biodegradable mulch aims to address plastic pollution in agricultural fields and promote sustainable farming practices. While traditional mulching involves laying sheets in the field, sprayable technology is gaining popularity due to its advantages. However, biodegradable mulch's properties and application volume provide a unique challenge, making the commercially available sprayer unsuitable for spraying.

In the first study, a liquid application system was designed, developed, and integrated with an under-canopy rover for row crops. This system includes a tank, diaphragm pump, hollow cone nozzle, boom, and plumbing system. Two booms, each 55 inches in height, were mounted at the rear side of the rover, with each boom equipped with three nozzles and solenoid valves. The control system utilized an STM32 microcontroller, Electronic Control Unit (ECU), and drivers to implement PWM technology. The microcontroller was configured with the main computing platform using micro-ROS. The control system was validated by assessing duty cycle response and pressure variations with different nozzle configurations. The voltage remained in the excitation state for the specified duty cycles, and the system and nozzle pressure remained within $\pm 5\%$ of the target across different duty cycles and nozzle operations. Integration of the liquid application

system with a pest detection system was achieved through a distance-based method using coordinate transformation. The 'tf2' library from ROS was used for this transformation, converting the detection frame from the camera to the world frame and then to the sprayer frame for precise spraying. The results demonstrated an overall effectiveness of 80%, with 100% accuracy in spraying plants infested with aphids. Additionally, 68.82% and 33.66% pesticide reductions were achieved, with pest severity levels of 11.11% and 22.22% compared to uniform whole-rate field spraying. Overall, the system's development and integration facilitated precise detection and spraying, significantly reducing pesticide usage.

In the second study, a liquid application system was designed and developed for spraying biodegradable mulch. This system comprises a double-action positive displacement double diaphragm pump, a strainer, a pressure relief valve, flood jet nozzles, an agitation system, hoses, and fittings. A Sotera double diaphragm pump, capable of delivering a flow rate of 13 gallons per minute (GPM) at 13 PSI, was selected. Quick Turbo Flood Jet nozzles were chosen for their pre-orifice design, which minimizes drift and reduces clogging risk. The spraying system was mounted on the Amiga platform by FARM NG for its modularity and payload capacity. Experiments with various Quick Turbo Flood Jet (QCTF) nozzles identified the QCTF-60 nozzle as optimal for spraying the BioWRAP formulation, delivering 5.59 GPM at 10 PSI pressure and covering a 28-inch swath width. The rover's speed was set to 25 feet per minute to achieve the desired application volume of 4276 GPA. The sprayed BioWRAP formed a consistent layer across different soil types, performing best with higher moisture content and soil densities. The average thickness of the applied layer was 0.022 inches. This developed system will facilitate quick experimentation with the ongoing development of different biodegradable mulch formulations.

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Chapter 1 - Introduction

The global population is projected to reach 9.1 billion by 2050, marking a substantial 30% increase from 2017 (FAO, 2009). This rapid population growth will drive an unprecedented demand for food, necessitating a dramatic increase in agricultural productivity. The challenge is clear: the same land area must yield significantly more food. According to the United Nations Food and Agriculture Organization (FAO), approximately 80% of the projected increase in food production must come from intensifying existing agricultural practices, with only 20% expected from expanding arable land (FAO, 2009).

Aside from the pressing issue of population growth, the agricultural production system is grappling with many other challenges, including labor shortages, climate change, pest and disease management, demographic shifts, and environmental concerns. In the United States, labor shortages lead to approximately 20% of food going unharvested (Gunders, 2012), with the state of Kansas alone suffering losses ranging from \$4.1 billion to \$11.7 billion due to this issue (Ifft et al., 2023). The agricultural workforce is also undergoing significant demographic changes, with a declining population of young laborers and an increasing proportion of elderly workers, raising concerns about the future labor supply for agriculture. This shifting workforce is more technologically inclined and seeks to adopt new technologies to address existing challenges (Bazargani & Deemyad, 2024).

Pest management continues to be a major hurdle for global crop production, with the FAO reporting that 20-40% of global crop loss is due to plant pests and diseases (FAO, 2017). Farmers increasingly turn to integrated pest management (IPM) techniques to combat these losses. IPM is a comprehensive approach that incorporates good agricultural practices, preventive measures, regular pest monitoring, and the strategic application of control methods, including chemical

pesticides, when necessary(Waskom, 1995). The role of pesticides in providing excellent crop protection, increasing crop quantity, and reducing the tillage need is undeniable(Gianessi & Reigner, 2005; Padgitt et al.). Pesticides used in large row crops are much like planting seeds, which means they are an integral part of the process ("Pesticides in Our Food System", 2024).

However, the excessive use of pesticides has raised concerns regarding their toxicity and impact on human health and the environment (Fernandez-Cornejo et al., 2014). There has been a staggering 80% increase in the use of pesticides worldwide from 1990 to 2017, with total expenses amounting to 130.7 billion US dollars (Tostado & Bollmohr, 2022). About 5.6 billion pounds of pesticides are used worldwide, and 1 billion pounds are used in the United States annually(Alavanja, 2009). Despite all of these, the pesticide is not reaching the target area. As a result, it has negative consequences on the environment with chemical runoff, degradation in water quality, and reduced soil fertility(Tudi et al., 2021). Moreover, the use of plastic in agriculture is another matter of environmental concern. Plastics are used in various forms, including mulch films, greenhouse covers, drip irrigation tubes, and silage bags(Baker & Thyngensen, 2021). Plastic mulch has many benefits in agricultural fields, from controlling weeds and insects to increasing soil and air temperature, reducing evaporation, and minimizing soil erosion. Plastic Mulch accounts for about 40% of agricultural plastic film (Sintim & Flury, 2017). Mulch films are one of the major sources of plastic pollution from agriculture(Khalid et al., 2023). These plastics are not biodegradable, leading to accumulation in landfills, stockpiled, burned, or buried in the farmland (Shrestha, 2023). Moreover, the residue remains in the soil with long-term use of Low-Density Polyethylene(LDPE) plastic (Baker & Thyngensen, 2021).

The challenges associated with the agricultural production system are unique in nature. One solution to these problems comes through the increasing adoption of precision agriculture

techniques. Precision agriculture encompasses a variety of farming technologies designed to tackle the spatial and temporal variability present in the field and enhance overall farming efficiency(T. Wang et al., 2023). Artificial intelligence and robotic systems are adding value to precision agriculture activities. Autonomous robotic systems are gaining popularity in the farmland due to their modularity, capability to work in harsh environments and decreased dependency on human labor. The robotic system is an effective tool to overcome challenges concerning labor shortage, pest monitoring and control, demographic change, etc. The agricultural robots are used for multiple tasks in the agriculture field, from land preparation before planting, sowing, planting, plant treatment, harvesting, yield estimation, and phenotyping (Oliveira et al., 2021). The advancements in artificial intelligence technology and its adoption in farm robotics are creating a unique environment in agriculture where manual tasks are being automated and challenging tasks are becoming easier. Substantial cost savings for farmers are predicted with the adoption of robotics in agriculture.

A liquid application system is used in agriculture to apply pesticides for crop protection and fertilizers for nutrient management. Using insecticides for row crops in the United States costs around 1.3 billion dollars(Nansen et al., 2011). The need for the right application at the right place is mandatory to keep this cost in check. The common technologies used for pesticide spraying are large-self-propelled sprayers and pull-behind sprayers. These sprayers carry out the uniform whole rate field spraying (broadcast spraying) without adequate knowledge of the pest severity, resulting in pesticide overuse. The bugs in the plant are small in size and usually reside underneath the leaves, and the point of infestation starts from the bottom of the leaves. Due to this, the localization of pests using a sizeable self-propelled sprayer is complex and challenging. The farmer is manually scouting the pest before deciding on any treatment. A sample of the field is scouted, and decisions

are made. So, there is a need to develop a system for real-time insect identification to make the proper decision for the liquid application system.

The under-canopy rover agricultural robots, which can navigate the row spacing available between the row crops, are gaining popularity. The under-canopy robot is used for various applications, from crop monitoring, cover crop planting, precise weeding, and spraying (Sivakumar et al., 2024). P-AgBot, developed by (Kim et al., 2022), is used to monitor and physically sample the plant. Another under-canopy robot developed by (Mueller-Sim et al., 2017) is used for high-throughput phenotyping. A Time-of-flight vision-based navigation system for under-canopy application was tested for corn/ sorghum fields (Gai et al., 2021). With their small footprints, these under-canopy rovers will help to look at the plants and pests from a closer angle, making detection easier and spraying precise and effective.

There has been a lot of development in the application of robotics in agriculture. However, there has not been an under-canopy rover that can localize pest detection and has the liquid application system to carry out the site-specific application. The developed system will help reduce the need for human labor and environmental concerns associated with the over-spraying of pesticides. Considering the above requirements, the objectives of the first study are to:

1. Design, Develop, and Validate Liquid Application System for Under-Canopy Rover
2. Integrate and Validate Liquid Application System with Pest Detection System for Pesticide Reduction

Another environmental concern with regard to plastic mulch has led to a switch to environmentally friendly biodegradable mulch. Recent developments have focused more on mulch, which is sprayed and termed Spray-on Biodegradable Mulch. Spraying a bio-degradable mulch has a lot of advantages compared to laying the mulch in a sheet, such as no headspace between mulch and soil,

high degradation rate, and use of common spraying technology (Adhikari et al., 2016). However, the properties of formulation in terms of viscosity and the high application volume create a barrier to utilizing the commercially available sprayer for spraying the biodegradable mulch. The application of the current developments of sprayable biodegradable mulch is being done by using a compressed air gun, graduated cylinder, and hand-pump sprayer to carry out the lab scale test (Giaccone et al., 2018; Gloeb et al., 2023; Immirzi et al., 2009). There is a need to develop a spraying system to test the spray-on formulation of biodegradable mulch at a large field scale.

Considering the need as stated above, the objectives of the second study are to:

1. Design a System for testing flowability and atomization of Spray-on BioWRAP (Bioplastic)
2. Design and Implement a Field Spraying System for BioWRAP application and assess its coverage area and properties

Chapter 2 - Design and Development of Spraying System for Under-Canopy Rover and Integration with Computer Vision System

Abstract

Chemical spraying, such as herbicides and insecticides, is essential in any agricultural field for controlling pests, weeds, etc., and ultimately increasing yield. About one-third of agricultural yields rely on the utilization of pesticides. However, around 5.6 billion pounds of pesticides are used worldwide annually, and their effective utilization is merely 1%. The precise application of these chemicals is necessary to reduce negative impacts on the environment and human health. Commonly, large self-propelled sprayers, tractor-mounted sprayers, aerial sprayers, etc., are deployed in the field for uniform application of the pesticides without precise information about the pest infestation. These sprayers do not have information about the pest location and cannot penetrate the crop canopy and reach the target points.

An under-canopy rover, designed to navigate through a 30-inch crop canopy, was equipped with provisions for installing a spraying system, recording sensor data, integrating computer vision, and providing real-time feedback. The designed spraying system consists of a 20-gallon tank, a diaphragm pump, a strainer, a pressure relief valve, a throttle valve, piping, and a boom. The boom has two sections with three nozzles, each spaced 15.75 inches apart. These boom sections have linear actuation capabilities of 7 inches to accommodate different varieties of row crops. The control system includes STM32 microcontroller, an Electronic Control Unit (ECU), and drivers. These components regulate the flow and distribution of chemicals and communicate with each other through the Controller Area Network (CAN 2.0B) communication protocol. The pressure, flow, and water level sensors were connected to STM and used to validate the system performance.

The main computing platform NVIDIA Orin acts as a micro-ROS agent, and STM32 as a micro-ROS client for configuring the spraying system. Duty cycle validation responses with different pulse width modulation (PWM) showed that voltage remains in an excitation state for the defined periods. Laboratory tests on individual nozzle pressure confirmed that pressure remained within $\pm 5\%$ of the desired settings.

The integration of pest detection with the spraying system was a crucial step in achieving precision spraying. A distance-based spraying method, relying on coordinate transformation, was employed. The transformation of 3D coordinates from camera detection to the sprayer was performed using the 'tf2' library in ROS. This process allowed for the localization of the pest position and the subsequent coordinate transformation from the detection frame to the world frame and then to the sprayer frame. This integration ensures that the spraying system targets only the areas with pest infestation, thereby reducing pesticide usage and minimizing environmental impact.

The integrated system achieved 100% accuracy in autonomously spraying plants infested with aphids. Additionally, the sprayer achieved an accuracy of 46.66% when spraying the plant immediately before an aphid-infested plant and 93% accuracy for the plant immediately after. The overall effectiveness of the integration was determined to be 80%. Furthermore, pesticide usage was reduced by 33.66% and 68.82%, with pest severity of 22.22% and 11.11%, respectively, compared to spraying without integration.

Introduction

Pesticides, including herbicides, insecticides, and fungicides, have increased crop yield and enhanced crop quality by managing pest infestation (Fernandez-Cornejo et al., 2014). One-third of the agricultural yield depends on pesticide use; without it, there would be a 78% loss in food production, a 54% loss in vegetable production, and a 32% loss in cereal production (Tudi et al., 2021). However, the widespread application of pesticides has led to growing worries about their potential toxicity and adverse effects on human health and the environment (Fernandez-Cornejo et al., 2014). The wind blows away the pesticides applied to the plant, termed pesticide drift. The drift can even travel up to 621 miles and negatively affects the health of farmers and the environment (Tostado & Bollmohr, 2022). The amount of money spent on pesticides by a farmer is a lot, but despite this, a large quantity of these chemicals never reaches the targeted weeds or pests with conventional sprayers (Ahmad et al., 2021). Despite chemical and non-chemical controls, around 37% of all crops are lost annually to pests, with 13% to insects, 12% to pathogens, and 12% to weeds (Mandava & Pimentel, 2018). Using a self-propelled sprayer is a common practice for spraying pesticides in agriculture. However, the lack of knowledge regarding pest severity leads to uniform whole-rate field spraying, and problems associated with it are inadequate coverage, untimely application, and off-target spray (Pokharel, 2021).

To overcome the challenges associated with the existing mechanism of pesticide spraying using a self-propelled sprayer, drone, or UAV, a proposal has been made to use a mobile pesticide spraying robot with targeted spraying based on pest localization (Meshram et al., 2022). Autonomous under-canopy robots, capable of operating in narrow spaces of approximately 30 inches, offer a wide range of applications from precise planting to spraying and weeding. These tasks are not feasible with traditional tractors and drones (Sivakumar et al., 2024). Under canopy robots have been

developed for row crop sampling, field scouting, plant phenotyping, etc. (Mueller-Sim et al., 2017; Sivakumar et al., 2024; Sprague & Evans, 2023).

Sorghum (*Sorghum bicolor* L . Moench), a row crop cultivated on 5.88 million acres in the US, is a significant economic crop valued at 1 billion dollars in 2020 and one of Kansas's top crops (USDA, 2021). Sorghum as a crop has both nutritional as well as environmental benefits. The best row spacing for sorghum was 30 inches as it was good in terms of light interception and enough water volume in soil for growth during drought (Bean, 2019). However, these plants are susceptible to pest insects, which cause significant losses every year. The sorghum aphid (*Melanaphis sorghi*) is a notable invasive pest that feeds on sorghum in the US. These aphids caused 50% to 100% yield loss in 2013 and 2014 (Le, 2023). The sampling method for sorghum aphids remains manual and labor-intensive. The entomology department at Kansas State University has developed procedures for field scouting of aphids. These procedures require manually counting the number of aphids and spraying insecticide once a threshold value is reached (McCornack et al., 2023). 40 number of aphids per leaf is defined as the economic threshold for sorghum aphids (Gordy et al., 2019). This process is cumbersome for both detecting and treating infested plants.

The advancement in computer vision technology has made pest detection and monitoring efficient and faster. This technology helps automate the tasks that the human visual system can perform in two phases: feature extraction and classification. With the advancement in deep learning, neural networks such as artificial neural networks (ANN) automatically extract the features from the dataset without a specific logic and build a robust model (Wäldchen & Mäder, 2018). This method has been applied for the feature extraction of sugarcane aphids in sorghum plants, and

convolutional neural networks (CNN) have been trained for real-time detection of the aphid clusters (C. Wang et al., 2023).

Precision spraying is a technique that minimizes pesticide wastage by adjusting the pesticide application based on the specific field characteristics (Tona et al., 2018). Precise spraying comes with a proper selection of the components of the application technology and seamless integration with the machine vision system. In sprayers equipped with conventional flow-based systems, variations in ground speed are compensated for by modifying the spray pressure to regulate the liquid flow rate. The challenge arises when the spray pressure exceeds the chosen nozzle's limited operational range, leading to spray quality irregularities, including droplet size and pattern. Pulse width modulation (PWM) technology was applied for agricultural sprayers to resolve issues with pressure fluctuations. Unlike traditional systems, PWM does not depend on spray pressure adjustments to control the flow rate in response to changes in ground speed. In PWM systems, flow rate adjustments are achieved by altering the intermittent cycling (duty cycle) of electronically operated solenoid valves while maintaining a constant pressure across the entire boom (Virk & Meena, 2022).

Robotic Operating System (ROS) is a middleware consisting of software libraries and tools for developing robotic applications. ROS 2 is the second generation of ROS, which uses a communication system based on Data Distribution Service (DDS). Its flexible transport configuration makes DDS suitable for real-time systems use (Cui et al., 2020). ROS 2 breaks down the complex system into nodes. An executable in ROS 2 is a node responsible for single or modular purposes, such as controlling the wheel, motors, etc. ROS utilizes different communication patterns for the nodes, mainly topics, services, and actions. Topics are the asynchronous message-passing framework, which helps to exchange messages between nodes in publisher subscriber

format, facilitating the system introspection. Services use the request-response style for communication between nodes. Actions are usually used for the long-running task and use asynchronous communication interfaces. The functionality of action is similar to services. However, they can be canceled during execution (Macenski et al., 2022). Micro-ROS allows a microcontroller to access all core concepts of ROS (Li et al., 2022). Micro-ROS supports various microcontrollers and open-source real-time operating systems such as FreeRTOS, Zephyr, etc. (Belsare et al., 2023).

The computer vision system detects pests, and spraying has to be done on the correct plant. This is achieved by distance-based spraying using coordinate transformation. The distance-based spraying method was utilized to detect the weeds and precisely spray on them (Nasir et al., 2023). Coordinate transformation helps to track the position of the robot's different sensors and objects in the environment. It also helps coordinate data between multiple models (Newman, 2017). The coordinate transformation is achieved by translating and rotating the coordinate frames. The affine or homogenous transformation matrix is the basis for the coordinate transformation. In the case of ROS, it handles transformations using TransForm version2 ('tf2') library. In the system, any node can broadcast or listen to the transforms to change from one frame to another. For a moving robot, the transformation has to be dynamic, which means it changes with time. A proper description of the robot is required for dynamic transformations. Each robot component must be defined, and a Unified Robot Description Format (URDF) file must be generated. URDF is composed of links and joints. Links are the individual components of the robot, and joints are the relationships between links in the parent-child tree structure. The joint can be fixed, revolute, continuous, or sliding. The robot state publisher node in ROS takes the URDF file and broadcasts the transforms to all other nodes using the topic `robot_description`. It also broadcasts `tf` (non-fixed joint

transforms) and `tf_static` (fixed joint transforms). For the dynamic transformation, the robot state publisher node subscribes to a topic called `joint_states`. The transformation takes place from the local frame to the world frame and back to the local frame (Foote, 2013; Newans, 2024).

Progress and development have been made in precise liquid application systems for agricultural applications. An autonomous grapevine selective spraying modular agricultural robot was developed, which could treat 85% to 95% of the disease area and reduce the use of pesticides by about 65% to 85% (Oberti et al., 2013). A robotic solution was developed to detect the tobacco leaves and carry distance-based spraying by synchronizing the image acquisition, object detection, and spraying in real time (Nasir et al., 2023). An orchard sprayer was developed to spray the specified trees precisely by integrating machine vision with a sprayer control system (Asaei et al., 2019). A precision variable rate spraying robot was built to spray pesticide on fruit trees based on the region of interest detected by the LIDAR sensor. The savings on pesticides compared to traditional spraying was 32.46% (Liu et al., 2022). SAM bot was developed by the University of California, Los Angeles, to detect under-canopy multi-class weeds using Deep-CNN, and the right amount of herbicide was sprayed on the weeds (Du et al., 2022). However, with all this development, an autonomous under-canopy rover for row crops carrying out precise pesticide spraying has not existed. A previous prototype of the under-canopy developed at Fusing Automation and Robotics in Ag Machine System (FARMS) Lab at K-State did the initial development of the spraying system and testing for coverage area and penetration in row crops (Pokharel, 2021). This version of the under-canopy rover can navigate through a row of sorghum crops, detect aphids in real-time, and trigger the sprayer to spray on the infected plants. This paper mainly focuses on developing a spraying system for an under-canopy robotic platform and its integration with a pest detection system.

Material and Methods

Rover Description

A 4-wheel drive platform with skid steering capabilities was developed. The design criteria set was a rover capable of safely navigating in row crops with 30 inches of row spacing and the possibility of adding a sprayer and other attachments. The modified design measures 60 inches in length, 21 inches in width, and 58 inches in height. The wheels were driven by an independent 24V, 450 W brushless DC worm gear motor ATO-GEAR-W450 from ATO with a 1:20 gear ratio. These motors can deliver a rated torque of 1.07 ft-lbs and have Hall effect encoders to get the position and speed of the rover. Each brushless DC motor was controlled by odrive S1 motor controllers, which support 12-48 V operation at 40 A of continuous current and can be controlled over a Controller Area Network (CAN). The wheel was attached to the motor shaft with the hub, which was designed and fabricated in-house. The rover houses two 24V, 60 Ah Dakota Lithium-Ion batteries connected in parallel, providing a total current rating of 120 Ah. These batteries power all the sub-systems of the rover. The rover's body was built using an extruded metal frame and aluminum sheet to make it lightweight and increase modularity. The extruded metal frame supports the electric box with a computing platform, cameras, tank, and sprayer boom. The electric circuit for the lower-level control was housed inside the rover's chassis. The rover also possesses hall encoders, an Inertial Measurement Unit (IMU), and a Global Positioning System (GPS) to determine the localized position. The inertial measurement unit IMU (3DMCV7-AHRS) from Microstrain has accelerometers, gyroscopes, and magnetometers. The auto-adaptive Extended Kalman Filter (EKF) in IMU helps to localize the robot's position. The navigation electric box houses NVIDIA Orin (8-core, ARM processor, 32-GB RAM, GPU), which was used as the

computational backbone for the rover to suffice the need for real-time processing, and ROS-2 serves as the middleware to integrate and ensure seamless communication among subsystems.

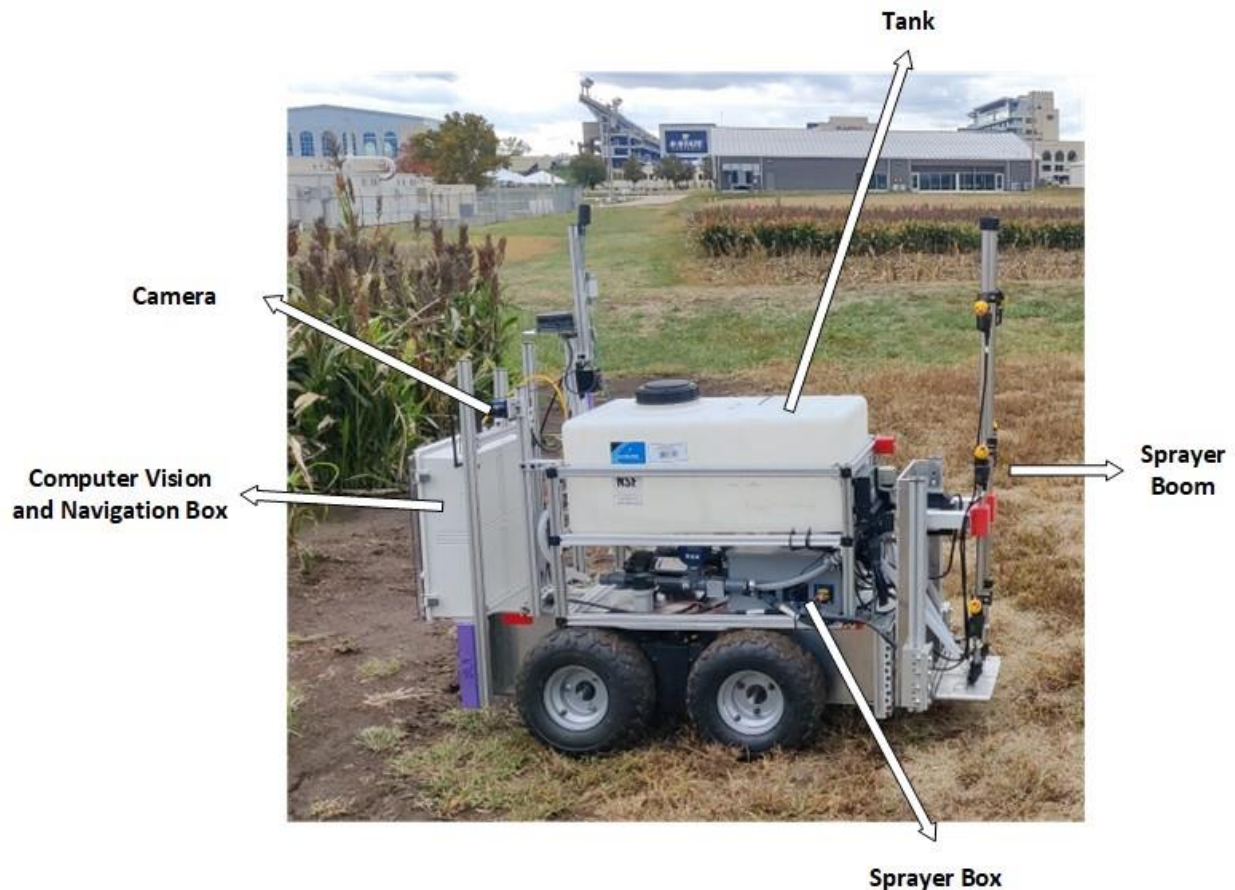


Figure 2.1 Different Subsystems of Under Canopy Rover

Computer Vision System

The images of the sugarcane aphids in sorghum plants were collected by colleagues from the Department of Entomology, Kansas State University. Training different segmentation and detection models was done to optimize aphid detection and quantification and to satisfy the need for real-time processing. Among the various models trained, the Real-Time Detection Transformer (RT-DETR) model demonstrated superior performance in detecting pest incidences compared to other models (segmentation and detection) with 20-30 frames per seconds of inference time (Zhao

et al., 2024). The Isaac ROS GPU accelerated package from NVIDIA was used to compute an efficient image processing pipeline and deploy the models.

Out of the various cameras tested, the Luxnois Arducam ar0234 camera was selected for the pest detection based on minimal focal distance, flexibility in changing the resolution, global shutter, and firm factor. The camera uses a 2.3 MP resolution global shutter with a maximum frame rate of 60 FPS. The camera was mounted on each side of the rover with the help of the t-slotted framing and 3D-printed mount. The camera mount was made reconfigurable to adjust the camera's angle in the rover. The aphids in sorghum plants usually reside beneath the leaves (Brown et al., 2015). The camera position and angle were optimized for properly viewing the aphids in the sorghum plant. The arducam camera was connected to the Oak-FFC 4P PoE baseboard and then to Orin.

Spraying System

The major components of the agricultural spraying system include a tank, pump, pressure gauge, flow control assembly, agitation, and distribution system. The spraying pressure can extend from 0 PSI to beyond 300 PSI, while application rates can span from under 1 to more than 100 gallons per acre (GPA). The spray system for diaphragm pumps was like piston pumps (Hofman, 2018). The rover spraying system consists of a 20-gallon Ace Roto-Mold NSF-approved rectangular applicator tank made of polyethylene plastic with a size of 28 inches x 14 inches x 12 inches. This tank structure allows easy filling and draining and is made from corrosion-resistant materials. The pump is the main component of the spraying system, and the capacity should be enough to have a flow of nozzles at a specified pressure to guarantee even and consistent distribution and agitation (Ozkan & Womac, 2016). The pump capacity should be 20% greater than the most significant volume required by the nozzle to account for agitation requirements and losses due to pump wear. A diaphragm pump was selected for the application as it maintains constant pressure throughout

spraying and does not depend upon the flow variation r (Grisso, 2020). Delavan 5850-111E Power FLO electric diaphragm pump with a maximum rated pressure of 60 PSI and flow limit of 5 GPM was used for the liquid application system. The pump runs on 12V and is suitable for low-pressure spray applications. The pump has viton valves and a santoprene diaphragm, making it corrosion-resistant. The pump's inlet and outlet port sizes were $\frac{3}{4}$ and $\frac{1}{2}$ inches. A T-line strainer AA122- $\frac{3}{4}$ -PP50 with a mesh size of 50 from Teejet Technologies and $\frac{3}{4}$ inches ball valve were installed before the pump to keep the foreign debris out of the system and to control the flow from the tank to the pump.

The pump capacity for the application was determined using (Grisso, 2020)

$$\text{Pump Requirements (GPM)} = \left\{ \begin{array}{l} \text{Boom Requirements (GPM)} + \\ \text{Agitation Requirements (GPM)} + \\ \text{Self Cleaning Strainers (GPM)} + \\ \text{Other Accessories (GPM)} + \\ 1 \text{ (GPM)} \end{array} \right\} \times 1.2$$

Where:

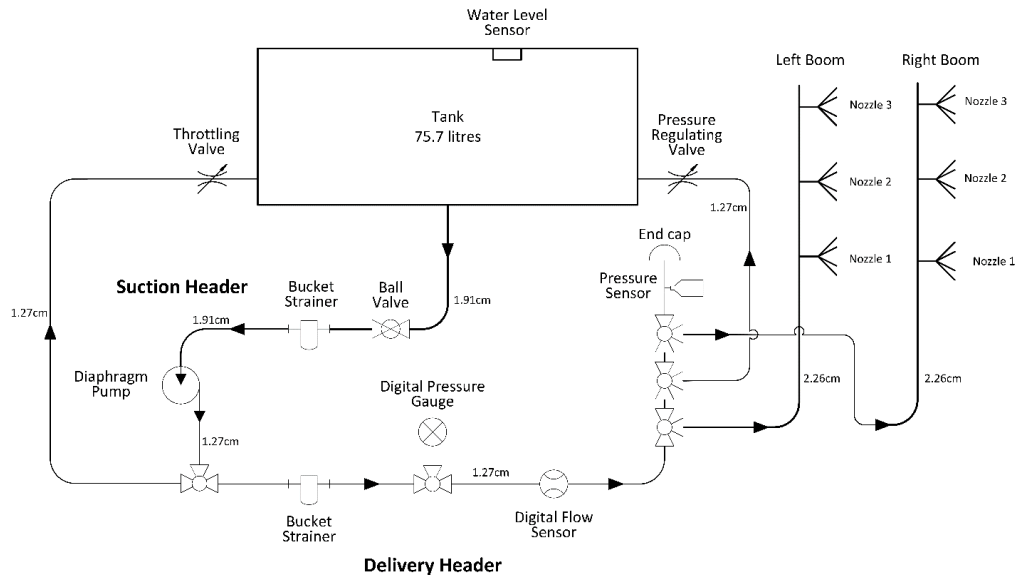
Boom Requirements = Number of Nozzles $\times$ Flow Discharge = 0.102 GPM

Agitation Requirements = (5-10) % of tank capacity = 1 GPM (20 gallons tank capacity/ 5% considered)

No Self Cleaning and Other Accessories

Pump Requirements = 2.52 GPM

Considering the need for additional flow requirements in the future, a Delavan 5850-111E Power FLO pump with a flow rate of 3.2 GPM at 40 PSI was selected for the application.



Hydraulics Diagram

Figure 2.2 Hydraulic Circuit Diagram for Spraying System

On the delivery side, the pump was connected to a three-way connector. One side was connected to the tank with a throttling valve, and the other to the main delivery header. The delivery header comprises an $\frac{1}{2}$ inch AA122- $\frac{1}{2}$ -PP16 T-strainer of 16 mesh from Teejet Technologies to protect the nozzle from clogging. A digital pressure gauge with a plastic case and 304 stainless steel bottom connection with $\frac{1}{4}$ NPT male connection was used to measure the pressure. The pressure gauge installed can handle pressure from 0 to 100 PSI, which is adequate for the application. During the validation test, the pressure gauge was also used to calibrate the pressure sensors installed on the main delivery header and each solenoid. The $\frac{1}{2}$ inch gravity liquid flow sensor measures the amount of insecticide applied as well as the flow rate of the system. This helps measure the amount of insecticides applied during spraying. The non-return valve in delivery line also helps maintain pressure at the boom after spraying. The main delivery header is attached to the two booms with the help of the 90-degree connector at the bottom, and the diameter of each boom was 0.89 inches. The boom was made of stainless steel to prevent corrosion and provide

better stability. The boom mounting for a robotic platform was designed and fabricated in-house. The mounting was made of aluminum sheet to make it lightweight. A 3D-printed sleeve was used to hold the boom in the correct position. The distance between the left and right boom was 6 inches. The spraying boom consists of three nozzles, with the distance between each nozzle being 40 inches. Each nozzle has a solenoid valve to regulate the nozzle flow based on the selected duty cycle. The 12V e-chemsaver (115880) solenoid valve from Teejet Technologies provides individual nozzle control (ON/OFF capabilities). The valve was equipped with a diaphragm check valve, which is normally closed and opens when the solenoid is energized.



Figure 2.3 CAD Design (Left) and Real Boom Mount on Under Canopy Rover (Right)

The nozzle is an essential component of the spraying system. The nozzle helps to determine the flow rate, atomizes the mixture, and distributes these droplets in a particular pattern. Proper selection of nozzles was imperative for the spraying system design. TXVS-1 stainless steel cone jet visible hollow cone spray tip from Teejet Technologies with a spray angle of 80 degrees was used as the nozzle. This nozzle was best suited for the directed spraying of insecticides. The nozzle

has a flow rate of 0.017 GPM at 40 PSI pressure. The sprayer boom was equipped with a linear actuation capability of 7 inches with a Linak (LA 25) actuator. The pressure sensor (M32JM-000105-100PG) from TE Connectivity was used in the delivery header to ensure the consistency of the pressure while the liquid was being delivered. A 1/2-inch pressure regulating valve (23120) from Teejet Technologies was connected from the delivery head to the tank to maintain and adjust line pressure at the different operating ranges. Waterproof ultrasonic sensor (SEN 0311) from DF robot was used to measure the liquid level in the tank. The ultrasonic sensor has a detection range from 1.18 to 177 inches, which will help measure the tank level with a total height of 12 inches.



Figure 2.4 Nozzle Spraying

Hardware Architecture of Spraying System

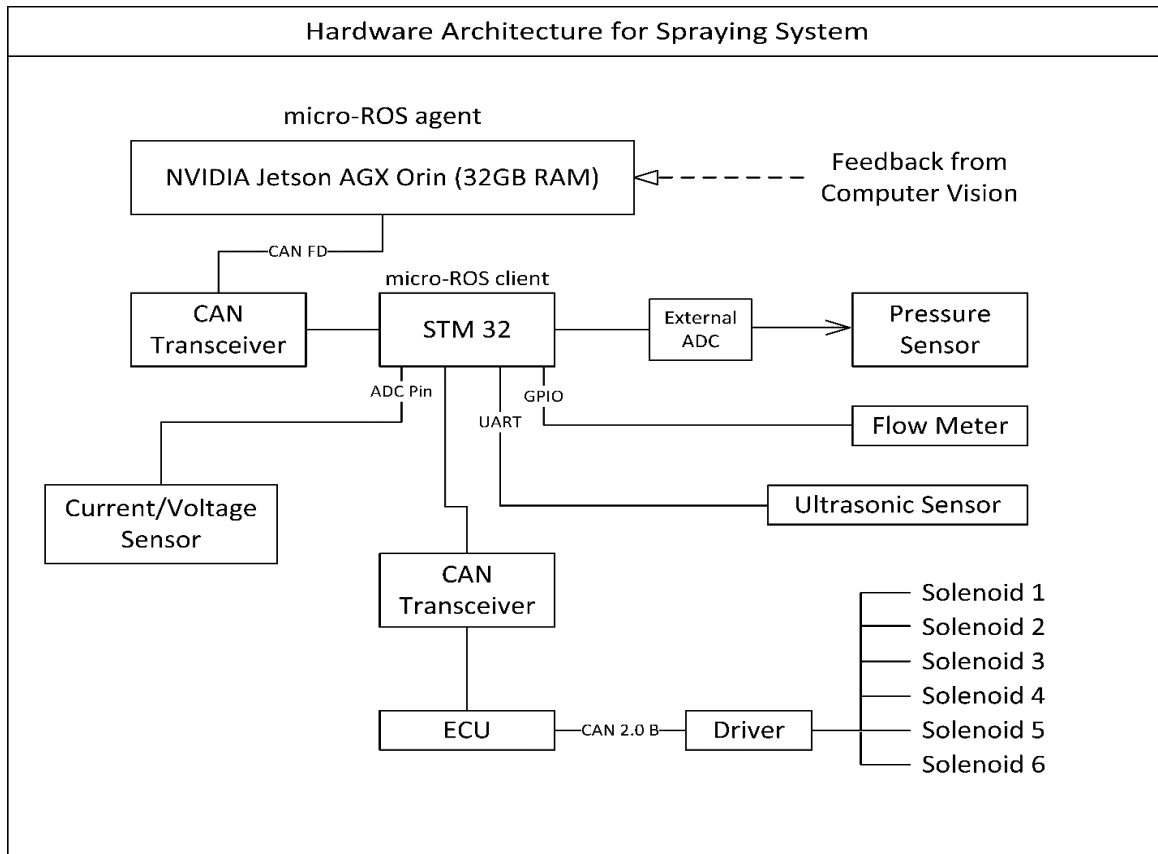


Figure 2.5 Hardware Architecture of Spraying System

NVIDIA Jetson AGX Orin is the main computing platform in the under-canopy rover. It is a compact, fan-less embedded AI system that can do real-time object detection, expedited data transmittance, and has the rugged elemental features that bring the whole AI application to the edge. It has an 8-core ARM v8.2 64-bit CPU processor with NVIDIA Ampere architecture. The vision system was deployed in the Orin to detect the aphids in the sorghum plant and provide feedback to the spraying system. The Orin acts as the micro-ROS agent. Given the physical distance between the sprayer sensors and the rover's main computer, an NVIDIA Jetson AGX Orin, a microcontroller, was decided to place near the sensors to avoid signal losses and long wiring. STM32G4 from ST Microelectronics was used as a microcontroller with its Arm®

Cortex®-M4 at 170MHz) in the LQFP64 package, featuring 512Kbytes of Flash memory and 32Kbytes of SRAM, which makes it suitable for configuring the spraying system. Moreover, this board supports micro-ROS to run on top of it and CAN communication. STM32 acts as a micro-ROS Client, which houses ROS nodes with the Jetson Orin, allowing seamless integration with the ROS 2 system running on the main computer. CAN Flexible Data Rate (CAN FD) was chosen as the transport layer between the microcontroller and the Jetson Orin. CAN transceiver was used between Orin and STM to support CAN FD Communication.

STM32 interfaces with the solenoid drivers and sensors of the spraying system. A 24 V supply from the battery was taken as the power source for the sprayer control system. A DC-to-DC buck converter (24 V to 12V) was used to decrease the voltage to 12V. The 12 V input was supplied to the pump via relay. The relay was used to control the pump operation based on the signal received from the microcontroller. The solid-state relay from Schneider Electric (861SSR115-DD) was used to handle the current up to 20 A. Teejet Technologies Dynajet Interface module (78-05136) Electronic Control Unit (ECU) serves as the primary hub on the sprayer, connecting and exchanging signals with different components of the spraying system. ECU was powered by a 12 V supply from the buck converter. CAN transceiver was used between the microcontroller and ECU to support CAN communication. ECU supports CAN 2.0 B communication protocol with 29-bit(extended) identifiers. The duty cycle and individual nozzle control command can be set in ECU to activate the solenoids. Dynajet HF Driver (78-05124) module from Teejet Technologies provides power and transmits PWM commands to the individual solenoid valves from ECU. ECU sends commands to the driver and activates the solenoid based on the input duty cycle and nozzle number. A 120 Ohm terminating resistor was available in the driver to establish the CAN communication.

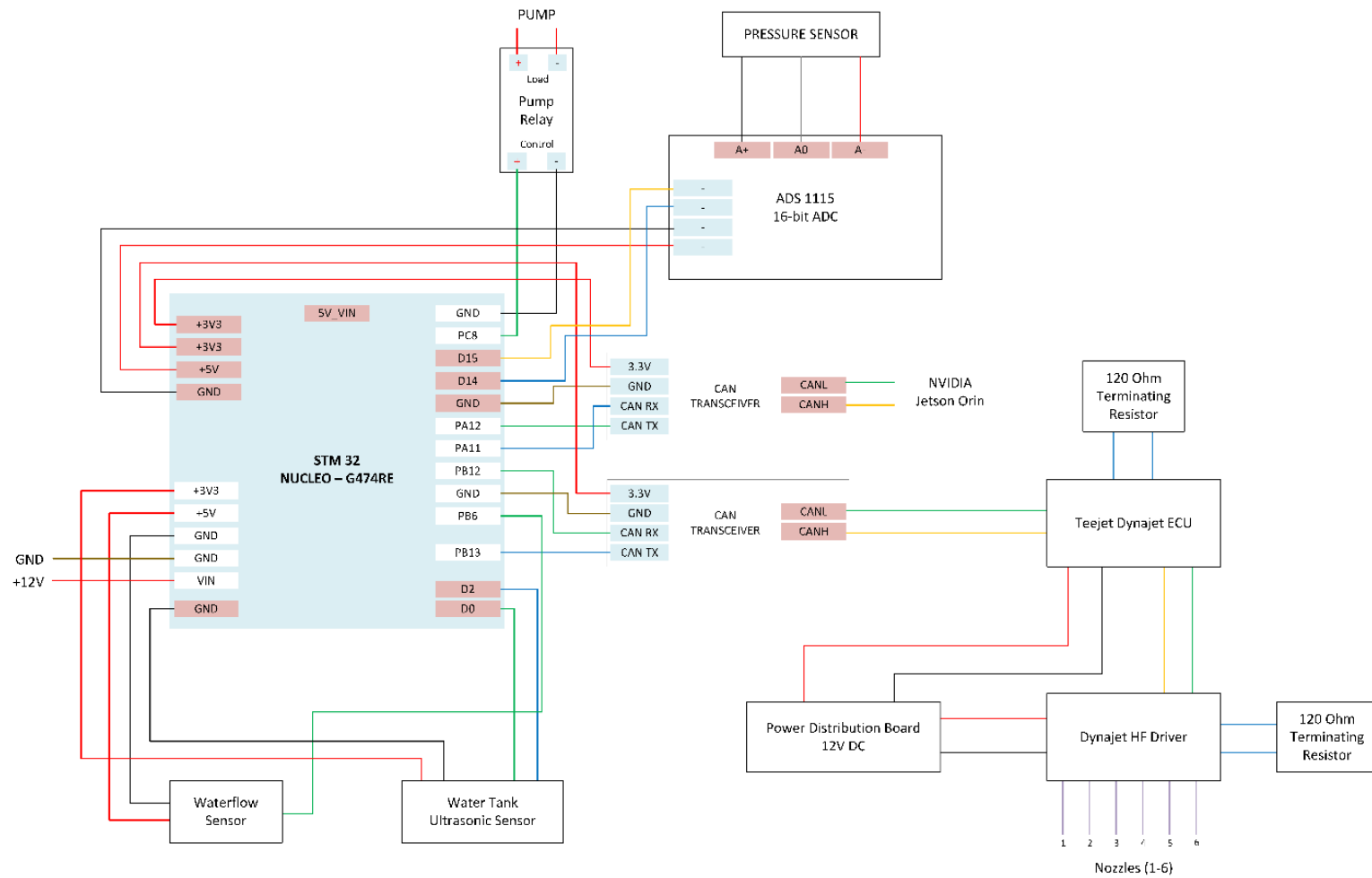


Figure 2.6 Electrical Circuit Diagram of Spraying System

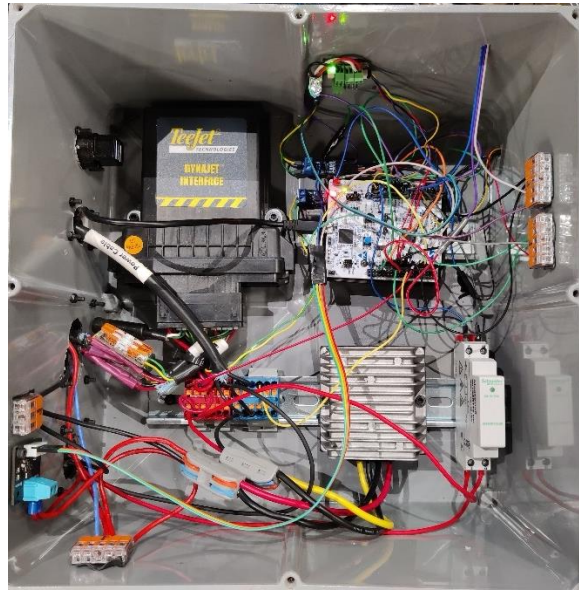


Figure 2.7 Sprayer Electrical Box

Pressure sensors, flow meters, and water level sensors are required to ensure the proper functioning and evaluation of the spraying system. The pressure sensor was configured with STM with the help of analog-to-digital converter ADS 1115 (16-bit precision). The ADS 1115 allows four sensors to connect at the same time. Inter-Integrated Circuit(I2C) was used as a connection protocol between STM and ADC. The continuous monitoring of spraying pressure becomes crucial to evaluate the performance of the spraying. The pressure sensor data was sampled at a frequency of 100 Hz. The set pressure for the sprayer operation was 40 PSI. The water flow and water level sensors (ultrasonic sensors) were configured with STM32 with the GPIO (General Purpose Input/Output) pin and universal asynchronous receiver/transmitter (UART) protocol, respectively. The flow sensor measures the NPN pulse signal to determine the flow of the liquid. A liter of liquid flowing through the sensor is equivalent to 150 pulses. The water level sensor determines the tank's water level by measuring the time lapses between sending and receiving the electronic pulse. The number of pulse signals received was converted to the amount of liquid flow. The sampling frequency for both flow and level sensors was 100 Hz. All the sensors were calibrated before use.

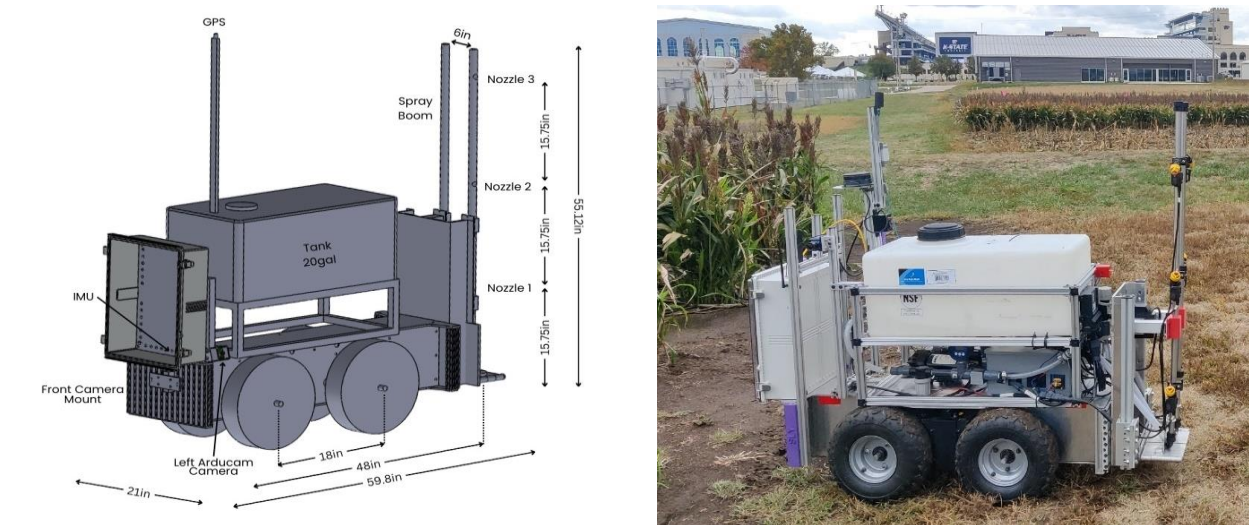


Figure 2.8 CAD Model (Left) and Under-Canopy Robotic Spraying System (Right)
Software Architecture of Spraying System

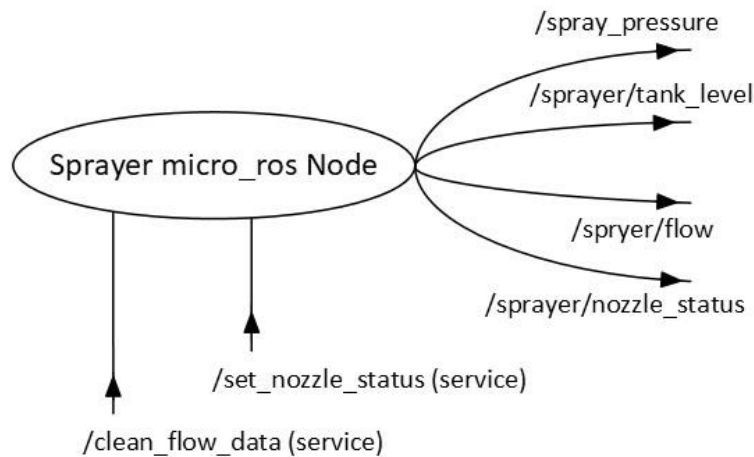


Figure 2.9 Software Architecture of Spraying System

The Sprayer micro_ros node was the main governing node for the sprayer operation. Micro-ROS humble was installed in the STM with Zephyr RTOS as the operating system. This node was used to send the duty cycle and PWM commands to activate the solenoids. Teejet documentation for Dynajet ECU was used as a reference to send the commands. The message to Dynajet ECU was

sent using CAN 2.0 B communication protocol with 29-bit extended identifier at a bit rate of 250,000 bits/sec. The first byte in this message's 8-byte data packet was the message identifier. The message identifier for 'Set Target PWM' and 'Send Extended Boom Status' was used to command the target PWM and activate the individual nozzle respectively. The set nozzle status service sent these commands and activated the spraying system. In the set nozzle status service, the entire left boom was treated as '0' and the right boom as '1' as systemic spraying was carried out instead of contact spraying based on the research carried out by colleagues from the Department of Entomology. The node also publishes the data from pressure, flow, and water level sensors with different individual topics. The sprayer nozzle status gives information about the activation of the boom during the spraying.

The clear flow data service was used during the experiment to clear the value of flow sensor after each experimental run.

Sensor Calibration

The calibration jar from Teejet Technologies was used to calibrate the flow sensor. The pump was activated, and water was collected in the calibration jar. The calibration jar was allowed to settle down until the water was stable before measuring the data. The data was collected for eight experimental runs and used to calibrate the sensor. The actual reading was noted from the calibration jar, and the sensor reading was observed from the foxglove.



Figure 2.10 Calibration Jar

Similarly, the water level sensor was calibrated by changing the volume of water and taking the reference of pre-calibrated marking in the water tank. Five different values were taken to calibrate the water level sensor, and the sensor reading was noted from the foxglove. Both flow and water level sensors showed a linear trend. The slope and intercept values were used as a parameter to calibrate the sensor.

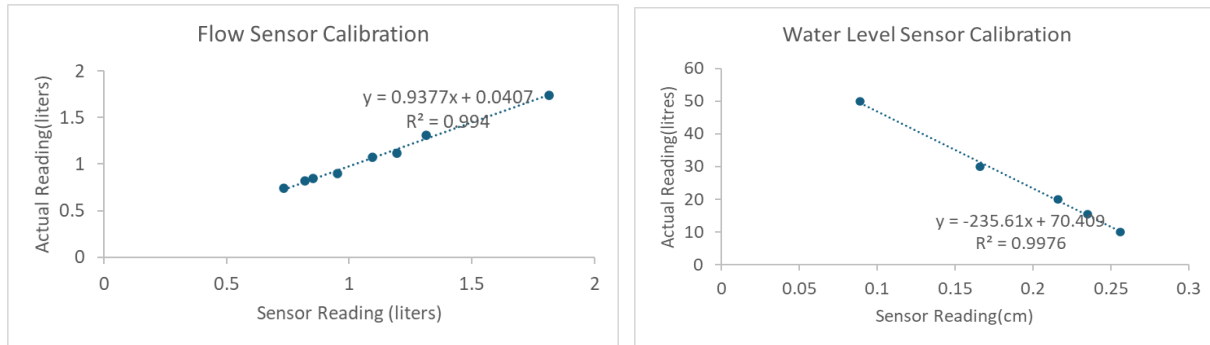


Figure 2.11 Graph for Flow and Water Level Sensor Calibration

The pressure sensors were calibrated using the reference from the digital pressure gauge installed on the line.

Sprayer System Validation Experiment

The spraying system was validated based on the response to the duty cycle and the pressure variation with multiple nozzle operations. The command for duty cycle and individual nozzle activation was sent from the laptop's serial terminal to Arduino UNO. Arduino UNO microcontroller was connected to the ECU using the CAN controller/ transceiver (MCP 2515), which converts the message from the serial peripheral interface (SPI) to CAN 2.0B. The power supply was used to supply 12V to Teejet ECU and the driver. On the other hand, pressure sensors were connected to the STM 32 microcontroller using ADS 1115 (analog to digital converter). Four pressure sensors were used to validate pressure variations. One pressure sensor was connected to

The diagram illustrates the hardware architecture for the microROS-based fuel injection system. The components and their connections are as follows:

- Power Supply:** Provides +12V and GND. The +12V line is connected to the Teejet ECU and the Teejet Driver. The GND line is connected to the Teejet ECU, the Teejet Driver, and the ADS 1115.
- Teejet ECU:** Receives +12V power and communicates with the Teejet Driver via a CAN 2.0 B bus. It is also connected to the CAN Controller + Transceiver via a CAN 2.0 B bus.
- Teejet Driver:** Receives +12V power and controls the three solenoids. It communicates with the Teejet ECU via a CAN 2.0 B bus. It is also connected to the Analog Discovery 2 via a 120 Ohm Terminating Resistor.
- CAN Controller + Transceiver:** Connected to the Teejet ECU and the Arduino UNO via a CAN 2.0 B bus. It is also connected to the Laptop via a USB connection.
- Arduino UNO:** Connected to the CAN Controller + Transceiver via a USB connection. It is also connected to the Laptop via a USB connection.
- Analog Discovery 2:** Connected to the Teejet Driver via a 120 Ohm Terminating Resistor. It is connected to the ADS 1115 via a 120 Ohm Terminating Resistor. It is also connected to the Laptop via a USB connection.
- ADS 1115 External ADC:** Receives +12V power and GND. It is connected to the Teejet Driver via a 120 Ohm Terminating Resistor. It is connected to the STM32 via I2C (SDA, SCL) and provides a 5V output.
- STM32:** Connected to the ADS 1115 via I2C. It is connected to the Laptop via a USB connection.
- Sensors and Actuators:**
 - Nozzle 1 Solenoid, Nozzle 2 Solenoid, Nozzle 3 Solenoid:** Controlled by the Teejet Driver.
 - Pressure Sensor (Nozzle 1, Nozzle 2, Nozzle 3):** Connected to the ADS 1115 via green lines.
 - System Pressure Sensor:** Connected to the ADS 1115 via a green line.

Distance-based Spraying Method

The distance-based spraying method integrates pest detection with the spraying subsystem. The idea was to transform the coordinates from the camera detection frame to the spraying nozzle frame for precise spraying. The ‘tf2’ package in ROS helps to track multiple coordinate frames, which in turn helps to localize the position of different components of the robot and the object in the world (Foote, 2013).

In the under-canopy rover, as depicted in Fig.2.7, the arducam camera for pest detection was positioned at the front of the rover, and the spraying boom, along with the nozzles, were at the rear end of the rover. The first step for transformation in moving objects was to generate a URDF file from the CAD model. The process starts by defining the base link of the rover. The base link for the rover was defined at the center of the rover, aligning with the plane of the wheels touching the ground. As per the convention for each link, the X-coordinate was defined towards the forward direction of the robot, the Y-coordinate towards the outside of the rover, and the Z-coordinate upwards from the rover. The base link was defined as the parent link of the rover, and the individual wheel link, navigation camera link, IMU mount link, GPS link, individual arducam camera mount link, and sprayer link were child links to the base link, as shown in Fig. 1.15. The left and right camera arducam camera link was made child link to the arducam camera mount link, and the imu link was made child link to the imu mount link. The axes were defined through a point on each link. Also, the coordinate axis for each link was defined on the point as shown in Fig. 2.12.

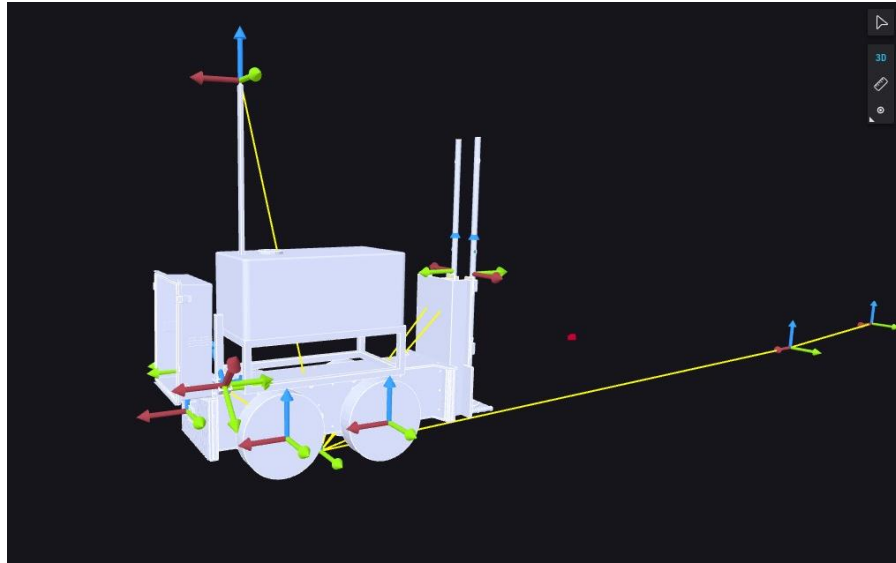


Figure 2.13 Coordinate Frames of Rover

URDF (Unified Robotics Description Format) Exporter plugin in SolidWorks was used to export the URDF from the Computer Aided Design (CAD) model. The joint name, reference coordinate system, reference axis, and joint type identity were defined for each link. The joint type for the wheel was made continuous as it has 360 degrees of rotation, and the arducam camera link was made a revolute joint with a fixed degree of movement. All other joints were defined as fixed. The exporter configures the properties of each defined joint, such as position and orientation, along with the axis. The properties of mass and moment of inertia for the joint were also automatically configured. Finally, the URDF and meshes from the CAD model were exported in URDF and STL file format, respectively.

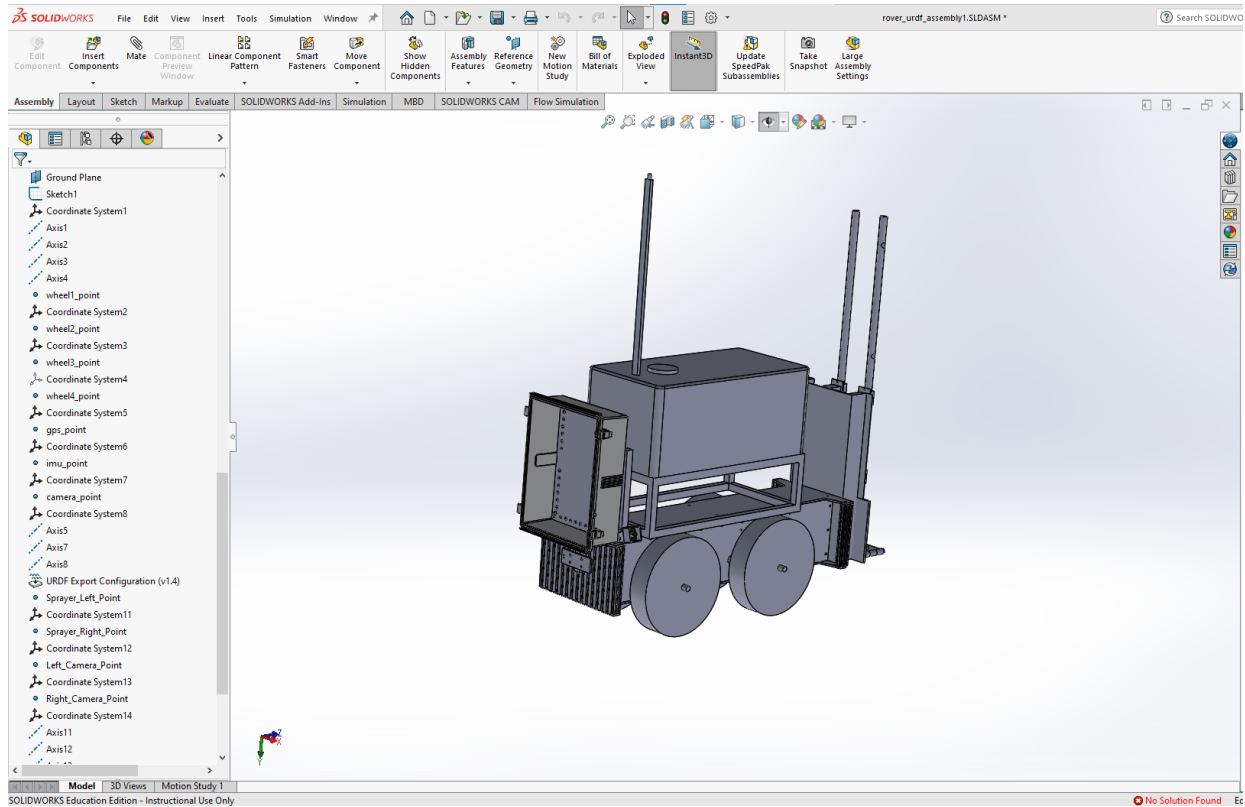


Figure 2.14 SolidWorks URDF Exporter

The robot state publisher node takes the URDF and broadcasts the transforms using the topics `tf`, `tf_static`, and `robot_description`. The skid steer controller node serves as the rover's primary driving node. It subscribes to the `cmd-vel` topic from the joystick node and drives the four independent motor controllers. The imu node gathers information on the rover's position, linear velocity, and angular rate and publishes it to the robot localization node (Extended Kalman Filter node). The Extended Kalman Filter (EKF) node subscribes to the information from the skid steer controller node and imu node using `vel` and `imu_data` topics. The Kalman filter localizes the robot's position by fusing the information from both nodes. Finally, the EKF node publishes the `tf`, `tf static`, and the odometry frame.

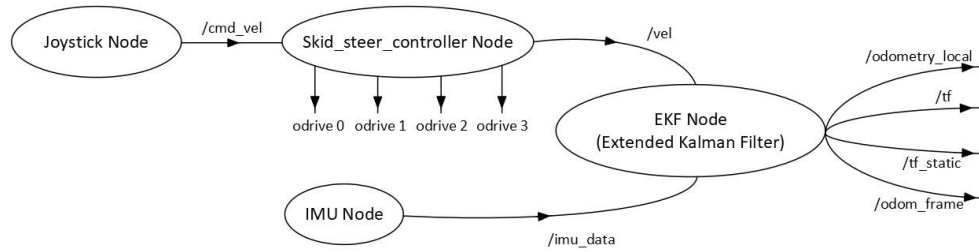


Figure 2.15 Architecture for Rover Localization

In the transform trees, the odometry frame was a child link to the map or the world frame, and the base link was a child link to the odometry frame. The reference could be taken from the map or odom frame to localize the robot and was kept as the parameter so that switching was possible between those. The transformation starts by localizing the aphids coordinates in 3D. The aphid of fixed size was considered for estimating its position in 3D coordinates. The two frames were defined for the camera: one in the ROS Standard format, which was the left camera link, and the other in image standard, which was the camera optical frame. In the ROS Standard format, X coordinates point outwards, Y coordinates backward, and Z upwards. In the camera optical frame, the X coordinates forward, the Y coordinates downward, and the Z coordinates outwards. The camera optical frame link acts as a child link to the left camera link.

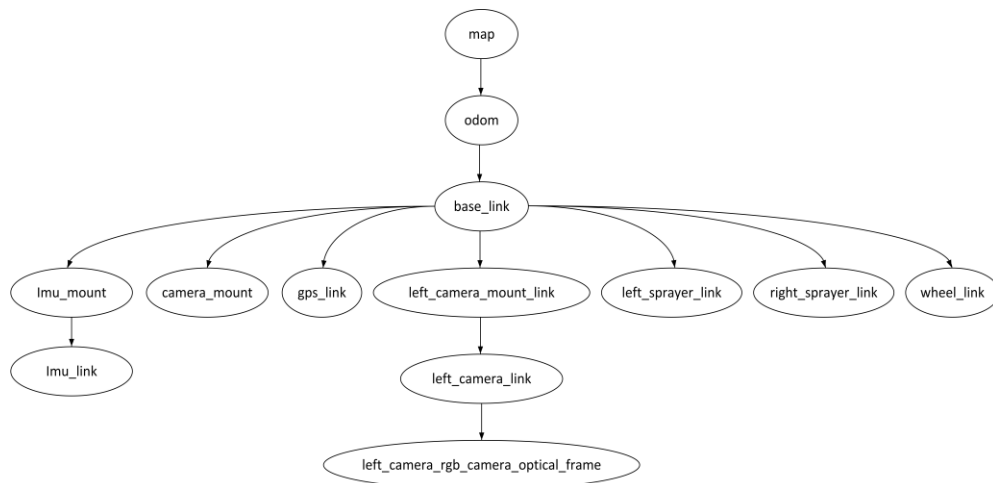


Figure 2.16 Transform tree for System Integration

The RT_DETR decoder node publishes the detection outputs from the camera and publishes them into detection to pose 3D node. This node estimates the position of the aphids in 3D coordinates and transfers the camera's optical link to the world or map frame. This transform was subscribed by the sprayer manager node, which transforms the coordinates from the world to the sprayer. A service set nozzle status was created to trigger the sprayer as the pre-set distance was reached. The detection to pose 3D node also publishes the camera link marker to visualize the detection of the aphids. The coordinate transformation helps to precisely spray on the plants with aphids when the coordinate reaches the sprayer.

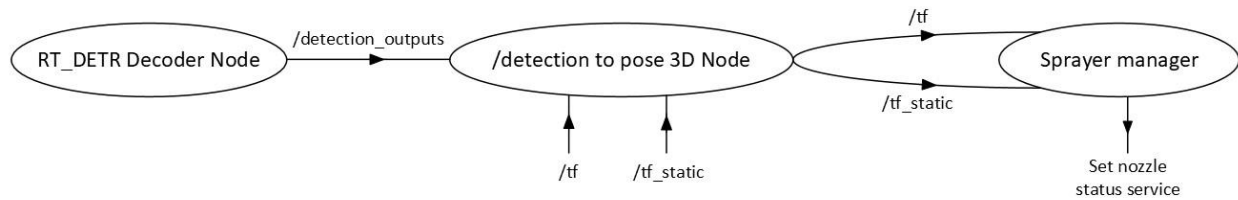


Figure 2.17 Architecture for Detection to Spraying

Experimental Setup

The experiment was conducted in the lab in the Seaton Building at Kansas State University. The 48" Dracaena silk plant was bought for the study. The artificial Dracaena silk plant has dimensions of 22 inches in width, 48 inches in height, and 22 inches in depth. Dracaena silk plant was selected as the height of the plant was similar to that of the sorghum (~40 inches height), and the spread was also similar. The pot size of the artificial plant has a width of 6.5 inches and a height of 5.75 inches. The plant-to-plant distance between the sorghum plant in a 30-inch row is 6 inches for 30000 plants/acre (Shroyer et al., 1996). 18 Dracaena plants were kept in a row with a plant-to-

plant distance of approximately 6 inches. The total length of the row was measured to be approximately 106 inches.



Figure 2.18 Distance Measurement between Artificial Plants

A dataset different from the one in which the model got trained was printed on water-protective paper and pasted underneath the artificial plant leaves using double-sided tape. Usually, aphids in sorghum plants grow from the bottom of the leaf to the top (Brown et al., 2015). For the experiment, the printed pictures of aphids were pasted on the bottom leaves of the plant.



Figure 2.19 Aphid Dataset used for Testing

A red flag was placed at the top of the plant, where pictures of the aphids were pasted. Water-sensitive paper turns dark blue from yellow when water droplets fall into it (Ahmad et al., 2022).

It is primarily used to assess the quality of the spray (Xun & Gil, 2024). Water-sensitive papers were put in the middle section of all plants. Three water-sensitive papers were pinned at the bottom, middle, and top portions of the plants infested with aphids, as shown in Fig. 2.19. The change in color of the water-sensitive paper helped indicate that the plant was sprayed.

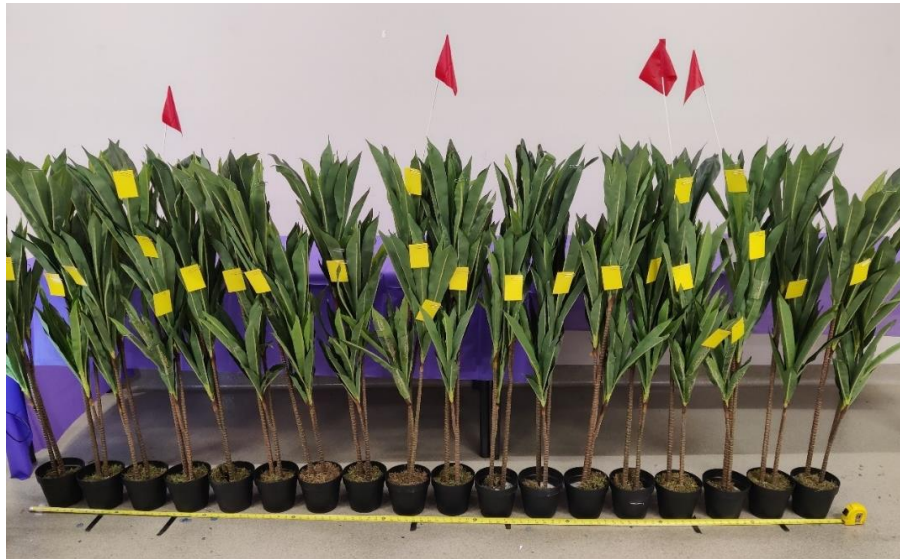


Figure 2.20 Experimental Setup with Artificial Plants

The robot was set parallel to the row of plants, and the starting point was marked. A fluorescent light was mounted above the camera, and the light intensity of 1100 lux was measured at the plant position. The light intensity at the lab was 300 lux. The rover's speed was calculated using the volume method to achieve the desired application rate of 12 GPA (Barbosa, 2010).

$$GPM = \frac{GPA \times W \times MPH}{5940}$$

Where:

GPM = Flowrate of Nozzle

GPA= Desired application rate

W= Effective Swath Width

MPH= Speed of the spraying system

The effective swath width for the directed spraying is row spacing divided by the number of nozzles, which will be 10 inches (Barbosa, 2010). The arducam camera was set at an angle of 45°. The nozzle was also set at an angle of 45°, showing the best coverage as per the study done by (Pokharel, 2021). With all these, the rover's speed was calculated using the volume method and found to be 0.33 MPH, equivalent to 0.15 m/s. The average speed of the rover with multiple calibration passes was set to 0.32 MPH.

Table 2.1 Speed Calibration

Particulars	Speed (MPH)
Run 1	0.32
Run 2	0.31
Run 3	0.31
Run 4	0.31
Run 5	0.30

The experiment was conducted with the pest severity of 11.11% and 22.22%. The number of plants infected with aphids was 2 and 4 out of 18. For each pest severity, three replications of the experiment were conducted. After the multiple trial runs, the pre and post-spraying distance was set to 9.84 and 1.18 inches, respectively for all experiments. The flow, water level, delivery pressure, and speed data were recorded in the ROS Bag for each experimental run. All the recorded data were time-stamped. Additionally, after each experimental run, the water-sensitive paper was allowed to dry for 10 minutes and collected in the zip bag for further analysis. Moreover, the plants that got sprayed and not sprayed were also recorded based on the change of color in water-sensitive paper. Fox glove was used to visualize the data from the sensor and transforms during the experiment.

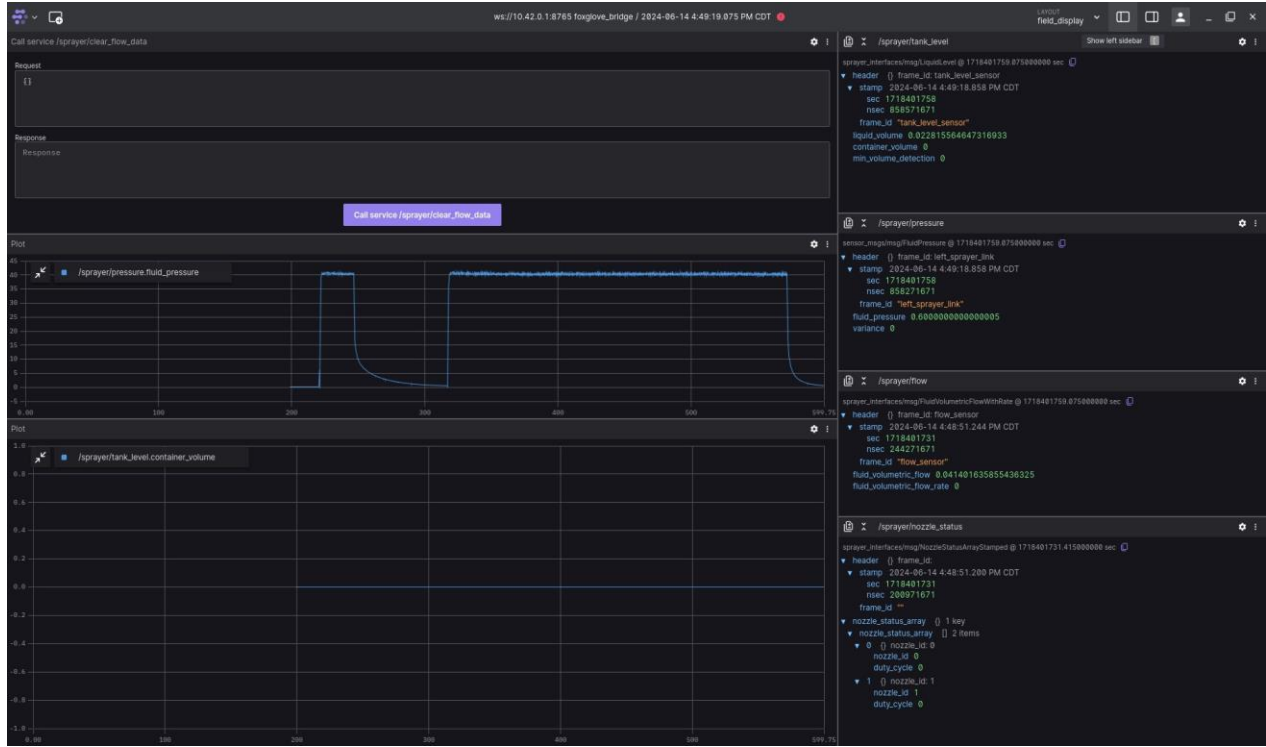


Figure 2.21 Visualizing Sensors Data in Fox Glove

Different metrics were formulated to check the effectiveness of the integration.

$$\text{Hit Percentage (aphid plants)} = \frac{\text{Total Plant with Aphid Sprayed}}{\text{Total Plant with Aphids}} \times 100\%$$

$$\text{Hit Percentage (plant before aphid)} = \frac{\text{Total Plant just before Aphid Sprayed}}{\text{Total Plant just before Aphids}} \times 100\%$$

$$\text{Hit Percentage (plant after aphid)} = \frac{\text{Total Plant just after Aphid Sprayed}}{\text{Total Plant just after Aphids}} \times 100\%$$

$$\text{Effectiveness} = \frac{\text{Total Plants (with + before + after) Aphid Sprayed}}{\text{Total Plants (with + before + after) Aphid}} \times 100\%$$

Results and Discussion

Validation of System Response to Duty Cycle

Different duty cycles were selected for the sprayer system response. The system pressure was set at 40 PSI for all the tests. Different duty cycles were commanded from the laptop. The sprayer system response was tested in 20%, 40%, 60%, and 80% duty cycle. The system response for different duty cycles was recorded on the Analog Discovery. For each duty cycle, the voltage remained in an excitation state as per the duty cycle. For example, at 20% duty cycle, voltage remained at 12 V for 10 milliseconds in a total cycle of 50 milliseconds; similar was the case in 40%, 60%, and 80% duty cycles. The system response for all duty cycles was as desired. The voltage fluctuation in each duty cycle was governed by the current required to engage the electromagnetic valve in the open state. A high current was supplied during the initial excitation of the voltage. However, as the coil inside the solenoid was energized, a low current was sufficient to keep the electromagnet engaged in an open state(Zhong et al., 2017). Moreover, during the valve's closure after the duty cycle execution, the polarity was switched so that the current was drained rapidly and the valve could respond swiftly. This method of adaptive switching helps reduce the current in the solenoid's coil, lessens temperature increase during the valve's operation, enhances the solenoid's life, and saves energy(Zhong et al., 2017).

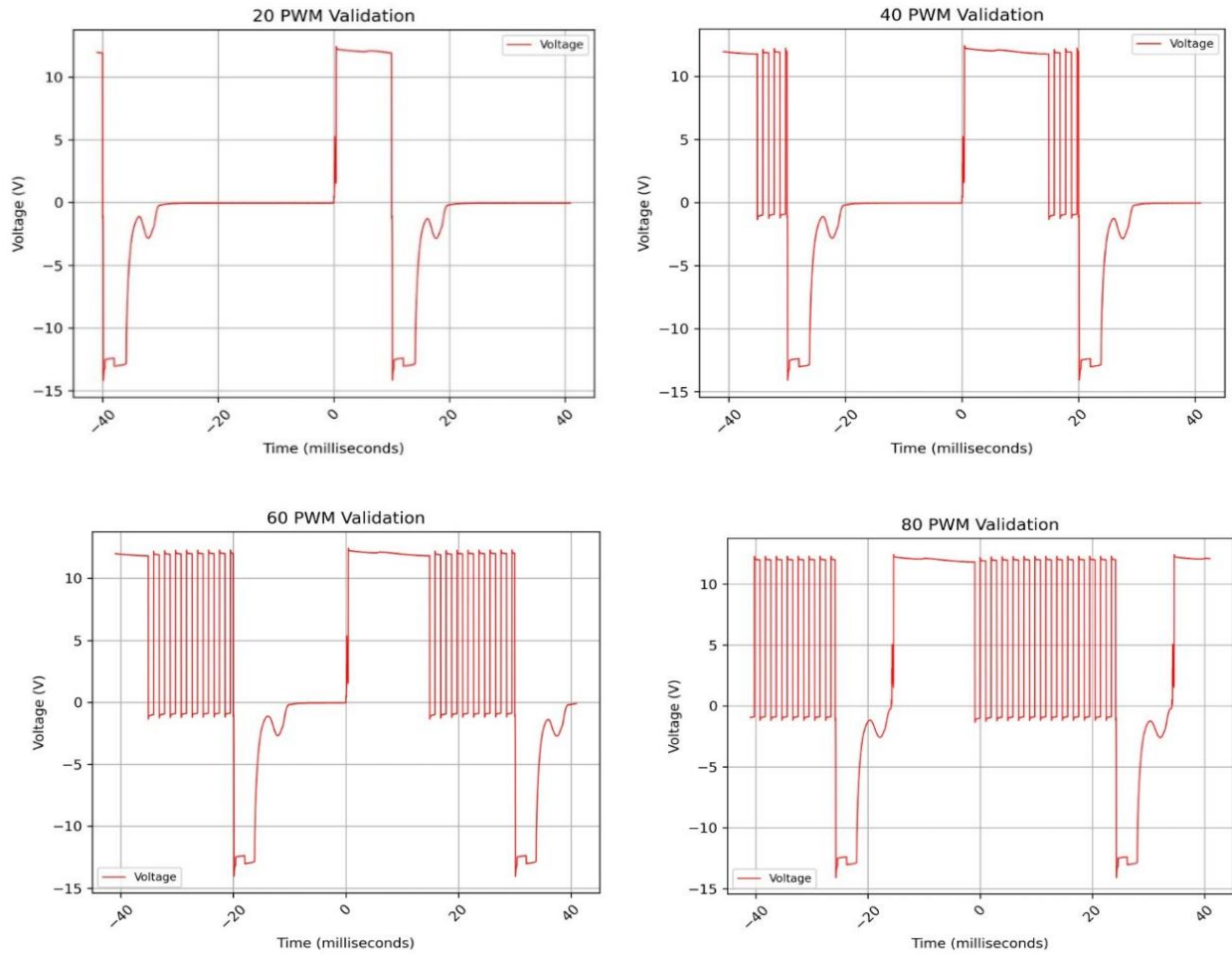


Figure 2.22 Duty Cycle Validation Graph

System and Nozzle Pressure with Different Duty Cycles

The system pressure was set at 40 PSI, and a different PWM was commanded to the ECU. System and nozzle pressure was noted for different duty cycles: 20, 40, 60, and 80 PWM. The nozzle and system pressure remained constant with changes in different duty cycles, as depicted in Fig. 2.22. This validates that the pressure remains constant with a change in flow rate, ensuring the spraying uniformity.

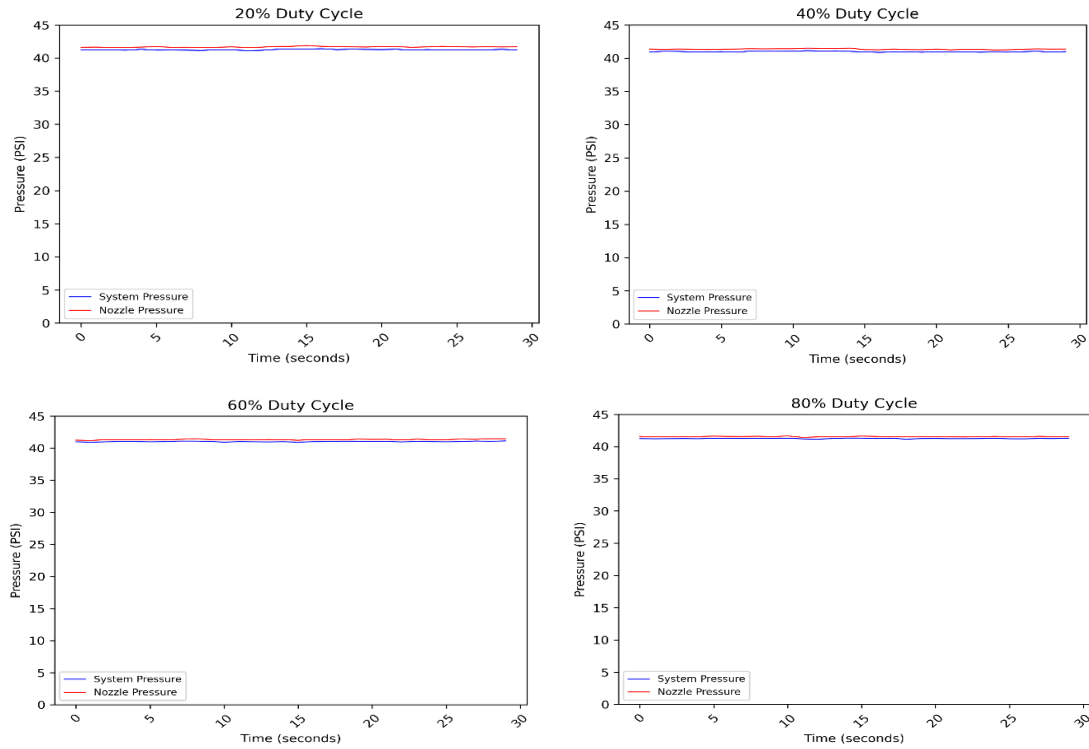


Figure 2.23 System and Nozzle Pressure for Different Duty Cycles

Nozzle Pressure Variation in Left and Right Boom Activation

The system pressure, left boom pressure, and right boom pressure were 41.2, 41.6, and 41.5 PSI, with standard deviations of 0.05, 0.06, and 0.06 noted at 40% duty cycle. The variation of the nozzle pressure in the left and right boom remained at $\pm 5\%$ of the operating pressure (Fabula et al., 2019). There was no deviation in pressure with different boom activations.

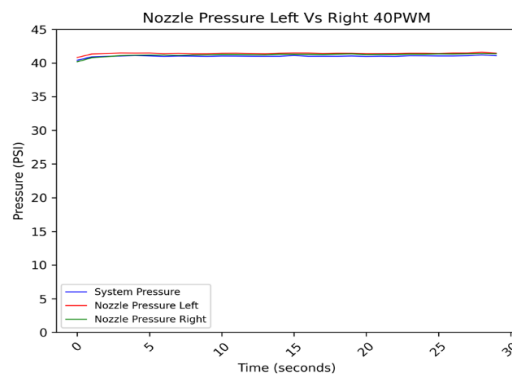


Figure 2.24 Pressure Variation with Left and Right Boom Activation

Pressure Variation with Height of Nozzles

The nozzle and system pressure were recorded with the nozzles at three different heights in the boom. The system and nozzle pressure noted at the bottom, middle, and top nozzles were 39.73, 40.16, 39.55, and 39.01 PSI, with standard deviations of 0.05, 0.05, 0.03, and 0.04. The pressure variation remained within $\pm 5\%$ of the system pressure (Fabula et al., 2019). No variations in the nozzle's pressure were observed due to its height in the boom.

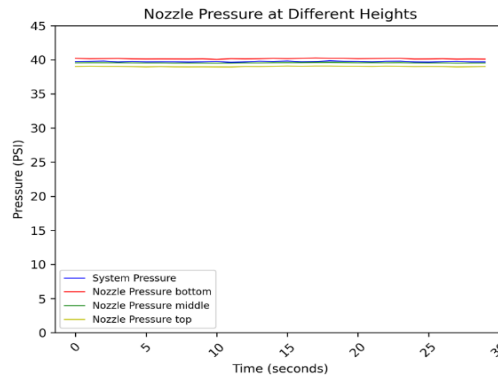


Figure 2.25 Pressure Variation with Height of Nozzles

Integration of Spraying System

The rover was operated, and spraying was carried out based on the aphid detection. The water-sensitive cards placed on the plant were observed to check the effectiveness of the integration of the spraying system with the pest detection system.

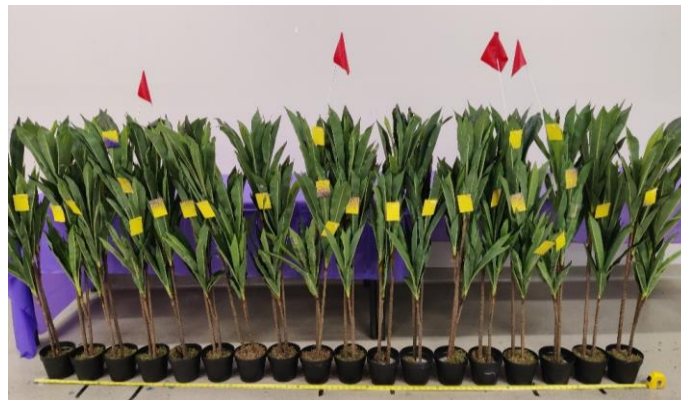


Figure 2.26 Experiment Setup for Integration Testing

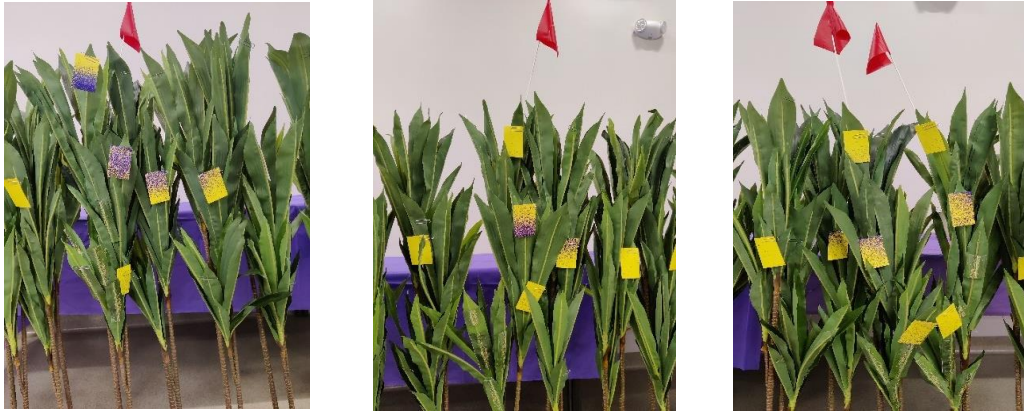


Figure 2.27 Spraying on Plants with Aphid

The visual observations of the water-sensitive card were made, and they were tabulated as:

Table 2.2 Results of Integration Experiment

Cases	Pest Severity-11.11%				Pest Severity-22.22%			
	Desired Value	Obtained Value			Desired Value	Obtained Value		
		Run 1	Run 2	Run 3		Run 1	Run 2	Run 3
Plants with Aphid Sprayed	2	2	2	2	4	4	4	4
Plant just before aphid sprayed	2	1	1	1	3	2	1	1
Plant just after aphid sprayed	2	2	2	2	3	3	2	3
Other plants sprayed	0	1	0	1	0	0	0	1

Table 2.3 Effectiveness of System Integration

Particulars	Values
Plants with Aphid Sprayed	100.00%
Plants before Aphid Sprayed	46.67%
Plants after Aphid Sprayed	93.33%
Effectiveness	80.00%

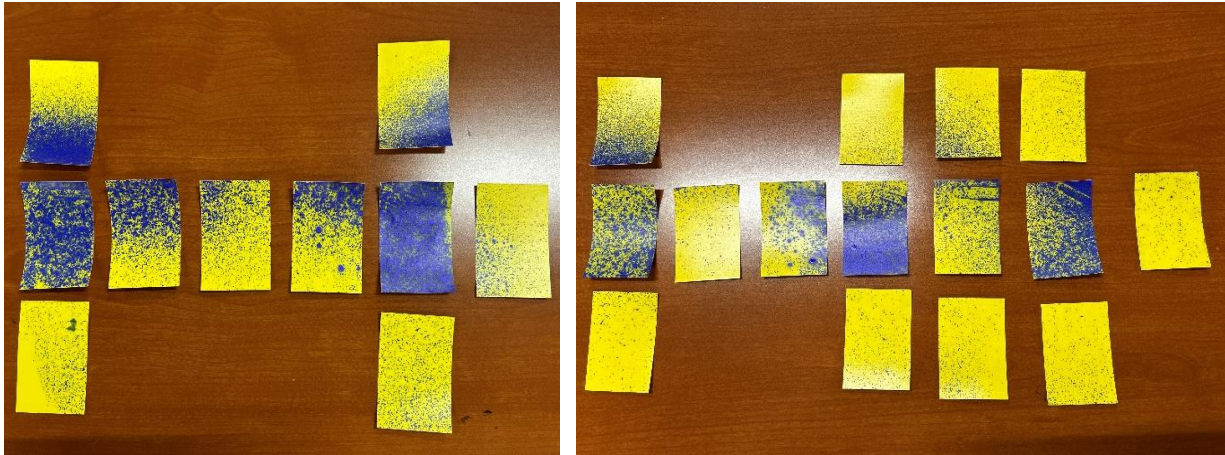


Figure 2.28 Water Sensitive Paper: Spraying Detection

The integration successfully sprayed all plants with aphids correctly. Moreover, around 50% of the plants before the aphid plant were sprayed. The errors in aphid localization and latency of the data transmission were the primary cause of the issue. Almost 95% of plants after the aphid were sprayed. During the test, only three plants were sprayed, not immediately before or after the aphid plant. The overall effectiveness of the spraying with the computer vision system was 80%, considering the desired result.

Pesticide Saving

The overall flow of the liquid was noted and collected in a ROS bag for each experimental run with aphid detection in various percentages of pest severity. The sprayer was run multiple times at full rate without the knowledge of the pest severity, depicting a case for 100% pest severity.

Table 2.4 Pesticide Saving with Pest Severity Percentage

Pest Severity	Average Flow (gallons)	Standard Deviation	Savings
100%	0.74	0.027	-
11.11%	0.23	0.016	68.82%
22.22%	0.49	0.055	33.66%

The average flow was 0.74 gallons, 0.23 gallons, and 0.49 gallons with 100%, 11.11%, and 22.22% of pest severity, respectively. Moreover, a pesticide saving of 68.82 % and 33.66% was achieved by spraying in a plot with pest severity of 11.11% and 22.22 %, respectively. Further, statistical analysis was carried out using analysis of variance (ANOVA) to determine the significance. The p-value (<0.05) signifies that the flow will vary based on the pest severity. Additionally, the Tukey HSD test was carried out to find the significant difference between different levels of severity. The result from Fig.1.28 shows that each level of pest severity is statistically different from the other one, even with a pest severity difference of 11.11%. This implies that if the insecticides are applied in the field with less pest infestation, the savings will be more than spraying after a higher infestation rate.

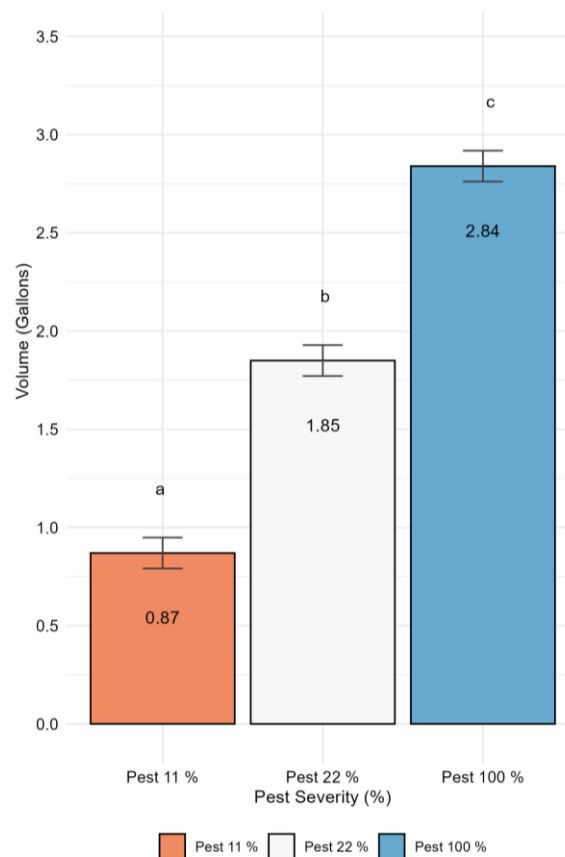


Figure 2.29 Tukey HSD test result

Summary and Conclusions

The liquid application system was designed, developed, and validated for the under-canopy rover. The system utilized a diaphragm pump with the capacity to deliver a flow of 3.2 gallons per minute at 40 PSI with a TXVS-1 nozzle. The solenoids were driven, and pulse width modulation was controlled using ECU and drivers from Teejet Technologies. A performance test of the liquid application system was conducted to measure the system's response for the duty cycle, which indicates the system's on-off time ratio, and to evaluate the variation in nozzle pressure.

The system validation encompassed tests at 20%, 40%, 60%, and 80% duty cycle settings. The voltage was maintained in the excitation state for the specified time period as per the commanded duty cycle. Also, the system and nozzle pressure remained constant despite changes in the duty cycle, ensuring consistent pressure even with varying flow. Furthermore, the variation in system pressure remained within $\pm 5\%$ of the operating pressure for left and right boom operations and for the operation of nozzles at three different heights.

In addition, integration of pest detection with spraying system was successfully implemented by using distance based spraying method with support from 'tf2' ROS library for pesticide reduction. The system demonstrated 100% accuracy in autonomously spraying the aphid-infested plants after detection. Moreover, the sprayer achieved an accuracy of 46.67% when spraying plant immediately before an aphid-infested plant and 93.33% accuracy when spraying the plant immediately after. The overall effectiveness of the integration was determined to be 80%. Furthermore, pesticide usage reduction by 33.66% and 68.82% was achieved, with pest severity of 22.22% and 11.11% respectively, compared to spraying without integration. Overall, the integration optimized the amount of pesticide applied based on the pest severity.

Chapter 3 - System Development for Application & Testing of Spray-on BioWRAP (Bioplastic)

Abstract

Plastic mulch films have been integral to agriculture, particularly in specialty crop production, due to their ability to conserve soil moisture, suppress weed growth, and elevate soil temperatures. Despite these benefits, using petroleum-based plastic mulch films poses significant environmental challenges, primarily due to the difficulty in their removal and subsequent ecological impact. These films must be removed at the end of each growing season, often leaving behind microplastic residues that contaminate the environment and stormwater runoff. Additionally, the recycling process is complicated by soil contamination on the plastic mulch.

Over the past decade, environmental concerns have spurred a shift from conventional bioplastics to biodegradable polymers. This transition emphasizes the development of biodegradable polymers that can be applied via spraying while maintaining robust mechanical properties and efficient degradation. Due to the viscous nature and high mulch application rate, commercially available sprayers are unsuitable. Chicken feathers, a prevalent waste material in the Midwest United States, have been utilized as a primary protein source for formulating these biodegradable plastics.

Developing an application system for Spray-on Biodegradable mulch necessitates carefully selecting pumps and nozzles capable of handling the viscous nature of mulches and ensuring effective atomization. Given the requirement to apply mulches in substantial quantities to achieve an adequate layer, i.e., 4276 gallons per acre (GPA), the designed system includes a double action positive displacement double diaphragm pump, a strainer, a pressure relief valve, flood jet nozzles, an agitation system, hoses, and fittings. A Sotera double diaphragm pump was selected for this

application, offering a flow rate of 13 gallons per minute (GPM) at 13 PSI pressure. Quick Turbo Flood jet nozzles were chosen for their pre-orifice design, which minimizes drift, and their large round orifice, which reduces clogging risk.

The application platform employed was the Amiga, developed by FARM NG based on the modularity and payload capacity. The whole spraying system was assembled in the application platform. Experiments with various Quick Turbo Flood jet (QCTF) nozzles identified the QCTF-60 nozzle as optimal for spraying the BioWRAP formulation, delivering a flow rate of 5.59 GPM at 10 PSI pressure and a swath width of 28 inches. Based on these configurations, the rover's speed was calculated to be 25 feet per minute using the volume method for the desired application volume. The sprayed BioWRAP effectively formed a consistent layer across different soil types with varying moisture levels and densities. BioWRAP produced a better layer formation with higher moisture content and high soil densities. The average thickness of the formed layer was measured to be 0.022 inches.

Introduction

Mulching is the technique used in agricultural production systems to improve crop yield by covering the soil with a layer of mulch. Since 1950, Polyethylene (PE) mulch has been used in agriculture, and 1 billion pounds of plastics is used yearly. “Plasticulture” as it is termed has been used quite often which signifies the large-scale use of plastic in agriculture. Plastic mulch films, with their good mechanical properties, help improve weed management, increase the soil temperature, reduce moisture loss, and shorten harvest time(Adhikari et al., 2016). The major challenge with plastic mulch is product disposal or recycling after its end-of-life use, as it is contaminated with soil, organic matter, and agrochemicals, and the process adds significant costs to the growers. Moreover, removing them is cumbersome as they are brittle and easily break into small pieces(Immirzi et al., 2009). Technological advancements have been made with respect to machines that removes plastic from the field. However, efficiently removing plastic from one acre of land takes about eight hours of labor (Shrefler & Brandenberger, 2016).

The environmental concerns associated with the traditional plastic mulch and the shift from conventional plastics to biodegradable polymers have begun. Biodegradable polymers are made from bio-based materials and can degrade in the soil after their useful life. Generally, these mulches come in rolls with fixed length and width. An alternative is biobased sprayable mulch, which can be applied using spray application technologies (with pumps and nozzles that can handle higher viscosity suspensions)(Gloeb et al., 2023). The advantages of spraying rather than laying the mulch are mostly associated with adherence to the soil surface with no headspace between the soil and polymer membrane(Adhikari et al., 2016). In addition, it has a higher degradation rate than plastic mulch and requires less manual labor. Also, the farmers are aware of the technology

and processes related to crop protection, such as spraying herbicides, insecticides, etc.(Filipović et al., 2020). The application of mulch via spraying will be faster than laying the sheet manually.

Biodegradable mulches are to be applied at a very high rate to form layers above soil, similar to plastic mulches. In the North Dakota State University experiment for spraying biodegradable mulch made of paper, the application rate used was 4500 Kg DM/ha (Gramig & Usda-Nifa-Orei, 2023). Different application rates from 2500 Kg/ha to 30000 Kg/ha have been used for sprayable biodegradable polymer membranes to study soil water conservation in different production systems (Braunack et al., 2021). Increasing the formulation's viscosity and reducing the water content helps mitigate soil wicking and absorption (Gloeb et al., 2023). However, the increase in the viscosity and high application rate poses a critical challenge to designing a spray application system for the mulch.

The commercially available sprayers are designed to spray herbicides, insecticides, fungicides, etc. The application rate varies from 10 GPA to 20 GPA depending on the product being sprayed (Sprayer Setup). The liquid's viscosity impacts the spray capacity, angle, and distribution. These will differ from the usual ones and impact the spray pattern ("Spray Impact, Pressure Resistance & Viscosity"). Moreover, it makes the commercial sprayer unsuitable for use.

The various formulations developed for biodegradable mulch were sprayed by using a hand-pump sprayer, graduated cylinder, and compressed air spray gun (Giaccone et al., 2018; Gloeb et al., 2023; Immirzi et al., 2009). The spraying was carried out for lab or small field-scale trials. The off-center nozzles from Teejet Technologies in different configurations have been implemented to spray biodegradable polymer membranes developed by (Braunack et al., 2021). A spraying system with the capability to pump and spray the viscous bio-plastics is required to test various

formulations of mulch for its effectiveness. Currently, no products are available on the market for field experiments, so there is a need to design and develop a system to fulfill this requirement.

BioWRAP Formulation and Trials

Chicken (*Gallus Gallus domesticus*) feathers are a waste from the poultry industry. The United States only produces about 3 billion pounds of chicken feathers yearly, most of which goes in landfills (Trump, 2023). Keratin in chicken feathers has an application in the development of bioplastic film (Ramakrishnan et al., 2018). Chicken feathers are available in abundant amounts in the Nebraska region. Chicken feathers, which are waste, were used to formulate BioWRAP solution by the University of Nebraska-Lincoln. The properties of the formulation will have a direct impact on the spraying capabilities. The viscosity of the BioWRAP formulation was 1100 cp, and the density was around 1090 kg/m³ with a pH of 7.4.

The experiments were conducted by the University of Nebraska-Lincoln, using different rates of BioWRAP formulation 2138 GPA, 4276 GPA, and 8552 GPA to control the weed and not disturb the plant growth. All application rates showed effectiveness as per the desired outcomes. However, a 4276 GPA showed the best results in terms of weed reduction. The properties of the formulation and the best application rate were inputs for the design considerations for the BioWRAP spraying system.

Materials and Methods

Initial Trials

The development of spraying systems starts with the selection of the various components. The major components of a spraying system are a tank, pump, nozzles, flow meter, pressure gauge, strainers, agitation, and distribution system (Hofman, 2018). The initial trials were conducted using a spraying system with a 12 V diaphragm pump (5537-2E1-63B, Remco USA) with a flow

rate of 5.5 GPM. The setup was utilized to conduct the initial trials for experimenting with BioWRAP. The pump got clogged with the viscous nature of the liquid. Another trial used the Honda FX 160 gasoline engine with a pump. 2 inches of inlet pipe and 1.5 inches of outlet pipe were used. In this case, the pump got clogged after multiple runs. These trials showed that the pump with a higher capacity was required to pump out the BioWRAP.

Pump Capacity Calculation

Biodegradable mulches with similar properties as BioWRAP were sprayed on the field with nozzles having high application rates of 1-2 GPM (Braunack et al., 2021). The best application rate of BioWRAP was 4276 GPA, so the nozzle with the application rate of 3 GPM was considered for the preliminary calculation.

Considering the viscous nature of the liquid, a hopper-shaped tank was searched to facilitate pumping the entire liquid from the tank, which was not possible with a rectangular tank. A 20-gallon ace rota-mold inductor full drain cone bottom tank (IBFD20-SET) was procured for lab testing. The tank was made out of polyethylene material and has dimensions of 19 inches in diameter and 22 inches in height. The outlet from the tank was 2 inches in diameter with a hopper cone angle of 50°.

The determination of pump capacity for agricultural applications was carried out (Grisso, 2020)

$$Pump\ Requirements\ (GPM) = \left\{ \begin{array}{l} Boom\ Requirements\ (GPM) + \\ Agitation\ Requirements\ (GPM) + \\ Self\ Cleaning\ Strainers\ (GPM) + \\ Other\ Accessories\ (GPM) + \\ 1\ (GPM) \end{array} \right\} \times 1.2$$

Where:

Boom Requirements = Number of Nozzles $\times$ Flow Discharge (Since the application rate was high, an assumption was made to use 2 nozzles with a high flow rate of 3 GPM) = 6 GPM

Agitation Requirements = 10% of tank capacity = 2 GPM (20 gallons tank capacity)

No Self Cleaning and Other Accessories

Pump Requirements = 10.8 GPM

The total pump capacity required with 2 nozzle configurations of 3 GPM was 10.8 GPM.

Pump Selection

Along with the minimum flow rate, the pump should be capable of pumping out the viscous liquid at the desired pressure for spray application. The experiment with the Honda FX-160 proved that centrifugal pumps are unsuitable for handling viscous liquids. The performance of the centrifugal pump becomes poor, with the viscosity greater than 300 centistokes (Whitesides, 2002). The diaphragm pumps are used in agricultural systems for spraying herbicides, insecticides, and fungicides. It is highly durable and can handle flow rates from 3.5 to 60 GPM and pressure from 200 to 700 PSI (Slocombe, 2019). Moreover, it can handle fluids that contain solids and are corrosive. Sotera 400 B positive displacement double action diaphragm pump with a flow rate of 13 GPM at 13 PSI was selected for the experimentation. The double diaphragm pumps deliver reliable performance by maintaining constant output pressure regardless of load, which is crucial for uniform spraying. Sotera 400B uses santoprene diaphragms, which are compatible with various fluids from agricultural pesticides, herbicides, and fertilizers and can handle a pH from 3.4 to 12. The pump can handle viscosity up to 3700 centipoise (cp) and a maximum particle size of 1/10

inches. Moreover, it has self-priming capabilities and can run dry without damage. It is suitable for field applications as it runs in 12 V DC and has a dimension of 8.75 inches in height, 14 inches in width, and 5.5 inches in depth.



Figure 3.1 Sotera 400B Double Diaphragm Pump

Flowability Test

A test setup was developed in a lab to check the flowability of BioWRAP with the Sotera 400B pump. The reducer from 2 inches to 1 inch was used in the outlet of the 20 gallons full drain cone bottom tank and it was connected to the inlet of the pump using a braided rubber hose of 1 inch and the outlet from the pump was connected to 1-inch braided rubber hose with a 1-inch ball valve at the end to control the flow. The pump was powered using a 12 V 60 Ah deep cycle battery from Dakota Lithium. BioWRAP Formulation- 4A was used for the test. The pump was operated for 20 seconds, and a calibrated jar was used to measure the amount of BioWRAP pumped out into the bucket. The experiment was repeated five times, and average flow was noted.



Figure 3.2 Flowability Test Setup

Nozzle Selection and Test Setup

Proper selection of nozzles is imperative to determine the flow rate, atomize the liquid, and distribute these droplets in a particular pattern. The viscous nature of BioWRAP, along with the high application rate, posed challenges in the selection of the nozzle. The nozzle selection was based on the formulation properties, application rate, pump flow rate, pump pressure, and recommendation from the manufacturer. Out of all commercially available nozzles, flood nozzles are used for the application where clogging is a problem similar to the BioWRAP application. The nozzles operate at 10 to 25 PSI pressure and produce large droplets (Slocombe & Sharda, 2013). Moreover, new turbo flood nozzles with pre-orifice and turbulent chamber design ensure excellent spray pattern and uniformity distribution (Grisso et al., 2019). Quick Turbo Flood Jet (QCTF) Nozzle from Teejet Technologies was chosen for the experimentation as it had all the features described above. QCTF nozzles have a flow rate range from 1.5 GPM to 24.0 GPM and a pressure range from 10 PSI to 40 PSI, along with a large, round orifice facilitating the reduction of clogging. QCTF nozzles have a wide-angle pattern with a spray angle of 130 degrees.

The flowability test setup was extended to check the spraying of BioWRAP using QCTF nozzles. A $\frac{3}{4}$ inches cam level coupling was added on the braided hose on the delivery side. Different nozzles QCTF-VS15, QCTF-VS30, QCTF-VS60, QCTF-VS80, QCTF-VS100, and QCTF-VS120 were used for the experimentation.

Application Platform

Applications platforms were selected based on the payload they can carry along with the modularity for assembling the spraying system components and conducting field spraying operations. Two platforms, Amiga (Farm-NG) and Gator_XUV560E (John Deere) were evaluated for the suitability of the application. Amiga, with a payload of 450 kg, ground clearances of 24.1 inches, 44 V DC batteries as a power source, adjustable cargo dimensions, and less cost, made it a preferred choice compared to Gator with fixed dimensions, gas-powered, and only 227 kg of cargo, box capacity. Amiga weighs 150 kg and uses a skid steer drive system. Amiga's maximum operation speed can be adjusted from the panel from 10 ft/min to 500 ft/min with an average speed of 174 ft/min. The adjustable cargo dimensions help to make the system modular, as the length and width of the platform can be changed by adjusting the T-slotted framing.



Figure 3.3 FARM-NG Amiga Platform

System Development: Hydraulic Design

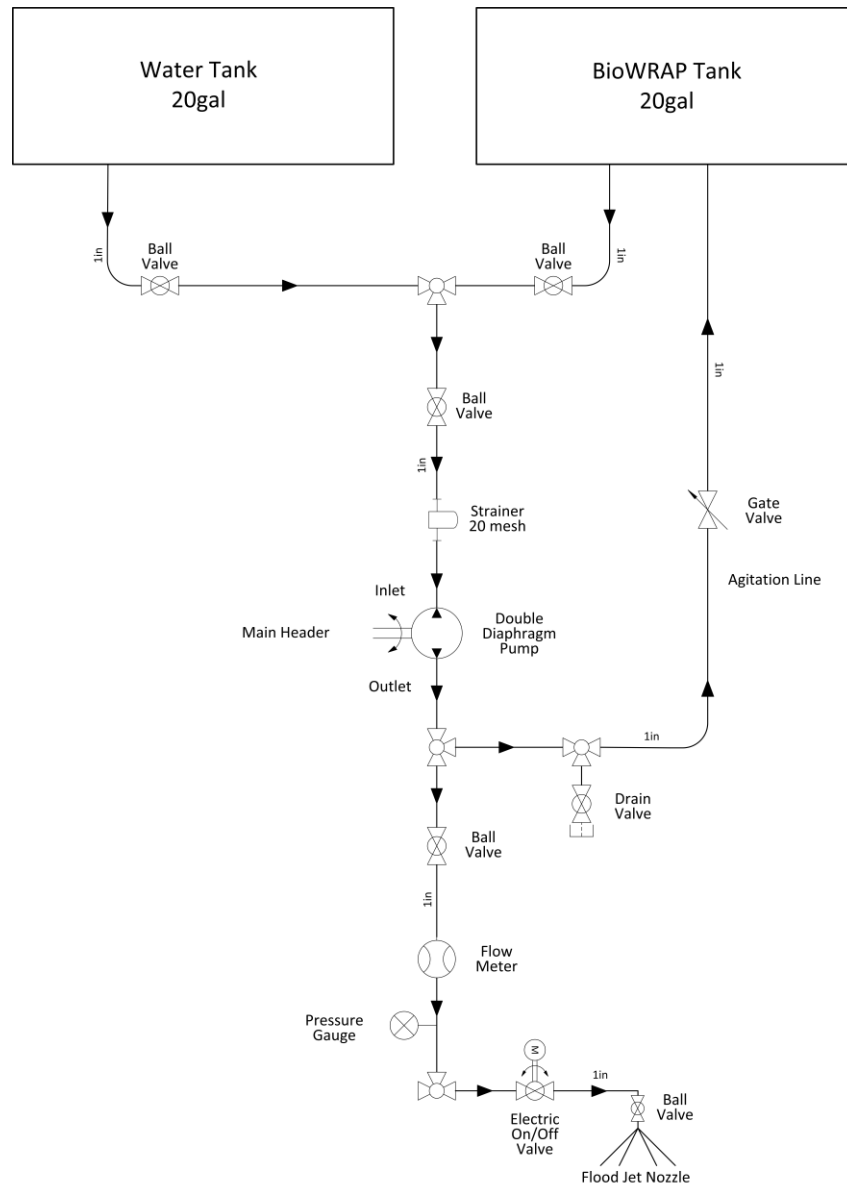


Figure 3.4 Hydraulic Circuit Schematic - BioWRAP Spraying System

The hydraulic system's design for the double diaphragm pump is the same as that of the piston pump (Hofman, 2018). Based on the spray system hook-up for the diaphragm pump, a hydraulic diagram was prepared to develop the spraying system. The ace-rota mold tank used for experimentation was also used for the application system. Two 20-gallon full drain cone tanks

were selected. One tank held the BioWRAP, and another was used for the water. A BioWRAP tank was used for the product application, while a water tank was used to rinse the system post-application. In case of necessity, a water tank can also be used for the BioWRAP to increase the holding capacity. A 1.5-inch hollow square metal pipe was changed in the Amiga platform with a 1.5-inch T-slotted aluminum extrusion to facilitate the securing of the spraying components. The mountings for the tank were designed, 3D printed, and secured with T-slotted aluminum extrusions. A reducer from 2 inches to 1 inch was used on the outlet of both tanks. A 1-inch ball valve was connected to the tank outlet to control the flow. Two tanks were connected before the inlet to the pump using a 1-inch threaded Tee-connector. 1-inch braided rubber hose was used for connecting all valves and connectors. A 1-inch ball valve and 1-inch chemical-resistant T-strainer with a mesh size 20 were placed in the inlet side of the pump. The size of the strainer was chosen based on the pump manufacturer's recommendation.

In the delivery side, the 1-inch threaded T-connector connected the outlet from the pump to the main delivery header and the recirculation/agitation line. The main delivery headers include a 1-inch ball valve, an 825 digital chemical transfer meter (Sotera), and low-pressure gauge for chemicals. 825 4-digit, multi-viscosity chemical transfer meter has a flow measuring capability up to 20 GPM at $\pm 1\%$ accuracy. It has a nutating disc technology capable of moving small debris, making it suitable for application. The selected pressure gauge ranges from 0 to 30 PSI, and it comes with a CPVC guard that protects the gauge from damage due to chemicals. Furthermore, the delivery header consists of a 1-inch threaded T-connector, an electric 1-inch ON/OFF valve from Banjo, a 1-inch ball valve, and $\frac{3}{4}$ inch cam coupling. The Banjo ON/OFF operates at 12 V DC and has a response time of $\frac{3}{4}$ seconds. The valve helps to activate/deactivate the nozzle based on the requirement. The QCTF nozzles were connected with cam coupling. The cam coupling

also facilitates the quick change of the nozzle as per the requirement. The re-circulation line has a 1inch gate valve to control the liquid flow back to the tank. A 1-inch ball valve has been placed in the re-circulation line between the tank and the outlet from the pump to facilitate the draining of the remaining BioWRAP solution post the application and rinsing the system.

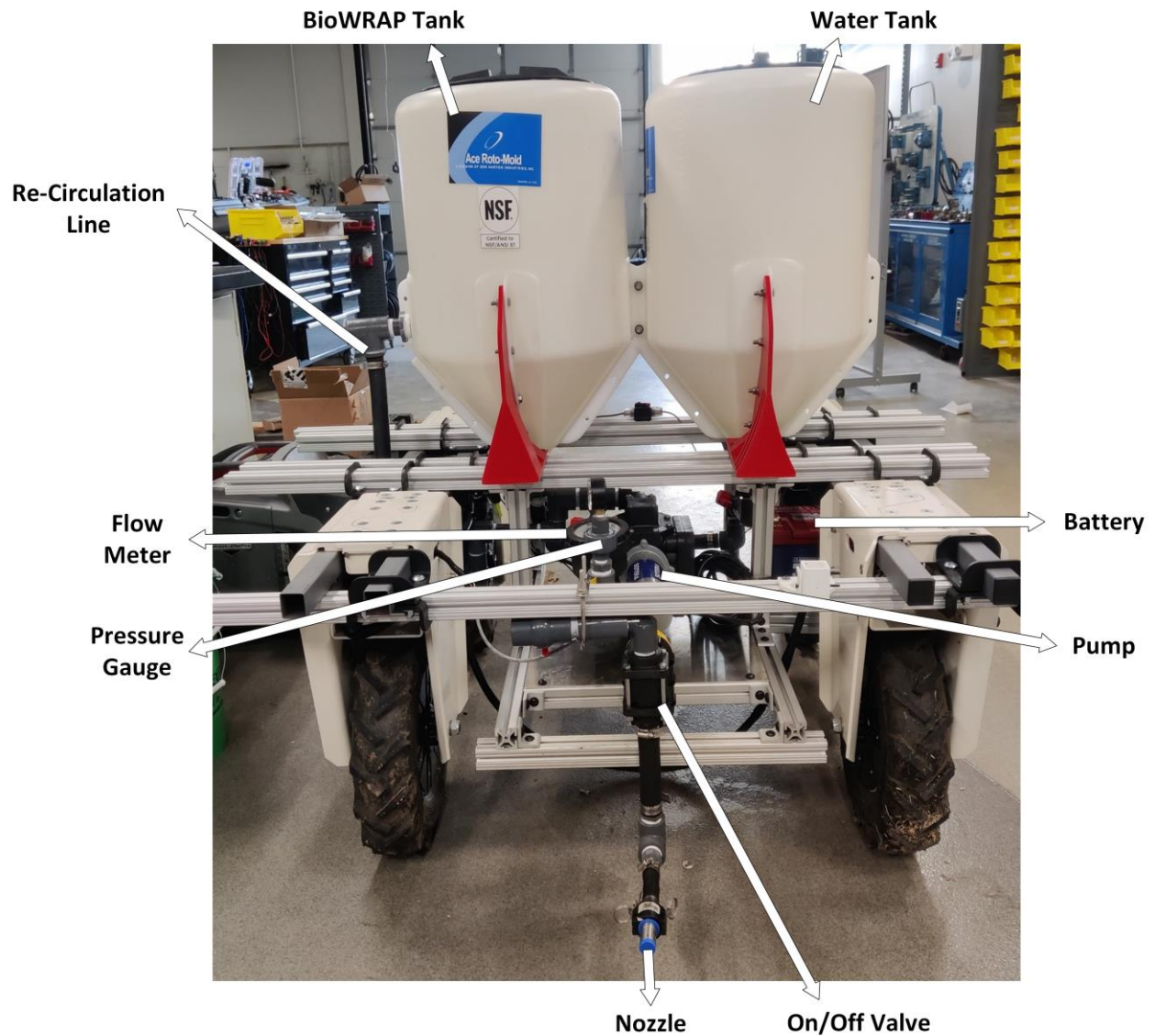


Figure 3.5 BioWRAP Spraying System

Circuit Schematic

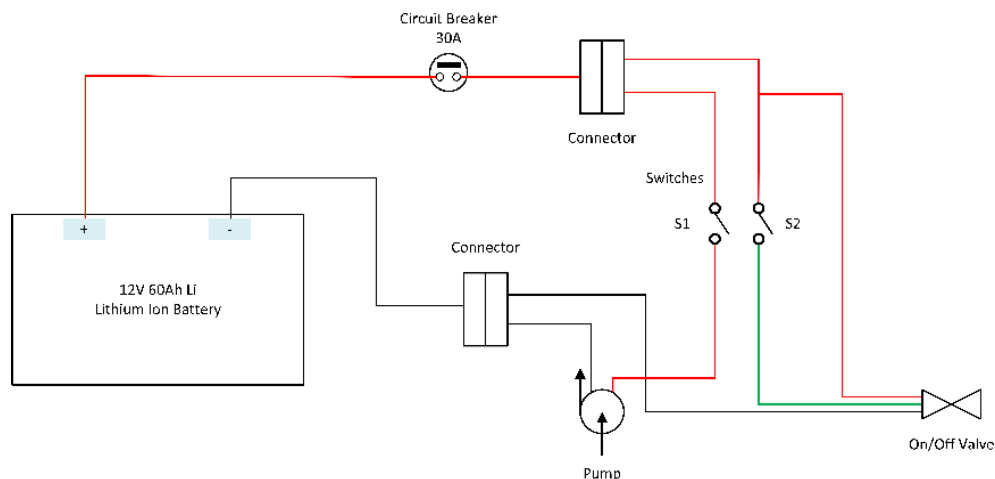


Figure 3.6 Circuit Schematic - BioWRAP Spraying System

The spraying system of the BioWRAP rover was powered by a 12V, 60 Ah Dakota Lithium-Ion Battery. The battery for the spraying system was separate from the powering the rover movement. The positive terminal from the battery was connected to a 30A inline circuit breaker and then to a connector before passing it through the switches. Two toggle switches, ILT05 from C&K Switches, were used: One to control the operation of the pump and another for the ON/OFF valve. The toggle switches have a current rating of 20 A and a voltage rating of 12 VDC. It has an LED indicator to indicate the activation of the switch. The negative terminal from the battery was split into two using a connector. One terminal end was routed to the pump, and another to the ON/OFF valve. A box to hold the switches was designed and 3D printed. The box was fixed beside the panel used for the rover movement.

System Performance Check

BioWRAP formulation-4A was used to check the performance of the spraying system. The University of Nebraska-Lincoln supplied the solution in a 5-gallon container. Before pouring the

formulation into the tank, the solution was stirred properly for 1-2 minutes using a 12-inch heavy-duty immersion blender from Waring to disintegrate the chunks in the liquid. The solution was manually poured into the BioWRAP tank while the pump was kept in operation with the re-circulation system open to avoid clogging. The formulation was re-circulated for 2-3 minutes with the gate valve fully open. Meanwhile, the water tank was filled out in the other tank.

A plastic tray of size 35.7 inches in length, 8 inches in width, and 5 inches in height was placed below the nozzle for collecting the sprayed BioWRAP solution. The pump was turned off, and the gate valve in the re-circulation line was closed. After that, the pump and the electronic ON/OFF valve were turned on, which activated the nozzle, and the liquid was sprayed. The experiment was conducted three times for each nozzle, and each experiment was 20 seconds long. The flow meter and pressure gauge were used to obtain different nozzle flow rates and pressure readings. The nozzle's rated flow rate and actual flow rate will vary due to the viscous nature of the liquid. Seven quick turbo flood jet nozzles were tested: QCTF-15, QCTF-30, QCTF-50, QCTF-60, QCTF-80, QCTF-100 and QCTF-120.



Figure 3.7 Test Setup- System Performance

Swath Width Measurement Setup

The effective width of the sprayed area in a single pass is the swath width of the sprayer. In the case of the banded spraying, the swath width is equal to nozzle spacing (Hofman, 2018). The effective spray swath for the boomless sprayer is 80% of the total width (Waters, 2019). An experiment was conducted to determine the effective swath width delivered by the nozzle. The application system was placed in the horizontal plane, and a white paper of 40 inches in length and 36 inches in breadth was cut into half and placed below the nozzle. The paper was aligned center to the nozzle that way spread will be the same on both sides. The formulation was stirred and poured into the tank with a re-circulation line in operation. Two different application heights, 4 inches and 5 inches from the ground level, were chosen for the experiment. The nozzle was turned ON/OFF quickly, and each experiment was repeated six times with three replications. The swath width was measured on each paper using a measuring tape.



Figure 3.8 Swath Width Measurement Setup

Sprayer Calibration: Volume Method

Calibration of the sprayers is important to achieve the desired product application rate. The four most important components are speed, effective swath width, nozzle flow, and operating pressure. The nozzle flow and operating pressure were obtained from the above sprayer performance check. The volume method was used to calibrate the sprayer (Barbosa, 2010).

$$GPM = \frac{GPA \times W \times MPH}{5940}$$

Where:

GPM = Flowrate of Nozzle

GPA= Desired application rate

W= Effective Swath Width

MPH= Speed of the spraying system

With the result obtained from the above experiments for flow rate and swath width, the speed of the rover operation was calculated using the volume method.

Spraying Uniformity and Layer Formation

Determining the spraying uniformity and proper layer formation is imperative for the effective functioning of the BioWRAP. A plastic tray 16 inches high, 3 inches wide, and 3.5 inches high was used to fill different soils at different densities. The bulk densities of soil are usually around 1 to 1.4 g/cm³. The soil used for the experiment was taken from various sites of University of Nebraska-Lincoln, commercially available garden soil and from Kansas State University and sent to a soil lab to test the soil type. From the soil textural triangle, soil type was found to be silty clay loam with 59% of silt, 29% of clay, and 12% of sand. The soil moisture from each tray was measured using the moisture meter in the lab. Trays 1, 2, and 3 were filled with the silty clay loam soil but packed at different densities. Tray 4 was filled with commercially available garden soil, whereas tray 5 was filled with silty clay loam soil with added moisture. Tray 6 was filled with silty clay loam soil and garden soil in a ratio of 4:1 to have the density of 0.8 g/cm³. All the trays were packed in the desired densities. The summary of the setup was as follows:

Table 3.1 Properties of Soil for Experiment

BioWRAP Spraying Test			
Tray No.	Type of Soil	Moisture (%)	Density (g/cm³)
1	Silty Clay Loam	5.47	1
2	Silty Clay Loam	5.48	1.2
3	Silty Clay Sand	5.50	0.8
4	Garden	27.03	0.5
5	Silty Clay Loam	9.98	1
6	Silty Clay Loam / Garden (4 :1 ratio)	11.38	0.8

All the trays were aligned in a row and placed on the ground. The nozzle was aligned with the center of the tray. The sprayer was filled with the BioWRAP formulation-4B, and the starting procedures were followed before spraying. The sprayer speed was maintained at 25 ft/min to obtain the desired application rate of 4276.28 GPA. The sprayer went over the trays, spraying the BioWRAP formulation in a single pass. The trays were cleaned from the outside and put in a controlled chamber. The controlled chamber was maintained at 25 degrees Celsius, with 53% humidity during the day, and 10 degrees Celsius, with the same humidity at night. The observations were carried out in 6-hour intervals until the sprayed BioWRAP was dried.



Figure 3.9 Soil Samples for Moisture Test and Experimental Setup for Spraying Uniformity



Figure 3.10 Post-Application of BioWRAP

Results and Discussions

Pump and Nozzle Performance

The flow of the BioWRAP formulation-4A from Sotera 400 B was smooth, with no clogging issue.



Figure 3.11 Flowability of BioWRAP

The flow measurement results from the pump are as follows:

Table 3.2 Pump Flowrate

Trial	Flowrate (GPM)
1	11.4
2	10.2
3	11.5
4	10.8
5	10.7

The average flow rate obtained from the experiment was 10.92 GPM, which met the pump capacity requirements.

QCTF nozzles exhibited excellent performance when spraying BioWRAP liquid. The desired spray pattern was obtained with no clogging issue during the run.

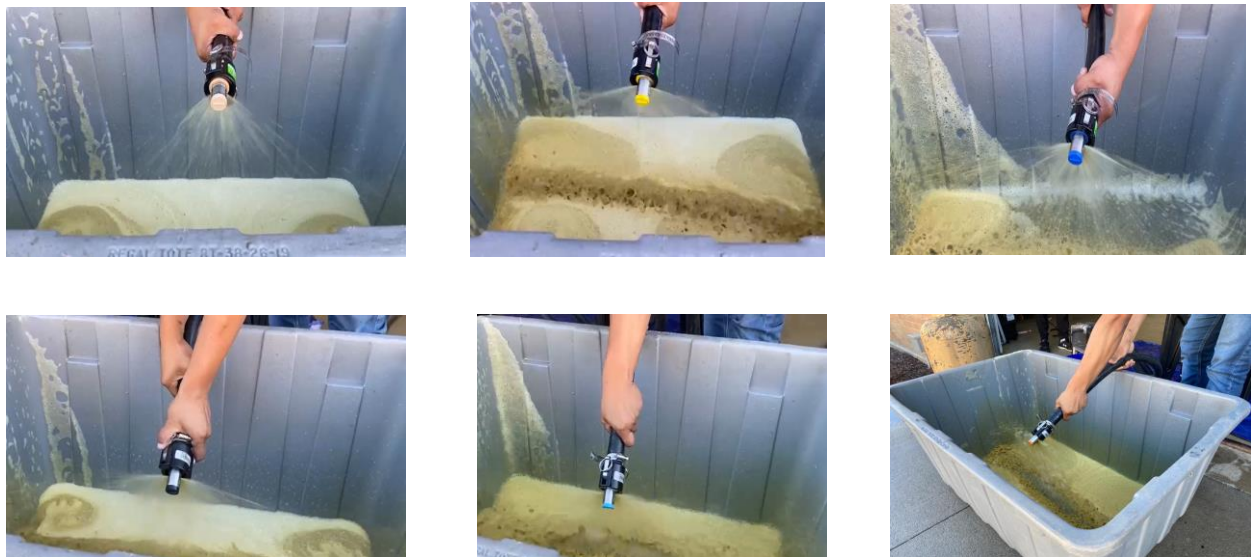


Figure 3.12 Testing of QCTF Nozzles

System Performance Check

In the system performance check, the nozzles' rated and actual flow rates and the pressure at which the BioWRAP was being sprayed were recorded.

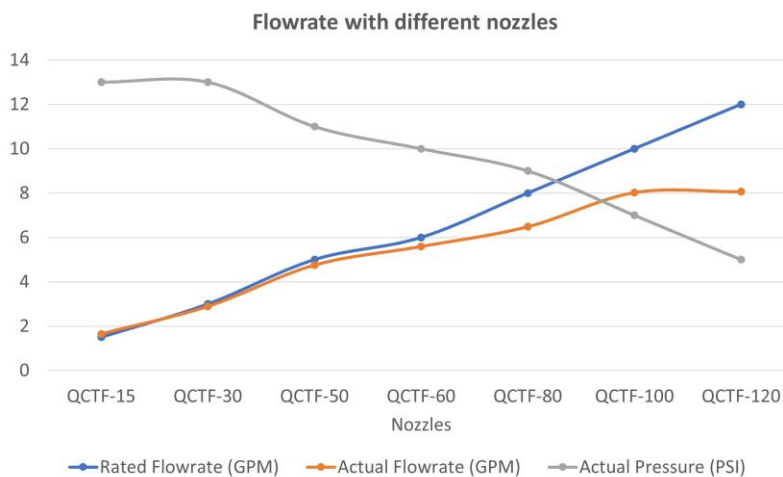


Figure 3.13 Rated vs Actual Flowrate for QCTF Nozzles

The rated flow rate of each nozzle at 10 PSI was noted from the datasheet obtained from Teejet Technologies for QCTF-VS nozzles. The actual flow rate aligned with the rated flow rate for the nozzles from QCTFVS-15 to QCTFVS-60; after that, the pump seemed stagnant in delivering more flow rate. The QCTFVS-60 nozzle delivered a flow rate of 5.59 GPM at a pressure of 10 PSI.

Swath Width

Swath widths of 24.88 inches and 28.08 inches were obtained at application heights of 4 and 5 inches, respectively, with QCTF-VS60 nozzles. The swath width was measured where the maximum volume of solution was deposited. The swath width of 28.08 inches was close to the desired width of 30 inches, so an application height of 5 inches was selected for further study.

Table 3.3 Swath Width Measurement

Experiment No.	Swath Width Measurement (inches)	
	Application Height – 4 inches	Application Height - 5 inches
P-1	24.6	29.1
P-2	25.0	26.2
P-3	25.7	28.3
P-4	24.5	28.4
P-5	24.2	27.5
P-6	25.3	29
Average	24.88	28.08



Figure 3.14 Swath Width Measurement

Speed Calculation

The results from all experiments were used as input for the volume method to calculate the optimum speed of the rover. The input parameters obtained from the above experiment were:

Table 3.4 Input Parameters for Volume Method

Particulars	Value	UOM
Best Application Rate	4	liter/m ²
Best Application Rate	4276.28	GPA
Pressure Considered	10	PSI
Swath Width	28.08	inches
Boom Height	5	inches

The vehicle speed for the QCTF-VS60 nozzle was determined using the volume method. The optimum speed for rover operation was 24.33 ft/min to obtain a desired application rate of 4276.28 GPA.

Thickness of Film Formation



Figure 3.15 6-Hours Post Spraying



Figure 3.16 12-Hours Post Spraying



Figure 3.17 24-Hours Post Spraying



Figure 3.18 48 -Hours Post Spraying

The formation of a layer on the topsoil is imperative for the proper functioning of the BioWRAP solution. Different studies have shown different thicknesses for sprayable mulch from 0.006 inches to 0.2 inches at the application rate of 2138 GPA to 5345 respectively (Giaccone et al., 2018; Kirchinger et al., 2024). The formulation sprayed in different trays exhibited different rates of percolation and layer formation. The percolation of the solution post-application in Tray 2 with the highest soil density was less compared to all other soils. Most of the sprayed liquids were easily visible above the soil. In contrast, the solution percolated fully in Tray 4 with only garden soil, and no solution was observed on the topsoil. However, the adhesion of the BioWRAP with the soil was firm and distinctively visible. Moisture content in the different trays also plays a role in forming the layer.

Trays were kept in a controlled environment for the observation. After 6 hours of spraying, the formulation was still in the liquid form in most trays except tray 4. In tray 4, as most of the solution had already percolated, it formed a good bond with the garden soil and started drying out. In tray 2, with a high soil density, a large portion of the liquid on the top soil was still mobile. After 12

hours of application, the BioWRAP formulation started to dry out in all the trays, and less liquid was observed on the topsoil. After 24 hours, trays 1, tray 2, and tray 5 had a jelly-like structure on the topsoil and were still mobile, whereas, in trays 3 and 6, the solution was dried out and turned whitish. In tray 4, the adhesion between the soil and solution was getting firmer, and the effectiveness of BioWRAP spraying was evident.

After 48 hours of application, the solution was dried out and formed a good layer in all soils based on the visual assessment. With higher soil densities, it formed like a jelly structure, black with a nice layer on the topsoil. In all the trays, there was a clear separation between the area where BioWRAP was sprayed and where it was not. It was noticed that soil moisture, density, and roughness impact the layer formation. The higher density of the soil, along with high moisture content, led to better layer formation. A portion of soil for the tray was taken to check the thickness of the layer after it was dried. The soil was cleaned before taking the measurements. The thickness of BioWRAP was measured using the vernier caliper. The average thickness of BioWRAP was found to be 0.022 inches.



Figure 3.19 Sprayed BioWRAP in different soils

Field Trials

The field spraying test was conducted by colleagues from the University of Nebraska Lincoln at multiple locations. The rover was able to spray the BioWRAP uniformly on barren land and land with corn residue. Moreover, the system sprayed BioWRAP in tilled and non-tillage soil.



Before

After

Figure 3.20 Field Spraying of BioWRAP

Summary and Conclusions

The developed spraying system was tested for different formulations of BioWRAP, and the desired application rate was achieved. The application rate of 4276 GPA was achieved with a swath width of 28 inches running the rover at 25 ft/min speed with a QCTF-VS60 nozzle on a single pass. Different application rates could be obtained by changing the rover's speed and using different QCTF nozzles with different flow rates. The system sprayed BioWRAP uniformly and formed a good layer for the proper functioning of the formulation. The average thickness of layer formation was 0.022 inches. The spraying system met all the design criteria and will help in quick experimentation with different formulations for multiple use case scenarios.

Chapter 4 - Conclusions

Summary

In the first study, a liquid application system for the under-canopy rover was designed, developed, and integrated for targeted spraying within a 30-inch crop canopy. The system comprises a tank, a diaphragm pump, hollow cone nozzles, solenoids, and a comprehensive plumbing assembly. Two spraying booms were equipped with three nozzles each. The spraying subsystem's control system utilized an Electronic Control Unit (ECU) and drivers from Teejet Technologies.

Laboratory-scale validation of the control system involved monitoring the commanded duty cycle and the corresponding voltage output from the drivers. Voltage fluctuations followed the duty cycle commands. Additionally, pressure variation tests under various operational scenarios demonstrated that system and nozzle pressure deviations remained within 5%, regardless of the number of nozzles activated or duty cycle variations.

Further, the computer vision system used for pest detection and the developed spraying system were integrated using a distance-based method. The 'tf2' library in the ROS ecosystem helped integrate the two different subsystems for precise liquid application. The transform library was used to transform the coordinate from the target detection to the sprayer. The integration was validated with the lab test, which showed an 80% effectiveness. Moreover, the initial integration result showed promising results regarding pesticide savings. An extensive field test can be done to validate lab results.

In the second study, a spraying system was designed and developed specifically for applying biodegradable mulch. The system incorporated a Sotera Double Diaphragm pump and a Quick Turbo flood jet nozzle. The Amiga platform from FARM NG was selected for its modularity and payload capacity. This application system successfully sprayed biodegradable mulch at the target

rate of 4276 gallons per acre (GPA) using the QCTFVS-60 nozzle while the rover operated at a speed of 25 feet per minute and covered a swath width of 28 inches. The sprayed mulch formed a uniform layer across soils with varying densities and moisture content. This system facilitates rapid experimentation with different BioWRAP formulations.

Future Work

The development of the spraying system for the under-canopy rover and its integration with the pest detection system has been a major milestone for the project. The next critical step, which is of utmost importance, involves integrating navigation autonomy with the existing computer vision and spraying system. This will enable the robots to navigate and precisely identify and target pest-infested plants without human intervention. Extensive field testing will validate the system's performance under diverse environmental conditions, ensuring reliability and effectiveness. Enhancing the vision and spraying algorithms will further help to optimize pesticide application based on infestation severity on each plant, minimizing pesticide use while maintaining control efficacy. Field trials will also help to validate pesticide savings, demonstrating the health and environmental benefits for farmers. Deploying multiple autonomous robots will showcase the system's scalability and potential for broader agricultural adoption.

The successful testing of the developed spraying system with different formulations of BioWRAP has paved the way for several future enhancements and investigations. One significant direction is the continuous improvement and optimization of the system. This involves refining the control algorithms to achieve even more precise application rates under varying field conditions. It also includes integrating sensors for real-time feedback to adjust the rover's speed and nozzle flow rates dynamically. Further research is needed to optimize the layer formation of the sprayed formulation. Enhancing the system's ability to maintain a consistent layer thickness across varying terrains will

also be a key objective. Additionally, field trials should be conducted to validate the system's performance over extended periods and larger areas. These trials will help identify potential challenges in large-scale deployment and provide data for further system improvements. Moreover, the output from this research could be utilized to modify the commercially available sprayers to carry out biodegradable mulch in future scenarios.

Implications

The robotic liquid application system with integrated pest detection and spraying for row crop environments has vast potential. The spatial variability of pests is always a bottleneck for making proper decisions. This system could detect different pests and, with further improvement, help geotag the location of various agricultural pests to make an informed decision. Moreover, design changes could be made to carry out site-specific spraying to control the weeds. Advanced spectral imaging could allow the rover to identify nutrient deficiencies, facilitating targeted fertilizer applications to boost plant health. By integrating early disease detection features, the rover could apply fungicides with pinpoint accuracy, curbing disease spread effectively. Further developments could enable the rover to assist in pollination, monitor plant growth, and measure soil moisture for irrigation decisions. Additionally, with yield estimation and harvest readiness assessment capabilities, the rover could provide critical insights for better crop management.

Also, the spraying system for biodegradable mulch has immense potential and usage. Biodegradable mulch development is taking place rapidly, and the system to spray these mulches will be highly sought after.

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