Design, development, and verification of a robotic spraying system and study on the application strategies for coverage optimization during site-specific chemical application

by

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Abstract

Typically, farmers use large sprayers to conduct a uniform rate whole field application for pest management without spatial pest severity knowledge. This approach leads to untimely application, inadequate coverage, and off-target spray. Large self-propelled sprayers also have inherent application rate accuracy concerns, challenges to manage boom height, and little to manage wind speeds in order to minimize drift potential. Hence, new novel concepts are needed for site-specific pesticide applications targeting critically infested plants to reduce the chemical input, decrease the negative environmental impacts, and sustainably maximize the food yield.

Robotic systems have shown tremendous potential to solve complex issues in the agricultural domain; however, systems lack which utilize a full stack of sensor and automated technologies to provide liquid application solutions to mitigate existing concerns. So, the overall intent of our research was to develop a robotic spraying system capable of site-specific chemical application to operate within crop rows and canopy, validate the sub-systems for accuracy and response time, test the performance of the overall spraying system for in-field application requirements, and quantify spray coverage using actual crop canopy structure in the greenhouse. To fulfill this objective, a four-wheel-drive differential steering mobile platform capable of maneuvering within 30 inches row crop spacing was developed to support necessary system components. In addition, a PWM-based individual nozzle-controlled spraying system having two solid vertical booms and six nozzles to conduct chemical applications was designed, built, and integrated with the robotic platform. The control system for both the platform and the sprayer was developed and validated through laboratory testing. Finally, an autonomous platform with a chemical application system was operated in a simulated crop environment in the greenhouse to

study the spray coverage utilizing different application rates, emitter orientations, and platform operating strategies.

The results demonstrated that the sprayer could maintain system pressure within ±5% of the target irrespective of the duty cycle and the number of active nozzles. The solenoids operated as intended, and the nozzle application pressure remains within ±5% of the target application pressure when operating one, three, and all six nozzles at 40% duty cycle. Also, the nozzle application pressure in two different booms and at three boom heights indicate no significant difference suggesting the developed system can spray uniformly and with a highly accurate application rate. The spray coverage data showed the highest overall deposition of 17.33% at both 15 GPA application rate and regular pass in 0° nozzle orientation (0BCT) and 15 GPA application rate and regular pass in 45° nozzle orientation (4BCT). The average spray coverage obtained was 26%, 16%, and 11% under 0BCT, and 21%, 19%, and 13% under 4BCT in the top, medium, and bottom canopy heights. In both 0BCT and 4BCT configurations, the spray coverage was higher (21.5%) in the inner lateral canopy region near the plant stalk than in the middle of the leaves (13%). The spray penetration data showed significant deposition of 21-56% of the total on plant canopy not directly facing the autonomous vehicle travel path, suggesting the capability of the sprayer to apply chemicals with sufficient droplet travel through crop canopies to provide coverage on the side of the crop not directly facing the sprayer. This study has provided valuable insights into the extent of spray drop coverage, which is significantly more than what is usually realized using over the canopy sprayers, and provided observations for potential system design improvements for great chemical deposition in the canopy in future.

Future research should include computer vision to autonomously detect the pest incidence and severity to provide decision feedback to the sprayer for site-specific chemical application. Autonomous path-planning of the rover for navigating it through the row-crops is another crucial work for seamless chemical application. Further, I recommend field testing of the robot in other crops by incorporating the findings of this research.

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Chapter 1 - Introduction

The world's population is expected to reach 9.7 billion by 2050 (UN Report, June 2019), and to feed this population, we require a substantial increase in global food production of 50% (FAO, 2017). Due to this ever-increasing demand for agricultural products and fierce market competition, farmers need efficient ways to optimize their productivity and reduce the cost of production. However, we are still much more dependent on the human workforce, and these labor-centric traditional agricultural practices are very costly; around 30% of the overall production costs are associated with the wages of employees (Henten et al., 2002). Additionally, due to the growing trend of urbanization, the wage of unskilled labor in agriculture is projected to rise by almost 100% by 2050 compared to 25% in other businesses (FAO, 2018). Hence, there is no certainty in the affordability and future availability of the human workforce in agriculture. In the meantime, the conventional agricultural machinery technologies are not fully capable of replacing human labor because of their limitations to perform highly precise tasks at a faster rate. Further, huge initial investment, high operating costs, limited efficiency, and negative environmental impacts are other disadvantages of complex and heavyweight technologies.

Improvement in farming practices, crop breeding, genetic modification, irrigation, mechanization, etc. and the development of new strategies such as integrated pest management, integrated plant nutrient systems, and no-till/conservation agriculture are assisting today's crop yields (Bawden et al., 2014 & FAO, 2003). However, these alone are not sufficient to stop the shortage of food in the near future, and due to which millions of people may be the victims of malnutrition, diseases, and starvation. Also, the additional pressure created by climate change, food losses, and change in the dietary pattern of people is increasing too much load on the land, water, and energy resources. To fulfill the global food need, either we need to substantially increase the yield growth or expand the arable land for agricultural purposes. However, the expansion of land will contribute only about 20% of the projected production increase, compared to the joint total of around 80% from yield growth (67%) and crop intensification (12%) (FAO, 2003). In order to help result in farm yields that can fulfill the needs of our nations and generations to come, we require considerable advancement in agricultural technologies, including autonomous vehicles, drones, precision in spraying, planting, fertilizing, irrigation, etc. Therefore, the research and development in advancing of above-mentioned technologies have become a prime concern for all around the world.

The advancement in sensors, control, and computer technologies enabled the realization of significant potential in agricultural food production. Consequently, there has been a considerable number of research and developmental works in agricultural automation and robotics from the past two decades in different applications such as planting, spraying, weeding, sorting, harvesting, phenotyping, etc. Although some of the developed systems are robust, precise, and fast enough in laboratory settings, the dynamic and highly unstructured agricultural environment makes these systems vulnerable in several different ways; as a result, they cannot perform all their intended tasks efficiently when it comes to real-world agricultural operations. For example, a robotic harvesting system needs to take into account the different plant shapes and size, fruit location, fruit color, texture, branches, leaves, etc. in every single plant in the field under different lighting, humidity, wind, and other environmental conditions and be capable of dealing with these inherent challenges to work efficiently (Shamshiri et al., 2018). Additionally, the robot subsystems such as computer vision, robot navigation, end effectors, data acquisition, and data communication must work in unison and be robust, consistent, and efficient enough to automate the tasks reliably. If we can precisely overcome such challenges, the world's agriculture could provide a new dimension to the socio-economic aspects of the people around the globe. Complete knowledge of the previously developed and currently available technologies with their pros and cons, therefore, is vital before moving towards the development of another system.

Agricultural spray applications have been historically one of the critical components of crop production systems; timely and effective pest control can significantly affect crop yield. The row crops, among other crop inputs, utilize $15.2 billion worth of agricultural insecticides and fungicides for insect and disease control, respectively. Hence, it is imperative to site specifically use the pesticides in a controlled manner. The limitation to only apply where the product is needed is primarily driven by the time it requires a person to extensively scout every part of the crop field and map the distribution of insects, which is not a realistic management strategy. In addition, understanding the spatial pattern of pests inside the crop field based on the sampling, in reality, is difficult as the bugs might be clumpy, patchy, or randomly distributed. Hence, the producers follow a human-centric approach to make spray decisions where they do not account for the actual distribution of pests in the field; instead, they depend on their past observation or experience. As a result, farmers conduct blanket insecticide applications intermixing plants at harmful levels with non-infested plants. It explains that current pest management strategies lack real-time spatial insect infestation knowledge and force producers to apply chemicals on areas that may not even have an insect infestation, leading to increased input cost and a detrimental impact on our soil, crops, water, and air.

In the US, crop producers commonly use large self-propelled and pull-behind sprayers to conduct broadcast pesticide applications over an entire field. These machines used flow-based liquid control systems regardless of the sprayer width and travel speed to manage the application rate. However, the nozzle application pressure usually varies during the field operation; the application variation of 6.7% to 20% was reported by Sharda et al., 2013. This high variation in application pressure causes the nozzle output to change, leading to the off-rate application away from the target in the majority of the field. The pulse width modulation (PWM) is a variable rate technology that offers several advantages over flow-based systems. The solenoid valves are electronically actuated by varying the duty cycle, which helps manage the flow rate at the nozzle level, reduce the pressure variation, and ultimately the application errors. Mangus et al., 2017 showed nozzle application pressure error within ±5% irrespective of section control actuation. Maintaining a uniform pressure also maintains spray angle and droplet size to provide proper spray coverage while minimizing the spray drift. This technology also provides a turn compensation feature and individual nozzle diagnosis capability. However, these large machines are not capable of conducting site-specific liquid applications based on pest severity knowledge. Only treating damaging pest populations is dependent on technologies capable of targeting insecticide applications; such a system or technology does not currently exist to our knowledge.

Intelligent spray application technologies capable of site-specific spray decisions can potentially reduce the amount of insecticides sprayed on field crops leading to improved efficiency, decreased cost of chemicals, and dramatic reductions in environmental impacts. There are primarily three areas not fully exploited but can potentially facilitate the site-specific application of pesticides in row crops. They are: 1) a computer vision system to identify the real-time pest incidence and severity to provide the spray decision to the chemical application system 2) liquid application system capable of conducting site-specific on target pesticide application 3) robotic platform capable of autonomously navigating within the crop fields carrying all the necessary system components. Once the system is in place, it is important to understand the pesticide coverage and distribution within the plant canopy. Also, the selection of different nozzles, emitter orientations, application rates, etc., might impact the coverage and provide critical information for system design improvement, commercial implementation, and adoption of robotic spraying systems. However, there are no past studies with the robotic chemical application system that focused on the spray coverage by aligning the water-sensitive cards in row crops.

Considering the above requirements, this study was primarily focused on the development and testing of a robotic platform and a liquid application system with the following four major objectives:

- Design and develop a robotic platform and a low-pressure spraying system to precisely apply pesticides in row crops.
- Validate the overall spraying system components and systematically evaluate the pulse width modulated (PWM) individual nozzle control spraying system.
- Quantify the spray coverage at three different plant heights under different application rates, nozzle orientation, and the number of passes.
- Using the same configurations, evaluate the spray coverage and penetration along the lateral canopy regions.

Chapter 2 - Design, development, and evaluation of a site-specific liquid application system for a robotic platform

Abstract

Despite having much improvement in sensing, automation, and control, the current broadcast spraying system has several drawbacks, such as skips, excessive chemical use, and off-rate applications. Typically, farmers use large self-propelled sprayers to spray on the entire field without spatial pest severity knowledge, potentially resulting in an unintentional application. However, application errors and the extent of chemical use can be optimized utilizing an intelligent sense, identify and manage platform (SIMPL) capable of site-specific decision-based spray to control pests at higher efficiency. Hence, the initial project goal was to design a robotic platform and a liquid application system to conduct accurate site-specific applications. The critical design considerations for the spray application system were modular; the ability to be mounted on an autonomous platform to go within 30-inch spaced crop; spray on either side of the crop row; onboard hardware and software for control and data acquisition; and record as-applied data. A system with desired design requirements was built, and individual sub-systems were tested under simulated lab scenarios to quantify the response time and accuracy of the spray system. The results showed that the sprayer could maintain a system pressure within ±5% of the target under different duty cycles and number of nozzles. Also, the individual nozzle application pressure is within the ±5% of the target irrespective of number of active nozzles, and no significant pressure difference was observed between nozzles installed at different heights in two different booms. Therefore, this application system will be a viable solution for autonomous platforms to apply pesticides only on critically infested plants, has the potential to decrease the overall input costs on chemicals, and reduce the negative environmental impacts.

Introduction

U.S. farmers annually spend around $12-15 billion worth of pesticides, but 37% of crops are lost due to damage by pests. This massive production loss despite high investment in pest management is a significant threat to global food security. Insect pests could be present in varying severity and potentially not present in the entire field, but the producers cannot manually locate the pest incidence, severity, and sites due to time and labor constraints. Hence, farmers use self-propelled and pull-behind sprayers to conduct a whole field application by waiting until the insect infestation reaches a certain minimum threshold, which is calculated based on a subset of the plant population. In some cases, plant injury has already occurred while other plants remain pest-free, and a proportion of the plants in a field will require intervention to prevent yield loss, where insecticides are warranted. Therefore, relying solely on blanket applications can result in untimely applications, unnecessary chemical use, and off-target spray.

The sensing, automation, and control enhancements have tremendously improved application accuracies. Introduction of variable rate technology (VRT) was one of the consequence advancements to implement and manage target application rates. Research have shown that VRT has provided a 58% saving in spray volume while maintaining the same spray deposition comparing to a conventional spray application method (Llorens et al., 2010). Over the past decade many new sprayers years much research has been conducted on design, implementation, and validation of variable rate sprayers (Escola et al., 2013; Gil et al., 2013; Jeon et al., 2012 & Chen et al., 2012) for orchard, vineyard, and nursery applications. Most newly designed sprayers conduct the liquid application based on the canopy volume. These sprayers can also conduct spot chemical application based on the sensory feedback, in crop like blueberry and others (Zaman et al., 2011). Recently, the application of machine vision approaches has been utilized to provide the decision feedback for a site-specific spraying system (Asaei et al., 2019). Machine vision systems have demonstrated that the site-specific management approach consumed 54% fewer chemicals compared to the continuous spraying method. However, current system only considers the presence or absence of a green tree canopy to conduct chemical spray.

Understanding the pest incidence and severity before conducting spray application could significantly reduce the chemical use, decrease the negative impacts on the environment and sustainably maximize the production yield. Row crops (typically 0.762-meter row spacing) offer a unique opportunity for small vehicles to maneuver between the rows to spray chemicals. It also allows a very high resolution vertical and lateral access to detect pests and site-specifically spray only on the infested plant in a row. Due to this, precise management of pests is possible, given that a suitable chemical application system can be developed and machine vision is effective at identifying pests in real-time. A robotic platform together with a spraying system can solve such pesticide application problems.

Numerous works both from the universities and industries show the development of various robotic platforms for different applications. Many robotic platforms designs have been conceptualized (Bawden et al., 2014 and Bakker et al., 2010) and developed (Shamshiri et al., 2019) for three types of operations: harvesting, spraying, and scouting. Past research and platform developed have provided significant background to design, develop and validate a robotic spraying system capable of site-specific spraying in row crops (Nuyttens et al., 2004 and Foque et al., 2012, Bode et al., 1992 and Grisso et al., 2014); however, no robotic system exists which can currently utilize computer vision-based insect infestation feedback to site-specifically apply pesticide while traveling with crop rows.

Therefore, the main objectives of this project were to: 1) design and develop a robotic platform that can maneuver within a 76.2 cm row-crop spacing carrying a liquid application and other sub-systems; 2) validate the overall spraying system components used to see if it can precisely apply pesticides; and 3) systematically evaluate the pulse width modulated (PWM) individual nozzle control spraying system.

Materials and Methods

The robotic platform and spraying system were designed with critical consideration to many desired features, numerous mechanical and control approaches and their compatibility to functional environment available within crop rows. A robotic platform with a spraying system was then developed and validated to quantify the functionality, response and accuracy of various sub-systems.

Crop Environment

The row-crop grain (corn, sorghum, and soybean) industry represents around 25% of the agricultural sector in the U.S., and proper pest management is an integral part of maximizing crop growth and protecting potential yields. Many factors such as row and plant spacings, headlands, soil type, canopy structure, and variability of inter-row spacing, is unique in every field. Therefore, knowledge about the row crop characteristics and the surrounding environment was the primary requisite to develop a robotic spraying system. This study was designed considering corn and sorghum crop environments, which provided baseline information to determine system specifications, such as the platform size, sub-component materials, spray boom position and height, and nozzle body integration. Additional design considerations included system stability, ground speeds, minimal crop damage, and smooth maneuvering. In summary, the complete knowledge of the crop, weather, topology, boundary, etc., were considered in determining the functional requirements (drive, steering, safety, load, navigation, maintenance, etc.) to develop a robust and operational spraying system for row crops.

Robotic Platform

The success of a robotic system depends upon the functionality and performance of the mobile platform in a particular environment. Thus, it was vital to consider different aspects of the vehicle and field conditions while designing a complete operating rover. Some of the functional requirements taken into consideration included: the ability of off-road locomotion; low cost, easy to manufacture and maintain; lightweight, robust, safe, and reliable; modular chassis with high payload capability. Based on the above requirements, a comparative study of a few sub-systems (Table-1) in different operational modes was done to get an understanding on the relative advantages of one over another.

Table 2-1: Comparative Study of sub-systems for a robotic platform design

S.N.	Subsystem	Option 1	Option 2
1.	Locomotion	Wheel	Track
2.	Drive	2 wheel	4 wheel
3.	Steering	Differential	Acreman
4.	Power	Battery	Engine

Also, a detailed study on material type, chassis construction, maintainability, modularity, and payload was done to build a sturdy system for agricultural domain. The following are some critical design and performance criteria of the vehicle:

a) Traction: Even though the track system can provide high traction, its high weight, mechanical complexity, cost, locomotive efficiency, and maximum soil disturbance make the wheel system a better choice in agricultural robots (Bawden et al., 2014). Taking all these factors into consideration, it was decided to design the platform having tires for locomotion.

b) Stability: The stability of the rover plays an important role, especially on uneven agricultural surfaces. A platform having four wheels is preferred over two or three wheels, and the center of mass of the vehicle should be kept as low as possible to reduce the chances of tipping. Hence, a four-wheeled platform option was considered in platform design keeping the total height within 30.5 cm.

c) Maneuverability: Agricultural fields have varying terrain, crop residue, irregular surfaces, varying soil and uneven surface wetness. In such environment, a 4-wheel drive differential steering system would provide greater stability for overcoming the obstacles. A suspension system would further help keeping the wheels in constant contact with the ground; however, suspension system increases the cost and mechanical complexity of the system (Bawden et al., 2014). Considering the cost reduction and narrow space available between rows, platform was designed without a suspension system.

d) Drive Type: Another important sub-system to be considered while designing the platform is the drive systems. Some field operations such as tillage demand high power; in such cases, robots with hybrid power supply (battery and fuel generator) might fulfill the requirements. However, the current system needed to navigate in straight lines between the crop rows in flatlands with a spray system of known payload. Hence, a fully electric drive type was deemed suitable. A motor (E722, Electro-craft servo products, Gallipolis, OH) with a reduction gearbox drives a tubeless tire (145/70-6, Clever) compatible with 6” diameter rims.

e) Batteries: The robot battery should power at least the wheel motors, sprayer pump, servomotors, solenoids, image processing systems, and data communication devices. Each large battery was composed of two 22.2V 16000 mAh lithium polymer (LiPo) batteries connected in parallel, doubling the total capacity to 32000 mAh. When connected in parallel, the two large batteries could provide up to 64 Ah, yielding a total battery capacity of 1.42 kWh. The battery housing was designed at the center of the robotic platform spanning the width of the platform and underneath the top mounting plate of the robotic platform.

f) Chassis: Producers will primarily operate these machines in rural agricultural fields far away from the cities or towns having fewer infrastructures, so the chassis of the vehicle was designed for easier operation, repair, and maintenance. T-slotted rails were used to connect the two sides of the platform and expedite the assembling and dissembling process. Also, aluminum was chosen as a material to construct this chassis for weight reduction.

g) Modularity: The ability of the robots to adjust to a different environment by simply reconfiguring track width, strength, length, height, implement type, etc., makes the rover more modular, versatile, and multipurpose. In this vehicle, the track width is made adjustable by replacing the aluminum rails. T-slotted rails at the front and back allow easy integration of any implement types. However, the length and height were designed to be fixed for this platform.

h) Payload: This platform can withstand the load of the entire system components and maneuver in the agricultural fields without fail. Preliminary tests were conducted in the laboratory and in the field environment utilizing payloads of up to 90 kg. It was able to maneuver without any concerns and was able to maintain operating speed of up to 11.3 km/h under all test conditions.

The resultant vehicle is a 4-wheel drive, differential steering platform capable of bidirectional movement between the crop rows. The payload capacity is sufficient to carry 75.7 liter pesticides and other required sub-systems. To integrate the spray booms, T-slotted framings were mounted at the back of the platform. Figure 2.1 shows the final 3D model of the developed platform.

Figure 2.1: Final 3D Model of the Platform

Platform Control

Goals of the proposed study were to develop a control system to operate the vehicle at constant speed in a straight line for systematic preliminary validation of spray system response time and accuracy during spray application. An incremental encoder (model 260 – incremental encoder, Encoder Products Company, Sagle, ID) that outputs 1024 cycles per revolution of the motor shaft having measurement accuracy within 0.01° mechanical was integrated to measure the vehicle speed. A same voltage can be supplied to the motors installed on the same side of the differential drive platform. Hence, a 2×60 dual motor driver (Sabertooth 2×60, Dimension Engineering, Hudson, OH) was deemed sufficient to power all the DC brushed motors of the vehicle. The selected motor driver can continuously supply up to 60A per channel, and it comes with thermal and overcurrent protection. It has two terminals (B+ and B-) to supply the power from the battery, motor terminals (M1A/M1B, M2A/M2B) to supply power to the motors, and signal input terminals (SP1 and SP2) to control the motor driver.

A closed loop proportional integral derivative (PID) control system was designed to sense the speed of the motor and adjust it based on the desired or the reference signal. To implement PID, a national instruments myRIO 1900 and encoders were programmed with LabVIEW software. A gravity MOSFET power controller was used to start or cut off the power supply to the motor driver battery terminal. It acted as an emergency stop switch as well.

In the developed LabVIEW program, the desired motor speed for each side of the rover was preselected. The software then reads the encoder counts and computes the error value from any difference between the actual motor speed measured by the encoder and the set desired speed. Finally, the PID program converts that error value into a command (PWM) signal that adjusts the voltage supplied by the motor terminals to run the motors at the set speed. The figure below shows the block diagram of the PID portion of the code:

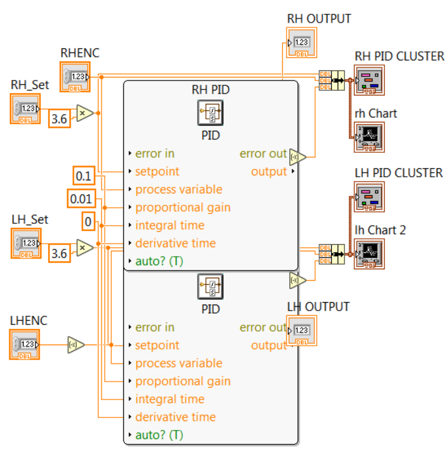


Figure 2.2: LabVIEW PID Program

A 24V supply from the battery was connected to a DIN rail terminal block and distributed to the motor driver battery terminal, and two rail converters (DDR-15G-5 and DDR-15G-12 DIN, Mean Well USA Inc., Fermont, CA). The 12 V output from the DDR-15G-12 DIN rail converter was supplied to power the NI myRIO. The 5V was fed into a separate terminal block and powered the encoders and gravity MOSFET controller. Additionally, three 30-Amp circuit breakers protect the circuit from damage in case of overload or short-circuit by preventing the current flow.

Figure 2.3: Platform Electrical Enclosure

The Data Dashboard software allowed us to create and control LabVIEW applications using iPad. A network-published shared variable created in LabVIEW, developed a real-time application, and deployed these variables as sliders and switches. The myRIO was configured through NI MAX to create a wireless network. It allowed the data dashboard app on the iPad to connect to the myRIO through wifi. On the iPad, a new dashboard was created and inserted the required sliders and switches. The dashboard was linked to the shared variables and customized to control the rover speed and direction.

Spraying System

Spraying site-specific insect-infested locations on field crops can substantially increase the spray efficiency, decrease the cost of chemicals, and reduce the environmental impacts. The basic functionality of a site-specific spray system is to accurately and effectively spray all the infested sites on the plant. Therefore, a liquid application system was designed and developed to spray on either side of the autonomous platform. The sections below describe the individual system components and the design process in more detail:

Tank Selection

One of the key design considerations was the tank selection. Two main tank selection criteria were the need to frequently fill the tank and the capability of the rover to carry the liquid. Besides the above two, corrosion-resistant, easy to fill and clean, tank profile, adequate openings for hydraulic lines, and fluid level markings were considered. The developed rover was capable of carrying 75.7 L of spray liquid. Also, considering the application rate of 112 LPh^{-1}, a 75.7 L of liquid can spray on a 0.68 ha field at 100% infestation condition. The area keeps increasing as the percentage of infestation keeps decreasing. For example, in a crop having 10% infestation, 75.7 L can cover a 6.8 ha field at 112.2 LPh^{-1}. Hence, 75.7 L tank seemed large enough volume for our application.

The polyethylene tanks are lightweight, compatible with many agricultural chemicals, have fewer chances of stress cracking, and are available in different sizes and shapes. However, this type of tank requires proper mounting so the tank does not dislodge or cause any damage while traveling over obstructions in rough agricultural terrain. Based on all above requirements, a 20-gallon polyethylene tank (72.39cm L × 39.37cm W × 19.05cm H) was selected and mounted with cradle and bands and placed over the robotic platform.

Boom Design

Two solid booms were designed for the left and right sides of the robotic platform. The boom length was estimated using the approximate height of the main row crops such as corn and sorghum. Each boom has a height of 1.2 m, where each nozzle was placed at 0.4 m spacing, starting from 0.2 m of the lower end of the tube. When kept at the center of the 30-inch row-row spacing crop, these booms can provide 50% vertical spray overlap during broadcast application. However, the percentage overlap varies depending on the boom placement and the crop row-row distance. The three nozzles at each boom can spray at any plant height, and the addition of individual solenoid actuation capability will fulfill the site-specific application requirement.

Figure 2.4: Vertical Sprayer Booms

Hydraulic Flow Requirement

The most important part of a spraying system is the pump selection. Many pump types are available and broadly classified into positive and nonpositive displacement pumps (Grisso et al., 2014). The output of a positive displacement pump is independent of the pressure, and it discharges a specific volume of liquid at each pump speed. On the other hand, the discharge capacity of a nonpositive displacement pump varies with pressure (Grisso et al., 2014). The diaphragm pump was selected and is a positive displacement pump with several benefits: less costly, energy-efficient, well-suited for chemicals, and can supply the desired flow rate at the desired pressure. The pump should supply to fulfill the spray requirements, agitation requirements, and account for the pump wear (typically 20% greater capacity). Based on these requirements, the pump capacity was determined as follows:

Pump capacity (LPM) = (Boom requirements + Agitation requirements + Other accessories + 3.78 LPM) × 1.2

where,

Boom requirements (LPM) = Number of Nozzles × flow discharge of each nozzle

Agitation requirements (LPM) = 5-10% of the tank's capacity (took 10% while designing)

Other accessories (LPM) = Extra flow needed for strainer cleaning, spray gun operation, etc.

3.78 LPM = To ensure the proper functioning of the bypass valve

1.2 = 20% greater capacity for pump wear

Pump capacity = 14 LPM

Considering there might be a need to expand this spraying system and the possibility to use large orifice nozzle tips, a diaphragm pump (5537-2E1-63B, Remco, Alexandria, MN) that can discharge 14.6 LPM liquid at 275.8 kPa was selected. This pump operates at a 12V DC power supply and can prime up to 4.3 m.

Hydraulic System Design

Hydraulic components such as the pipes, hoses, fittings, and other accessories that fall in the hydraulic lines should be able to withstand the chemical chemistries at the operating pressure. So, it is critical to consider the construction, composition, sizes, and environmental factors while selecting individual components. Polypropylene fittings were used on the suction and discharge side of the motor rather than hoses to eliminate the chances of collapsing. The polypropylene material is highly resistant to aggressive chemicals reducing the likelihood of wear and possible breakage. The lines were constructed to be as short as possible and easily fit within 38.1 cm spacing under the tank. Also, it was essential to select correct-sized lines to maintain an adequate velocity in the circuit. If the inside diameter of the hoses is large, the fluid speed will be low, and the pesticides will settle down. On the other hand, the small-diameter lines will create an excessive pressure drop. Therefore, for the flow rate of 14.6 LPM, the suction side line diameter of 1.9 cm and the discharge side line diameter of 1.3 cm were selected (Grisso et al., 2014).

For the proper operation and sustainability of the spraying system, some other components are necessary. These components include a strainer with right mesh size, shut-off valve, pressure relief valve, agitation valve, hoses, nozzle bodies, caps, etc. The line strainer plays a crucial role by preventing the chances of pump damage, nozzle clogging, and spray non-uniformity issue. As we have a positive displacement pump, a screen (Teejet, AA(B)122-3/4-PP-30) having 30 mesh size was installed between the tank and the pump (suction side), and other smaller strainer (Teejet, AA(B)122-1/2-PP-50) having 50 mesh size was installed after the pump on the pressure side. A pressure relief valve installation is an integral part of any spraying system having a positive displacement pump. The spring-actuated relief valve allows the liquid to flow back to the tank while maintaining the required system pressure. Therefore, an adjustable pressure relief valve (Teejet (23120-*-PP-60-VI) - 1/2) capable of handling system pressure up to 413.7 kPa was used. A separate agitation line ensures a constant volume flow for the agitation irrespective of the number of nozzles activated or sizes. Therefore, a jet agitation shut-off valve was installed at the jet agitator return line. Another shut-off valve installed right after the tank allows the cleaning/maintenance of successive components without clearing the entire tank. 1.3

cm white braided hoses were used in the hydraulic lines and can easily handle the system pressure. Nozzle bodies from Teejet (QJ17560A-NYB) were fixed on the wet booms, and PWM solenoid valves were mounted. Finally, the hollow cone nozzle tips were fitted with the nozzle bodies using nozzle caps (25608-6-NYR). The figure below shows a complete hydraulic circuit:

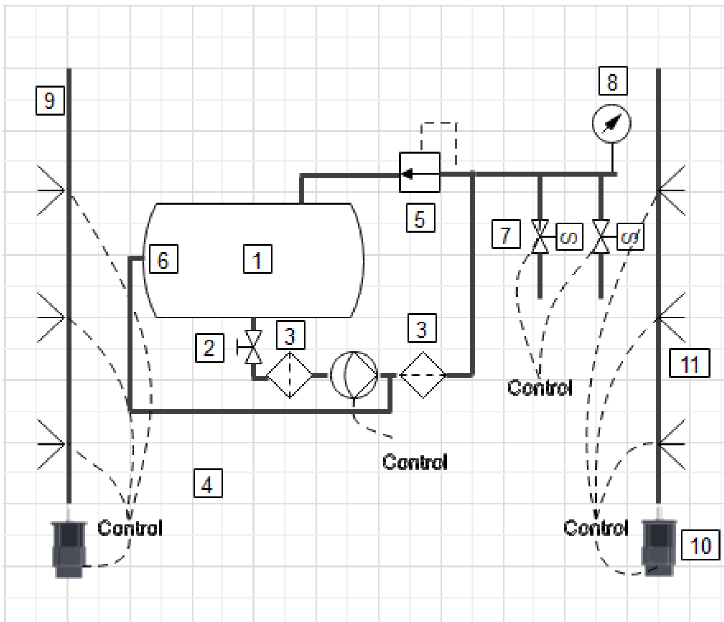


Figure 2.5: Hydraulic Circuit

PWM Technology and Nozzle Selection

The flow-based liquid control system is available in many large self-propelled sprayers. While conducting chemical application using these systems, the operator needs to vary the speed due to the obstacles, field shapes, headlands, etc. In such situations, the flow-based sprayer control changes the liquid flow rate to accommodate the speed variation and maintain the target application rate. Due to this, the pressure at the nozzle varies and affects the droplet size distribution, drift potential, and ultimately the spray coverage and penetration in the crop canopies. A study conducted by Sharda et al., 2013 showed that the nozzle pressure varied between 7-20% of the target. However, the emerging PWM technology markedly reduces the above drawbacks of a flow-based spray control system by maintaining the pressure within ± 5% of the target regardless of section control (Mangus et al., 2015). In this system, the solenoid valves are installed in front of the nozzle tips without any structural changes. The solenoid valve helps to maintain a constant application rate at constant pressure by changing the actuation pattern based on the duty cycle input according to the speed variation. This technology allows individual nozzle shut-off control and a turn compensation feature to ensure a consistent application rate.

The purpose of nozzle tips in the sprayer is to break the pressurized liquid into fine droplets and form a unique pattern while discharging. Appropriate nozzle selection is vital as it determines the application volume, droplet size, foliage penetration, and even drift tendency among other variables. Hence, a proper understanding of the nozzle types, materials and identifying the right orifice size is essential. In low-pressure applications, the commonly used nozzles types are a fan, hollow cone, and full cone. Several material options are available while purchasing the nozzle tips. The Stainless-steel nozzles usually last for a longer duration producing a uniform spray pattern than nylon and brass (Klein et al., 2011). Therefore, a hollow cone nozzle made from stainless steel was selected for this system as it can penetrate the foliage and provide maximum coverage on the leaf surfaces (Slocombe et al., 2015). Even though the drift potential of the hollow cone nozzles is high due to the small droplet sizes, this nozzle deemed suitable as there will be very little to no air movement inside the crop canopy.

The nozzle size depends on the application rate, effective spray width, and the ground speed of the sprayer. The calculation of proper nozzle orifice sizing of the PWM system is similar to that of flow-based sprayers. The only difference being the PWM system takes the duty cycle into account. The target application rate, application pressure, and sprayer speed are 112.2

LPh^{-1}, 275.8 kPa, and 1.6 kph. Hence, we selected a stainless-steel Hollow cone nozzle based on the nozzle selection guidelines provided by Fabula et al., 2019.

Boom Rotation

A servomotor was installed at the bottom of each boom to rotate them forward and reverse during spray application. This mechanism helps in automatically setting the boom position to the desired angle before conducting a real-life experiment. Additionally, we can explore the effect of quickly rotating the booms on the spray coverage in the canopy. Hence, a Lynxmotion high torque (Lynxmotion HT1, Roboshop Inc. company, Swanton, VT, USA) smart servo was chosen to rotate the tubes. The main base plate was fabricated from aluminum, and a housing cover was 3D printed to fix the servo and protect it from environmental conditions. A 24-tooth hub shaft connects the servomotor shaft to the boom base plate, which sits on the top of a lazy susan bearing. Two1.3 cm pillow blocks were embedded at the top and bottom of the main base plate to support the hub shaft and free the rotational movement. The outer part of the lazy susan bearing was fastened at the main base plate, and the inner side allowed the free rotation of the boom base plate. Dual side mounts secured the aluminum channel vertically on the top of the boom base plate. Finally, the booms were installed inside the aluminum channel with support from bore-side tapped clamping mounts. It allowed solid structural support and rotating ability to the tubes.

Structural Features

Numerous structural designs were accessed while developing the liquid application system, integrating it with the rover, and providing different functionalities. A cradle (72.39cm L × 39.37cm W × 19.05cm H) was designed to place the tank on top of it, and enclose all the hydraulic and electronic components underneath it. Three bands were fabricated to secure the tank with the cradle to protect the tank and avoid any damages while maneuvering. Most of the structural components were fabricated from aluminum to reduce the overall weight of the system. A rectangular frame was developed and fixed at the rear side of the platform to attach the booms. A support rail extension beneath the frame makes the tubes rigid in all directions. These booms can slide along the width of the frame, and this functionality is critical to adjust the spray overlap as per the row spacing. The entire rectangular frame can move up and down. It allows us to change the vertical positioning of the boom, and this capability lets us use this system in different crops and throughout the crop cycle. Additionally, the rectangular frame together with the tubes can be forward-folded to protect the system from possible damages during transportation.

Figure 2.6: Structural Design of Robotic System

Sprayer Control

The sprayer control and data acquisition system must manage four primary components; a liquid pump, the PWM solenoids, servomotors, and the pressure sensors. The pump is considered a heart of an agricultural chemical spraying system and is the most power-consuming part. Hence, we have decided to operate the pump only when there is a need to spray the liquid rather than continuously running it. Thus, a gravity MOSFET controller was used and programmed in LabVIEW to switch the pump on and off. This controller has a 1KHz switching frequency, and it works when it gets the digital-high signal in the 3.3-10V range.

The solenoid valve is an electromagnet that typically remains in a close state by a plunger and a spring to eliminate the product drain. The solenoid achieves the opening and shutting of the product flow based on the duty cycle and frequency of the PWM signal. The duty cycle determines the amount of time the solenoid is in ON-state out of total duration. For example, if the nozzle operates at 10 Hz frequency and 60% duty cycle, it means the electromagnet remains activated for 60 milliseconds out of every 100 milliseconds. This feature of PWM technology helps maintain constant system pressure, offers a variable rate capability, turn compensation feature, and provides higher application resolution. Six relays (70G-ODC15, Greyhill Inc., La Grange, IL) and two I/O relay module racks (70GRCK4R, Greyhill Inc., La Grange, IL) with NI 9375 DIO module were employed to energize/actuate the solenoids within milliseconds. The relays are DC output modules having 0.02 milliseconds turn-on time and 0.05 milliseconds turn-off time. The relays require 15V DC input and outputs 3-60V, 3.5A DC. Each rack has four channels which allow the fitting of four relays with the help of screw terminal blocks. Since the solenoid is an inductive load, flyback diodes were installed to prevent the inductive kick (back e.m.f.) and possible damages.

Four pressure sensors (PTC-2, PCB PIZOTRONICS, Depew, NY) were installed to seamlessly acquire the pressure data from different points of the sprayer hydraulic circuit. These sensors can measure the pressure between 0-689.5 kPa, outputs the signal in the range of 0-10 V, and has a sensitivity of 0.1 V/psi. They were installed at the sprayer manifold and bottom, central, and the top nozzle body. The pressure sensor at the manifold records the system pressure, and the sensors along the boom height measure the pressure at each nozzle.

The control and the test data collection were accomplished using a NI cRIO 9042 chassis. This chassis was coupled with three different c series I/O modules. The NI 9375 c series module is a 32 channel (16 DI and 16 DO) industrial logic capable digital I/O interface whose input and output lines are 24V and 6-30V logic level compatible. This module has a 7 µs input and 500 µs output update rate and was used to energize the relays to switch the solenoids on and off. The NI 9403 digital I/O module is a bidirectional module having 32 channels and an update rate of 7 µs. It was used to send the digital output signals to drive the servomotor and switch the pump. The NI 9221 C-series voltage input module is an 8-channel single-ended module having an 800 KS/s sampling rate and a 12-bit resolution. This module was employed to collect the pressure data from the pressure sensors installed at different positions in the sprayer.

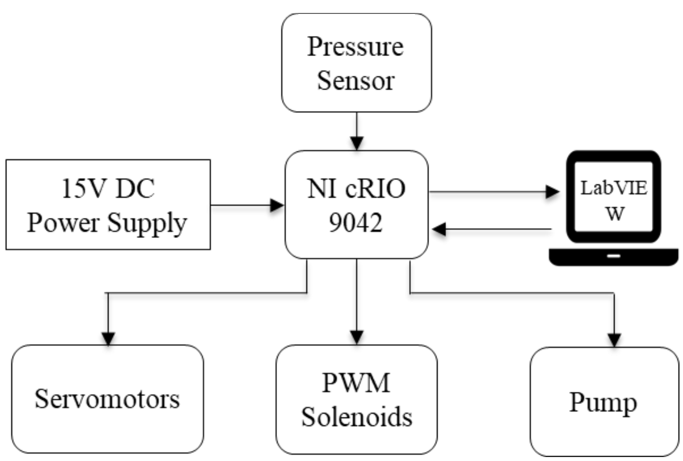


Figure 2.7: Sprayer Control Flow Diagram

A LabVIEW program was developed to run on the cRIO to control the sprayer and collect the pressure data. The input parameters such as the solenoid frequency, duty cycle, data loop rate, etc., can be provided from host VI. It was programmed to compute the PWM signal to the servomotor, write the pressure data with the time stamp in a text file, and store the text file at a specified location. On the other hand, the FPGA VI switches the six solenoids, two servo motors, and a pump and reads the pressure sensor data. Inside a while loop having 1ms loop timing, a flat sequence structure was developed, and shift registers were kept running at an increment of 1. It allowed us to develop the code such that the shift register resets and another cycle starts when the count reaches a set frequency value. Under the same while loop, when the counter value remains under the input duty cycle time (ms) obtained from the host VI, the solenoids turn ON, otherwise remains OFF. It switches the pump and servomotor directly based on the input it receives from the host vi. The software continuously reads the pressure data based on the defined sampling rate. The overall system (cRIO and LabVIEW) was tested by connecting to the laptop using a c type USB cable. Each component was switched ON and OFF to see the functionality and observed the incoming data stream on the LabVIEW front panel. The text file was checked to see if it is writing the correct data at the desired sampling frequency or not. It ensured all our hardware and the developed software were working fine.

A 24V battery power was supplied from the terminal block of the rover to a terminal block of the sprayer. It was then brought down to 15V, 12V, and 5V using three voltage transformers and supplied to three separate terminal blocks. The 15V power was required to provide input to the relays and cRIO, 12 V to run the pump, solenoids, servomotors and pressure sensors, and the 5V to switch the gravity MOSFET controller. To convert 24V to 12V, an industry-grade DC-DC step-down converter (24V-12V, KEEDOX) having 96% power conversion efficiency was used. This device is IP68 rated (weatherproof) and comes with under/over-voltage, overload, and short circuit protection. It can output 240W power (20A output current) and provides ±1.5% voltage accuracy, which was good for our application. For the 15V and 5V conversion, two step-up/down power modules (Hilitand84oh3qztv0, Hilitand) capable of converting 5-32V to 1-30V in both directions were used. This converter also comes with voltage protection and can output a maximum 10A current and 130W power. All the signal and power lines are connected from the devices to the control enclosure using a 24-pin box mount receptacle and a circular straight-pin connector. It allows for quick engagement and disengagement of the control box and helps in diagnostics and troubleshooting. The data dashboard app was customized to include the solenoid duty cycle, pressure sensor reading, and switches to activate the nozzles for remotely controlling the sprayer.

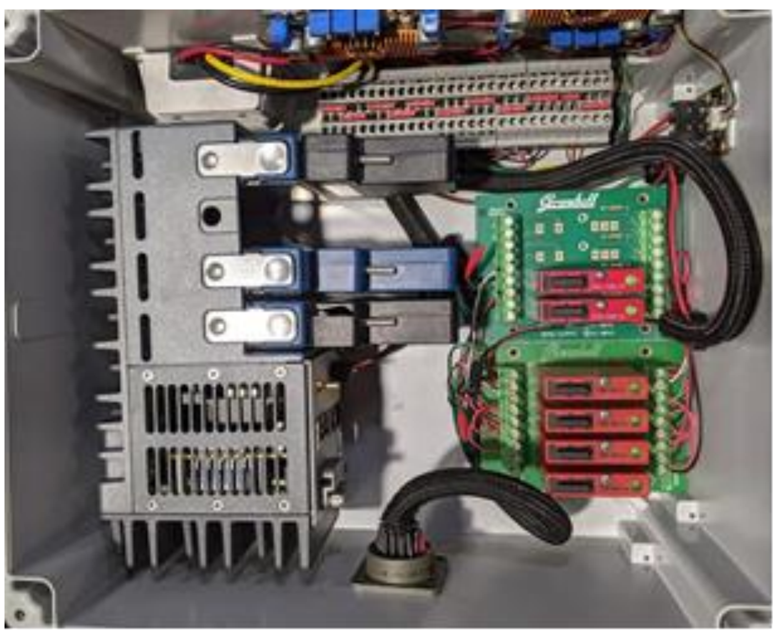


Figure 2.8: Sprayer Electrical Enclosure

Data Acquisition and Processing

One of the significant advantages of PWM spray controllers is maintaining a constant system and nozzle pressure. Hence, it was essential to measure the pressure at few different locations and understand the functionality and capability of the developed spraying system during operation. A pressure sensor was installed at the sprayer manifold, and four other pressure sensors were mounted right before the nozzle tips at four nozzle bodies. The sensor model was PTC-2 from Piezotronics with a less than 1 ms response time. At all tests, the solenoids were operated at 10 Hz, and pressure data were recorded at 1000 Hz using NI cRIO, NI 9221 I/O module, and LabVIEW 2019. The pressure data was recorded in the text (.txt) format for about 20 seconds and was imported into the excel sheet for further processing. The system pressure data were averaged to get 1-sec data and plotted for 20 seconds to see the pressure variation due to duty cycle and number of active nozzles.

The signal input to the solenoid was measured at the same frequency (1000 Hz) and plotted for one solenoid cycle (100 ms) together with the nozzle pressures to evaluate the functionality of the PWM system. Measurement was done at the bottom nozzle of the right boom by turning ON one, three, and all six nozzles at a randomly selected duty cycle (40%) to compare the nozzle pressure stability with the target pressure under different active nozzles. It was important for a vertical boom spraying system to understand the nozzle pressure variation at three different vertical positions. For this, the nozzles installed at three heights were individually activated to measure the corresponding signal and pressure data. Finally, to ensure the pressure consistency between two booms, the measurement of pressure and solenoid signal was done at the bottom nozzles of each tube. The .txt files were imported into excel and processed further.

Results and Discussion

System Pressure Response with Duty Cycle

The system pressure was recorded at different duty cycles by turning ON one nozzle. The mean pressure values obtained were 283.5 kPa, 281.0 kPa, and 282.3 kPa with a standard deviation of 0.04, 0.02, and 0.06 for 20%, 40%, and 60% duty cycle respectively (Figure 2.9). It explains that there is no significant difference in the system pressure due to changes in the solenoid duty cycle. Also, the very low standard deviation suggests that the spraying system can maintain a constant pressure for an extended period.

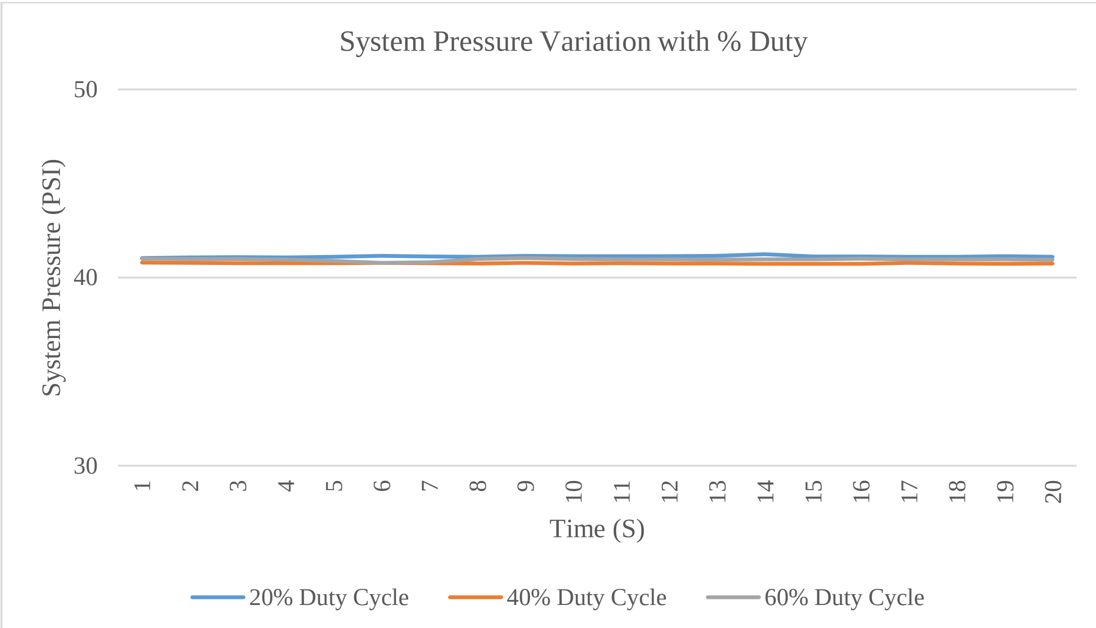


Figure 2.9: System Pressure Variation with % Duty Cycle

System Pressure Response: Single Vs Multiple Nozzle Actuation

Even though the sprayer was developed for site-specific spot spraying, there might be the case during actual field operation when all six nozzles will get activated based on the infestation level. Despite the number of energized nozzles, the sprayer should be able to maintain uniform system pressure. It ensures that the nozzle applies the product at the desired pressure and maintains a constant application rate and droplet size. Hence, it was essential to understand the pressure consistency despite varying the number of nozzles. The average pressure obtained at 20% duty cycle while operating one, three, and all six nozzles are 283.5 kPa, 276.3 kPa, and 265.0 kPa with the standard deviation of 0.04, 0.07, and 0.03, respectively. This variation in pressure is consistent with the results obtained in research by Sharda et al., 2016. It shows that the pressure while operating one nozzle was 2.8% above and 3.9% below the target pressure (275.8 kPa), which is well within the ±5% limit typically considered for consistency. This small change in system pressure changes the nozzle output by a very little value keeping the application rate constant.

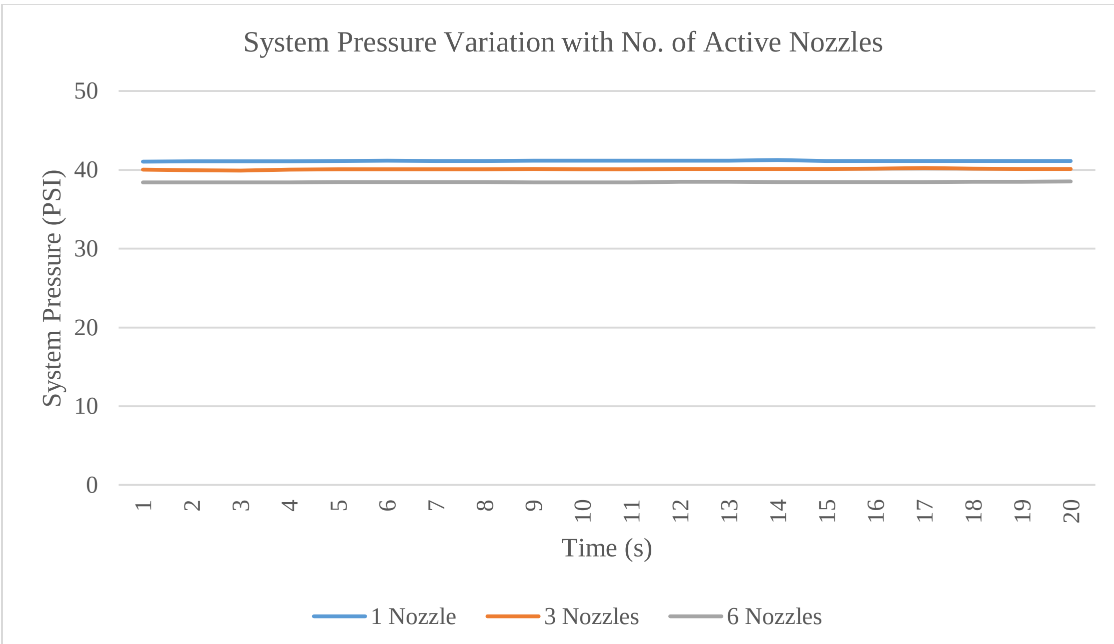


Figure 2.10: System Pressure Variation with Number of Nozzles

PWM Signal and Nozzle Pressure Response

The PWM system exhibited desired pressure dynamics during nozzle actuation (Figure 2.11). The results indicated that the system sent the correct control signal; the solenoid received digital high for 40 ms and low for 60ms. The pressure sharply increases and reaches the targeted pressure (275.8 kPa), remains constant for the duration of 40 ms, and sharply drops down to zero kPa. However, the pressure started increasing after 5 ms, then the ON signal, mainly due solenoid valve capacitance. The plot below shows that the application pressure at the nozzle remains within ±5% of the desired pressure (275.8 kPa) despite the number of active nozzles.

The above findings prove that the developed sprayer can apply products at the targeted pressure with high accuracy providing droplet size uniformity and better coverage. PWM technology provided low response time and the ability to turn ON and turn OFF instantly. Therefore, the solenoid can hold the product at the target pressure during the OFF state and applies the chemical at the desired pressure when it gets energized.

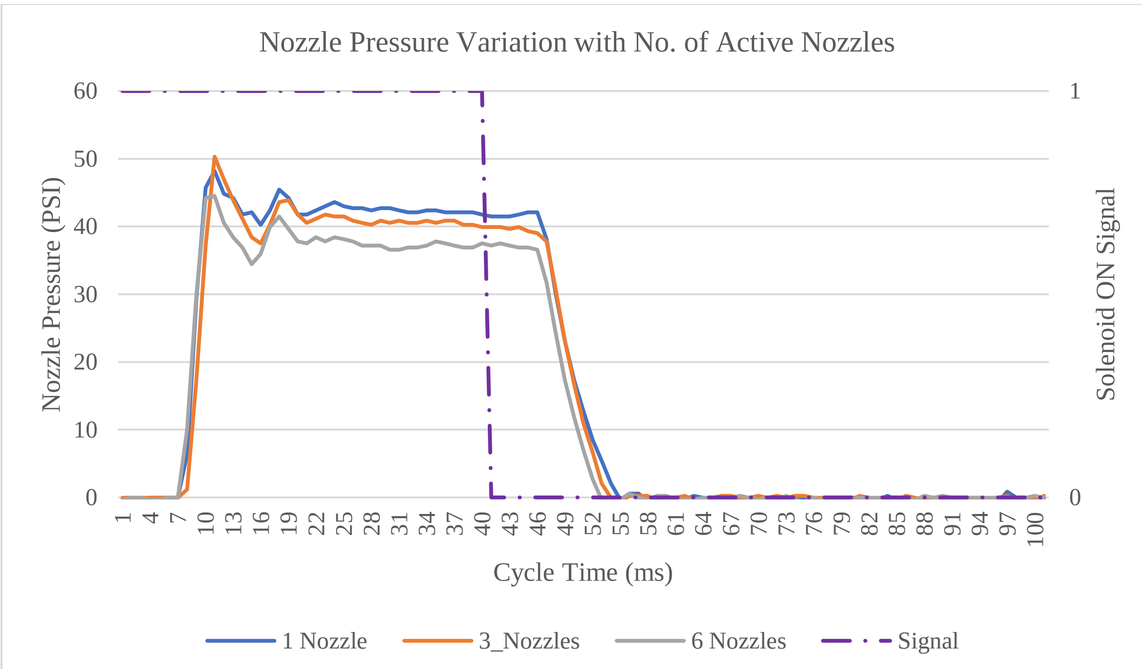


Figure 2.11: PWM Signal and Nozzle Pressure Response with no of Active Nozzles

The pressure and control data recorded at three different heights by turning on each nozzle were plotted as shown in the figure 2.12. The result indicated no significant difference in application pressure at three nozzles installed at three different heights in a boom. Understanding of pressure drop at the nozzles installed at different heights in a boom or two separate booms indicated that application from any combination of nozzles will always be conducted at desired pressure, maintaining target droplet size.

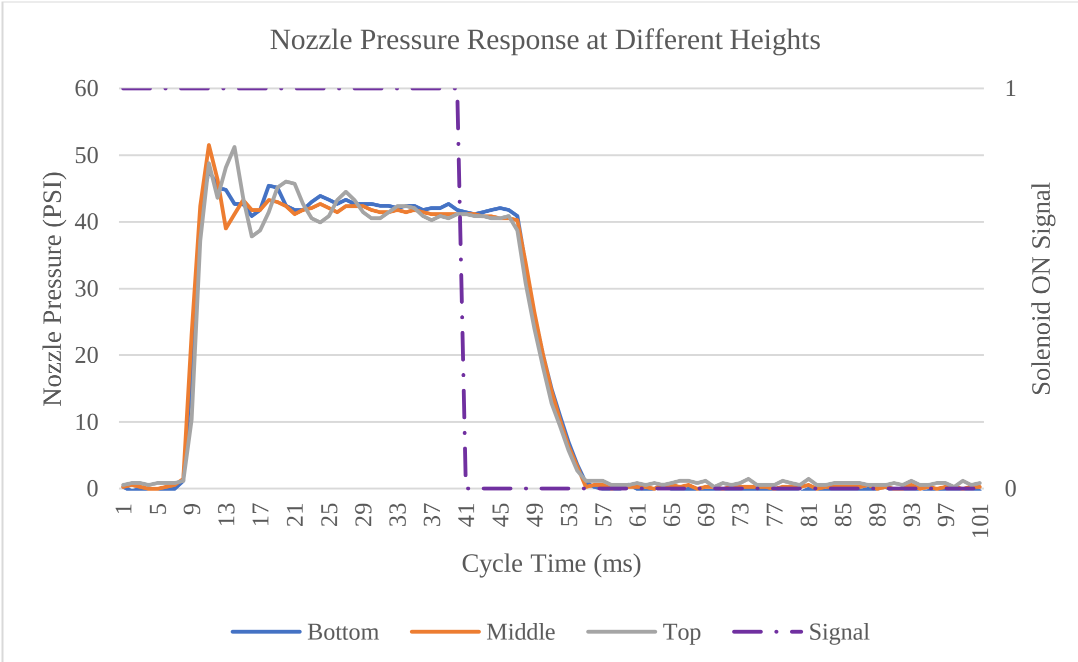


Figure 2.12: Nozzle Pressure response at different heights in a boom

The data obtained by measuring the signal and pressure response at the bottom nozzles of both right and left booms showed a similar response. However, there is slightly more pressure variation at the left tube compared to the right. It might be due to the position of the liquid inlet point of each boom. The right-side boom inlet is at the end of the manifold after the pressure relief valve input, whereas the left boom inlet is before the pressure relief valve. Due to this, when the relief valve releases the pressure, the liquid might take the horizontal path first, followed by the vertical, resulting in a slight pressure fluctuation. The plot below shows the pressure response in the right and left boom.

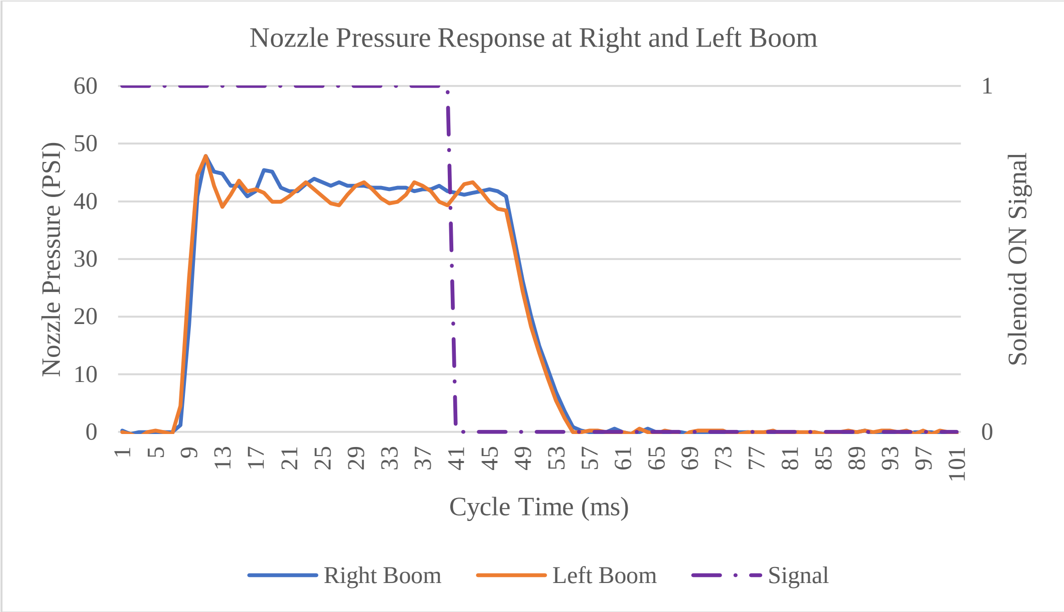


Figure 2.13: Nozzle Pressure Response in Left and Right Booms

Conclusion

In this research, a liquid application system was developed for row crops by integrating a robotic platform and a low-pressure spraying system. The rover was designed considering a few important factors such as the crop environment, traction, stability, maneuverability, payload, and programmed to remotely control the speed and direction to make it suitable for traversing between crop rows. The spraying system is equipped with PWM actuated solenoids, has the individual nozzle control capability, and can spray on either side of the crop rows at a particular spot. The results of the laboratory testing showed that the sprayer operates as intended, can maintain a uniform nozzle application pressure within ±5% of the desired pressure despite the number of active nozzles and nozzle position, and spray with high accuracy. Future research can focus on the integration of computer vision and autonomous path planning to conduct spot application and spray coverage evaluation in row crops.

Chapter 3 - Study on application strategies for coverage optimization during site-specific chemical application

Abstract

A pulse width modulation (PWM) based robotic liquid application system has the potential to apply the correct amount of pesticides, while providing maximum coverage and sustainably managing insect pests in row crops. Hence, a robotic spraying system was developed, and a spray coverage study was conducted using water-sensitive cards under different emitter orientations, application rates, and platform movement strategies. The water-sensitive cards were scanned and processed using MATLAB to quantify the percentage coverage in many sampling locations. The configuration with 15 GPA and regular pass in both 0° (0BCT) and 45° (4BCT) provided the highest mean deposition of 17.33%; both provided the maximum coverage in the high canopy height than the medium and lower. In configuration 0BCT, the spray coverage on the top, medium, and bottom zone was 30%, 22%, and 13% in the inner and 22%, 9%, and 8% in the middle canopy region. 4BCT provided 25%, 22%, and 17% in the inner and 16%, 15%, and 9% in the middle canopy region on the top, medium, and lower heights. It shows that the 4BCT configuration provided more consistent coverage across the sampling locations with minor variance. In all test case scenarios, the spray coverage was higher in the inner canopy region near the corn stalk than in the middle of the plant leaves. In both 0BCT and 4BCT configurations, there was around 62% of total coverage in the inner and 38% of the total in the outer. Also, the spray deposition of up to 56% of the total on the other side of the crop row shows a significant penetration capability of the spraying system.

Introduction

The row-crop grain industry represents around 25% of the agricultural sector in the U.S., and effective pest management is required to reduce crop damage and maximize profits. The use of manual chemical application as well as spraying technologies is the most common pest management strategy. However, the current manual labor costs are too high, and modern spray technologies are too inaccurate. Furthermore, the lack of automated technologies to locate pest incidence and severity within a crop canopy and provide spray decisions based on application needs is a significant drawback. Due to this, the infestation is treated based on the entire field mentality. In many cases, depending on the pest dispersion, percentage of plants infested, and spatial relation of the infestation to one another, only a tiny fraction of areas receives a justified amount of pesticides, some part receives superfluous spray, and some areas might lose yield due to delayed timing. Also, the current spray application approach may harm the beneficial organisms and causes non-point source environmental contamination. Hence, advanced robotic spraying technologies are needed to reduce the pesticide usage that can site-specifically manage pests in row crops such as corn and sorghum.

Typically, row crops such as corn and sorghum are planted with 20-40 inches of row-row spacings. The individual waypoints within the field allow the small robotic vehicles to navigate through the crop rows. This feature provides very high pest detection and spot application capability, given that an innovative and small spray system can be integrated with the rover. It is primarily because the spray system can traverse very close to the plant canopy and will have more access to the different parts of crop canopies. The use of vertical boom spray application systems has been well documented for greenhouse and other close environments (Nuyttens et al., 2004 and Foque et al., 2012). Also, a vertical boom sprayer from Holland Green Machine is commercially available that uses the pipe rails to move and spray in the greenhouse (www.hollandgreenmachine.com). However, validating such vertical boom robotic spraying systems in row crops is very important to understand the spray coverage and penetration in different parts of the plants.

The use of water sensitive cards is the most common and widely used method to quantify the as-applied spray coverage (Asaei et al., 2019; Chen et al., 2012; Sinha et al., 2019; Hocevar et al., 2009; Zaman et al., 2011; Jeon et al., 2012; Sharda et al., 2015). When the water or the spray solution droplets fall on the water-sensitive paper (WSP), the original color changes from yellow to blue, providing an opportunity to distinguish spray with paper. Fox et al., 2003 found that the optical measurement provided higher spot density than the image-system measurement method. Research by Panneton B., 2002 showed that the image processing system could measure the percent area covered within ±3.5% of actual coverage. Similar and comparable results were obtained using three different image processing methods while quantifying spray droplet sizing (Hoffman W. C. and Hewitt A. J., 2005). Also, some researchers were able to develop portable systems for spray parameter quantification (Franz E., 1993 and Zhu et al., 2011). Hence, the image processing tools are preferred to digitized the two different colors for spray coverage quantification. Research shows the potential of estimating the volumetric flow rate of agricultural sprayers using water-sensitive papers (Sama et al., 2016). Further, the same team has demonstrated the feasibility of using the percentage coverage method using water-sensitive cards for the field validation of as-applied spray coverage (Sama et al., 2018).

As-applied pesticide coverage knowledge is essential in understanding the distribution of spray within the plant canopies. This information will help identify the issues present in the vertical boom robotic sprayer and provide the framework for the further development and commercial implementation of such a system. Many factors such as the application rate, nozzle/emitter configuration, and application strategies might affect the coverage and distribution in plants. Nevertheless, there is no reported work on the spray coverage using small robotic spraying systems with vertical booms that can navigate row crop fields such as corn and sorghum. Hence, this study aimed to provide coverage information from the current system, identify the possible design changes, and make such systems practically feasible.

The primary objectives of this research were to:

1) Quantify the spray coverage at three different plant heights under different application rates, nozzle orientation, and the number of passes.
2) Using the same configurations, evaluate the spray coverage (at the middle of leaves and near the stalk) and penetration along the lateral canopy regions.

Methodology

Test setup

This test was conducted at the college of agriculture greenhouse complex at Kansas state university in March 2021. The corn was planted in round pots and waited until their tasseling stage (VT growth stage). The greenhouse facility allowed consistent environmental control in temperature, humidity, and wind speed over the open fields. Finally, the test was conducted simulating different parameters of the actual cornfield. For example, typically the row crops such as corn and sorghum are planted in terms of plants/acre unit. In Kansas, corns are planted at 30" row spacing having a 6" plant to plant distance to get 30000 plants/acre harvest corn population from irrigated land (Shroyer et al., 1996). The sorghums are planted at 3" plant to plant spacing for 30" row spacings to get around 45000 plants/acre based on 20-26" rainfall (Shroyer et al., 1996 & Ciampitti et al., 2018). Farmers may choose different row/plant spacings, and plant height and canopy structures may vary based on crop genotypes. However, we have chosen inbred line B104 corn genotype and the most common row (30”) and plant spacings (6”) for the testing purpose. A set of five corn plants were randomly chosen and placed in a straight line simulating a real cornrow. Out of five trees, only the middle three plants were considered in this study for quantifying the spray coverage. This setup allowed us to study the spray coverage and penetration at different plant heights and lateral canopy regions.

Figure 3.1: Test plants in the greenhouse environment

A robotic sprayer with vertical booms was developed especially for row crops at Biological and Agricultural Engineering, Kansas State University. The two primary components of this system were a) a mobile robotic platform b) a low-pressure spraying system. The robotic platform is a four-wheel drive, differential steering rover that can pass through the 30” row crop spacing carrying over 200 lbs. weight. It has four electric motors, one on each wheel, driven by two large LiPo batte ries. The spraying system has a 20-gallon tank and two wet booms installed on the rear side of the platform close to each other. Each boom has a 1.2 m height, and three nozzle bodies can be fitted at an interval of 0.4 m starting from 0.2 m of the lower tube end. Nozzle bodies (Teejet, QJ17560-NYB) and PWM solenoid valves (Teejet, 115880-1-12-05) were mounted at all six boom holes. Hollow cone stainless steel nozzles can penetrate the foliage and provide maximum coverage on the leaf surfaces (Slocombe et al., 2015). Hence, fitted the hollow-cone nozzle tips were with the nozzle bodies using nozzle caps (25608-6-NYR). The liquid spray from this arrangement can cover the entire canopy height of row crops such as corn and sorghum.

The tests were conducted at two different nozzle orientations, two application rates, and two spray strategies, as shown in the table below:

Table 3-1: Test Configuration Parameters

Nozzle Orientation		Application Rate		Number of Passes	
0° $_{(0)}$	45° $_{(4)}$	12 GPA $_{(A)}$	15 GPA $_{(B)}$	1 $_{(O)}$	2 $_{(T)}$

*Letters/numbers in parenthesis identifies the treatments applied for this study

In this experiment, we selected two nozzle orientations (0° and 45°) to see the effect of nozzle orientation on the coverage, assuming that the 45° upward spray direction could provide better coverage on the plant leaves. The 45° configuration was made possible by using an adapter (Teejet, 22674-1/4-NYB) and a cap (Teejet, QJ4676-1/4-NYR) in addition to the nozzle body (Teejet, QJ17560-NYB) and cap (Teejet, 25608-6-NYR) for straight (0°) orientation. The most common application rate is 12 gallons per acre (GPA) for broadcast applications using pull behind and self-propelled sprayers. Hence, the same application rate was used and quantified the spray coverage. In addition to this, we chose another application rate (15 GPA) to see if there is a significant difference while using a slightly higher application rate. Two different rover movements were experimented with: pass through all the rows and skipping a row after each pass. If the sprayer can provide a higher spray penetration, it might provide adequate coverage on the leaves present at the other side of the row. If this happens, we may not necessarily need to pass through each row. Based on the above parameters, we have a total of 8 configurations

(0ACO, 0ACT, 0BCO, 0BCT,4ACO, 4ACT, 4BCO, 4BCT) in this study, where C represents the corn plant. The tests were replicated 3 times under each configuration. All the experiments were conducted at the same rover speed, and the vertical height and lateral position of the booms were kept constant.

Figure 3.2: 0° Nozzle Orientation

Figure 3.3: 45° Nozzle Orientation

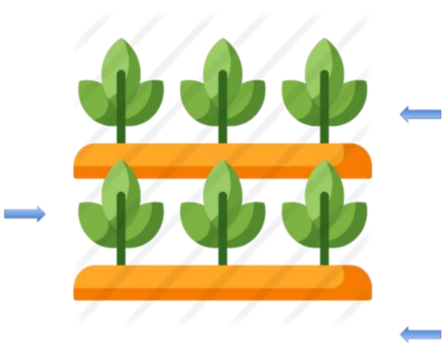


Figure 3.4: Rover movement strategy: Pass through all rows

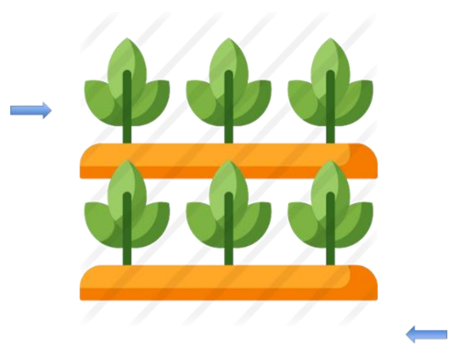


Figure 3.5: Rover movement strategy: Skipping a row after each pass

Control and data acquisition

The rover was set to operate at a constant speed of 1 MPH using the PID control program in LabVIEW and MyRIO 1900 controller. The sprayer was programmed in LabVIEW and cRIO system (cRIO 9037, NI 9375, NI 9221, NI 9403) to operate solenoid valves at a frequency of 10

Hz and picked the duty cycle based on the desired application rate. The national instruments data dashboard app was used to operate the platform and sprayer, set the rover speed, solenoid frequency, duty cycle, monitor the system pressure, and log the pressure readings. Selecting a proper nozzle orifice size is essential; that depends on the application rate, effective spray width, solenoid duty cycle, and the ground speed of the sprayer. The nozzle selection method at a specific application rate, application pressure, and sprayer speed has been demonstrated in an extension work by Fabula et al., 2019. For example, to spray at a 12 GPA application rate at 40 PSI pressure and 1 MPH platform speed, a stainless-steel Hollow cone nozzle (TX1) from Teejet was selected. The 12 GPA application rate was maintained by operating the solenoid at a 61% duty cycle. Similarly, we used the same nozzle tip to spray at an application rate of 15 GPA by changing the solenoid duty cycle to 77%.

In this study, water-sensitive cards (Syngenta Crop Protection AG, Switzerland) were used to quantify the spray coverage. These cards were clipped at 12 different locations per plant and a total of 36 cards in three plants for each experiment. Each sensitive card had a dimension of 2.54 × 2.54 cm and was aligned to match the natural orientation of the leaves using paper clips. To better understand the coverage and penetration, it was essential to place the water-sensitive cards covering all the locations in a plant. Therefore, we chose three different heights, two lateral canopy regions, and two sides of the row as sampling locations. The water-sensitive cards were placed at the bottom, middle, and top canopy regions after measuring the average plant height, dividing into three regions, and visibly marking the regions. The two lateral positions were: near the corn stalk and at the middle of the leaves. Additionally, the cards were placed on both sides of the crop row to understand the penetration. The cards placed on the spray-side and other-side of the row were marked for identification. The figures below demonstrate the placement of the water-sensitive cards in corn plants.

Figure 3.6: Water sensitive cards placement in the crop canopies

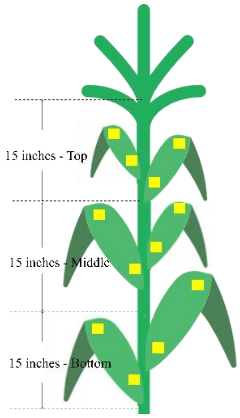


Figure 3.7: Three vertical and two lateral regions for coverage analysis

The water-sensitive cards were properly labeled on their back to identify their position in the plants and for further analysis. Before conducting the tests, the robotic platform was set in its starting position, and the labeled cards were placed on the corn plants as described above. A pressure sensor (Pizotronics, PTC-2) was installed in the sprayer manifold to measure and ensure the correct system pressure. All three nozzles of the right boom were turned ON, provided the duty cycle input, set the platform speed, and monitored the system pressure using the data dashboard app on iPad. After each treatment, the plants were allowed to dry for about 10 minutes and collected the water-sensitive cards. These cards were put in properly labeled, air-tight, plastic Ziplock bags after each experiment.

This study was conducted in a controlled environment with little to no difference in temperature, humidity, and wind speed. Hence, it will not explain the effect of such parameters in spray coverage and was outside the scope of this work. Also, the application rates were chosen based on the reference from large self-propelled sprayers. Therefore, for identifying what application rate yields optimum coverage in such a vertical boom liquid application system, further research needs to be done based on the findings of this work.

Data analysis

The water-sensitive cards were first pasted on an A4-sized paper with properly labeled configurations as headings. Further labeling was done to identify the lower, middle, and upper heights, inner and middle lateral canopy regions, and spray-side and other-side of the rows. The sensitive cards on the spray side were pasted first and then the cards on the other side of the row. These water-sensitive cards were digitized using a Scanjet scanner (Scanjet Pro 3500 f1) at 1200 dpi resolution. The scanned cards were then imported in MATLAB (R2019a, The MathWorks Inc.) and cropped to remove the borders and shades. For separating the droplet with the yellow background, the greythresh function was used in MATLAB, which calculated the threshold normalized to the range [0, 1]. Then, the image was converted into binary using the imbinarize function using the threshold of the previous step. Next, the area covered by the spray droplets was computed by dividing the pixels covered by the droplets by the total pixel counts. Finally, the droplet size was calculated by using the regionprops function of the MATLAB image processing toolbox. All these data were saved into an excel sheet for further analysis. The coverage data obtained from different locations were categorized to calculate the spray coverage in the bottom, middle, and top canopy regions. Also, calculations were done to get the spray coverage in lateral canopy regions to analyze the spray penetration. The spray coverage on both the spray-side and other-side of the row was accessed at all these locations.

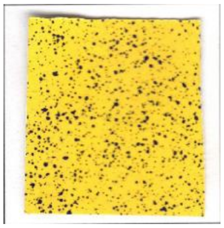


Figure 3.8: Scanned Image pasted on the A4 sheet

Figure 3.9: Cropped Image to remove boarders

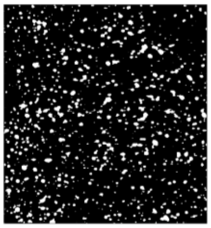


Figure 3.10: Binary Image for the coverage

Results and Discussion

Coverage in different canopy heights

The charts below provide information on the spray coverage with different configurations at different plant regions. Under all the straight (0°) nozzle orientations, the average spray coverage at the higher canopy height is more, followed by the medium and lower. The corn leaves typically align across the rows towards the row gaps. During the test, it was observed that the liquid tank was slightly disturbing the leaves present at the medium plant height, and both platform and the chemical tank were disturbing the leaves present in the lower region. Additionally, due to the small gap between the boom and the tank, there was not enough time for the leaves to settle before the nozzle sprays. Therefore, there is less coverage in medium height and even less coverage in the lower region due to the higher disturbance factors.

However, the spray deposition is higher in the medium plant heights, followed by top and bottom at three out of four 45° nozzle configurations. The spray coverage at the medium region in 4BCT is slightly less than the top; but, they are very close. The 45° orientation can deposit more liquid in the medium canopy height because the spray droplets travel upward, start losing its velocity early and fall to the leaves underneath after taking some elevation. Also, the droplet cloud formed within the medium crop canopy from both the medium and the lower nozzles causes the medium leaves to intercept more spray droplets. The 45° provided better overall spray coverage at all the medium and lower plant heights in all four configurations than the 0° configurations. The coverage due to 45° upward nozzle in top plant height is comparatively higher under 4ACT and 4BCO and lower under 4ACO and 4BCT than 0° orientation. Overall, 45° provided better coverage over 0° in 10 instances out of 12.

The spray coverage on the leaves in all three plant heights and all the configurations is significantly higher in double pass. The mean coverage achieved was 1.83 times higher compared to the single-pass method. It was expected that the spraying system to provide enough horizontal velocity, the spray droplets to penetrate the plants, and liquid droplets to deposit on the other side of the crop row. However, the exact amount of deposition on each side is still required to understand the spray penetration and coverage on the other side of the row. The coverage data on each side in a single pass will help make any decision about the vehicle traversal scheme.

The test data was separately compared for a single and dual-pass to understand the effect of application rates (12 GPA and 15 GPA) on spray coverage. First, the rover was operated in a single pass scheme and separately compared the two straight (0ACO & 0BCO) and two 45° upward (4ACO & 4BCO) configurations. The test results show no significant difference in coverage while operating the sprayer at two different application rates. However, the spray coverage was higher while driving the sprayer at a 15 GPA application rate in a double-pass scheme in both 0° and 45° nozzle orientations compared to 12 GPA.

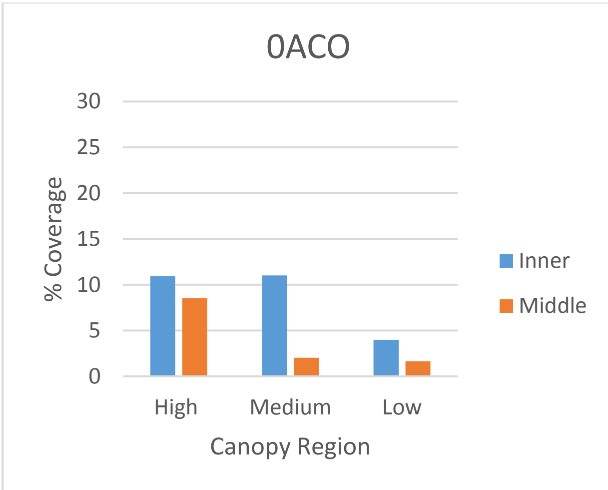


Figure 3.11: Coverage under 0ACO in different canopy regions

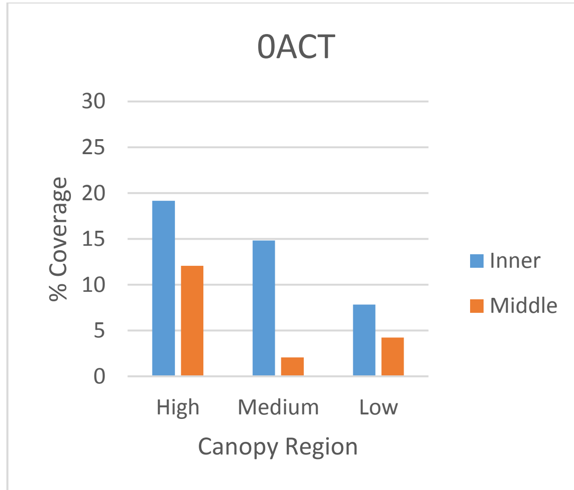


Figure 3.12: Coverage under 0ACT in different canopy regions

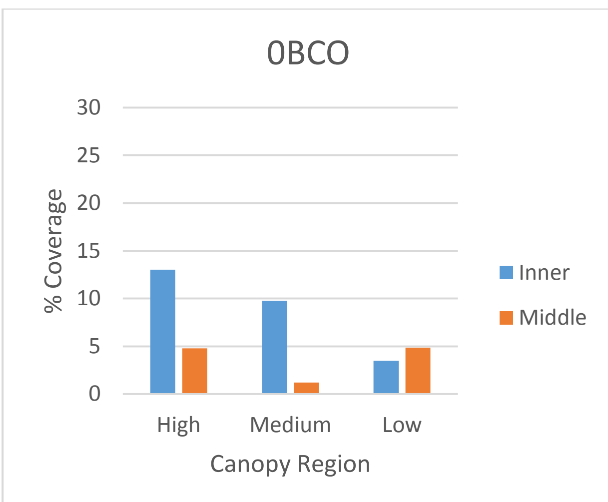


Figure 3.13: Coverage under 0BCO in different canopy regions

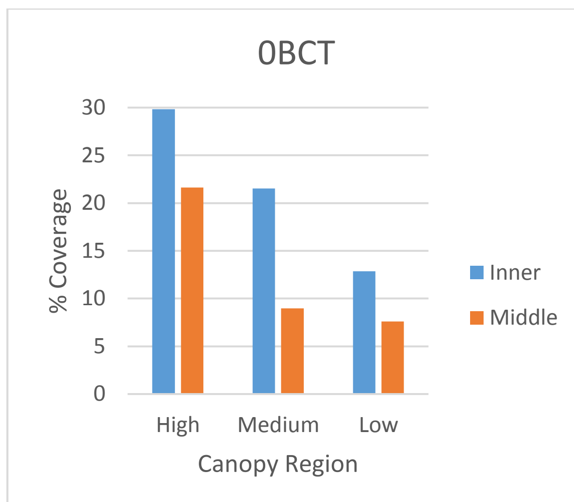
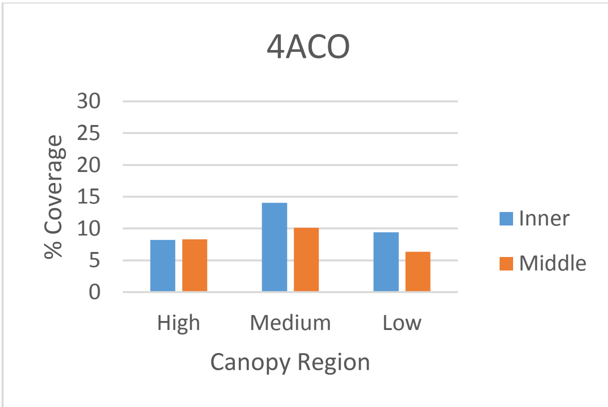


Figure 3.14: Coverage under 0BCT in different canopy regions



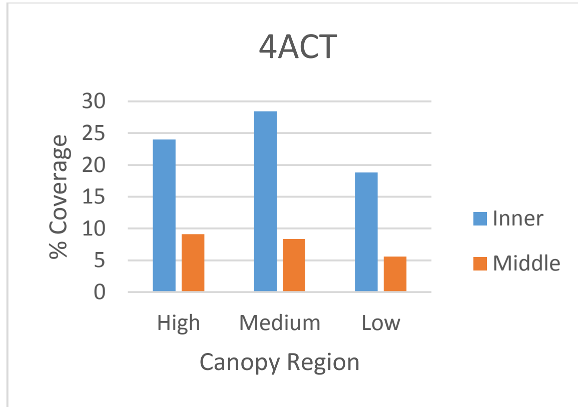
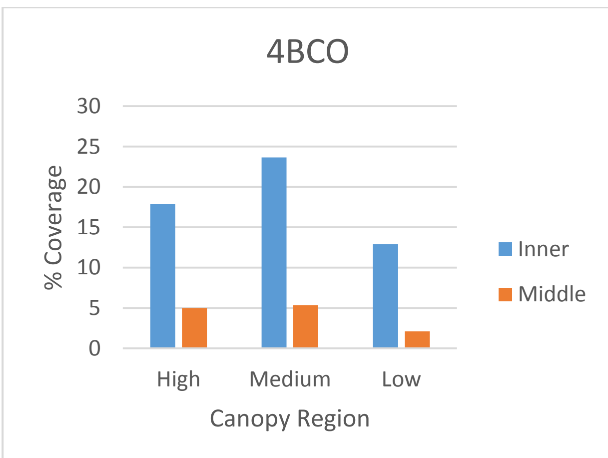


Figure 3.15: Coverage under 4ACO in different canopy regions

Figure 3.16: Coverage under 4ACT in different canopy regions



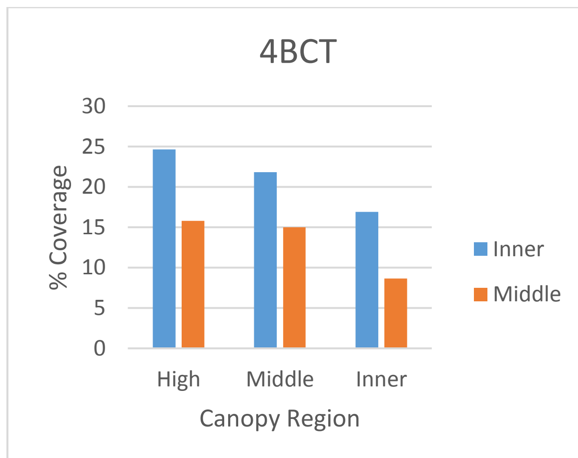


Figure 3.17: Coverage under 4BCO in different canopy regions

Figure 3.18: Coverage under 4BCT in different canopy regions

Coverage in different lateral canopy regions

The table below shows the spray coverage in lateral canopy regions (middle and inner) under all eight configurations. The results show that the spray coverage is much higher near the corn stalk than in the middle of the plant leaves. A maximum of 30% and 22% coverage was seen in the plant's inner and middle canopy region under the configuration 0BCT in the top height. The 45° orientation provided higher spray coverage in the middle canopy region of the medium zone compared to their corresponding 0° configurations. It might be due to the 45°

vertical direction of the droplets, which starts falling early on the leaves underneath. Among both 0° and 45° categories, 0BCT and 4BCT provide maximum coverage in the middle canopy region in all three heights. The double pass strategy provided better deposition in both inner and middle canopy regions.

The plant leaves are extended towards the row gaps, and there was a smaller gap between the nozzle tip and the middle canopy regions. Hence, most spray droplets reach the central part without ultimately forming the cone, so less coverage. The higher spray coverage in the inner areas is due to the adequate distance between the nozzle tip and the plant stalk. The higher gap allows the full-cone formation, and the cone base covers a larger area. It was observed that both the liquid tank and the platform were dragging forward the leaves from their original position. Hence, when the leaves cross the tank, they remain in motion for a few seconds. Also, the gap between the tank and the spray booms was so less that the leaves did not get enough time to settle down. In the meantime, the sprayer sprays to apply the chemical, providing less deposition in the outer leaf regions compared to the inner.

Hence, it is essential to move the tank forward around 38.1 cm and provide enough gap between the tank and the spray boom to allow enough time for the leaves to settle down. Also, the results suggested the need to shift the boom position further inside to provide more gap between the nozzle tips and the middle canopy region. Additionally, it was seen that the straight boom angle causes the spray droplets to directly hit the front part of plant leaves, leaving the leaves behind unsprayed. It suggests the need to find some alternative strategies or test multiple boom angles to find the optimum angle that can provide better coverage in the middle and the inner region.

Table 3-2: Mean spray coverage on different canopy regions

Canopy Region		Mean Spray Coverage (%)							
		0ACO	0ACT	0BCO	0BCT	4ACO	4ACT	4BCO	4BCT
Mean coverage in different plant heights and lateral canopy regions (%)									
High	Inner	$11_{(5)}$	$19_{(7)}$	$13_{(6)}$	$30_{(10)}$	$8_{(7)}$	$24_{(10)}$	$18_{(9)}$	$25_{(7)}$
	Middle	$9_{(15)}$	$12_{(19)}$	$5_{(8)}$	$22_{(15)}$	$8_{(8)}$	$9_{(9)}$	$5_{(7)}$	$16_{(14)}$
Medium	Inner	$11_{(12)}$	$15_{(10)}$	$10_{(6)}$	$22_{(13)}$	$14_{(13)}$	$28_{(10)}$	$24_{(10)}$	$22_{(14)}$
	Middle	$2_{(3)}$	$2_{(2)}$	$1_{(1)}$	$9_{(9)}$	$10_{(11)}$	$8_{(13)}$	$5_{(7)}$	$15_{(13)}$
Low	Inner	$4_{(5)}$	$8_{(6)}$	$3_{(4)}$	$13_{(9)}$	$9_{(10)}$	$19_{(9)}$	$13_{(7)}$	$17_{(9)}$
	Middle	$2_{(2)}$	$4_{(5)}$	$5_{(7)}$	$8_{(6)}$	$6_{(9)}$	$6_{(7)}$	$2_{(3)}$	$9_{(9)}$

*Numbers in parenthesis represents the standard deviation

Spray Penetration into crop canopies

The coverage data obtained show a significant volume of liquid droplets deposited on the other side of the plant leaves. The coverage was higher on the spray side on three configurations out of four. The deposition varied between 44% - 79% of the total on the spray side and 21% - 56% on the other side of the row. Under 0ACO, the coverage was 53% of the total on the spray side and 47% of the total on the other side. 0BCO shows similar results; 61% of the total on the spray side and 39% of the total on the other side. However, the coverage on the spray side was 79% of the total in 4ACO. In 4BCO, the deposition was higher on the other side (56% of the total) compared to the spray side (44% of the total). It might have happened when the robotic platform moved very close to the crop rows. In that case, the spray might not deposit on the middle canopy region of the spray side. Instead, more deposition happens in the inner part of both sides and the central area of another side. Comparing the coverage on the middle canopy region of the other side in all four configurations, we can see that the spray coverage is highest in the 4BCO, supporting the above statement.

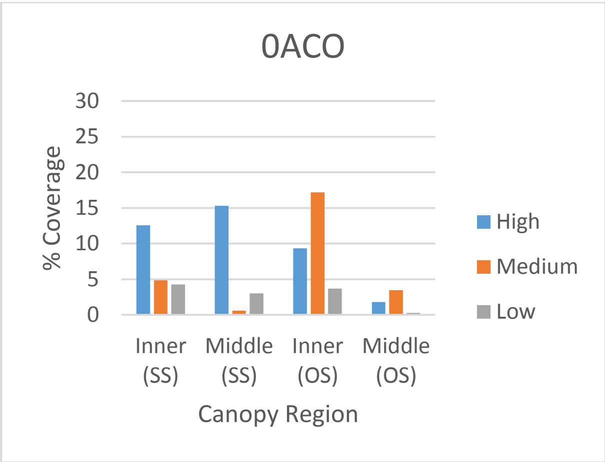


Figure 3.19: Coverage under 0ACO in both spray side and other side

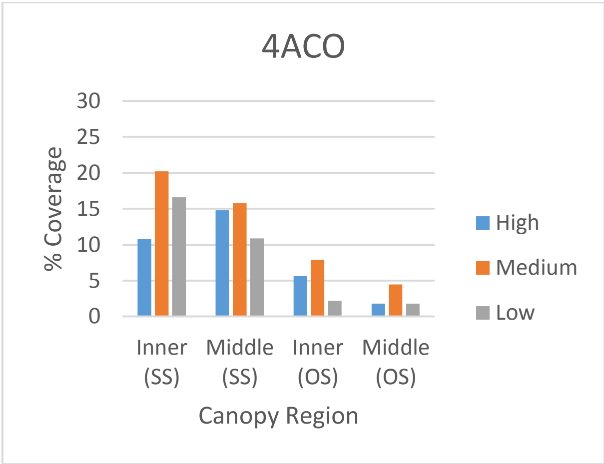


Figure 3.20: Coverage under 4ACO in both spray side and other side

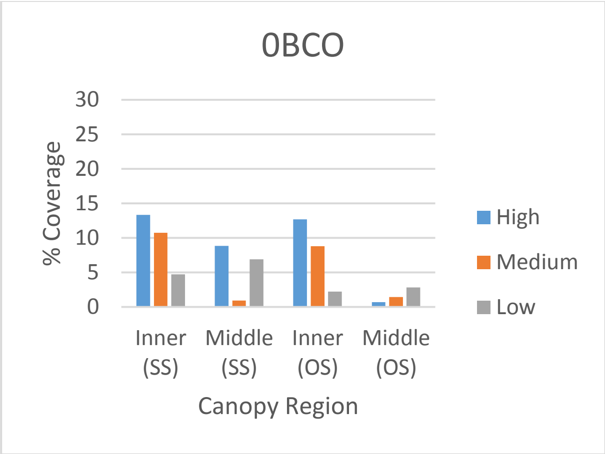


Figure 3.21: Coverage under 0BCO in both spray side and other side

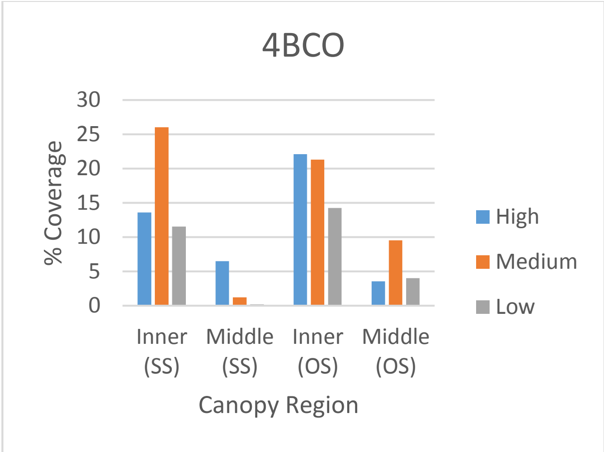


Figure 3.22: Coverage under 4BCO in both spray side and other side

The above data shows a significant potential of the developed system to spray with sufficient velocity and deposit the droplets on the leaves present at the other side of the crop row. The higher penetration allows the spraying system to apply chemicals from one side and skip one row after each pass. With proper pest scouting technology, this robotic spraying system can effectively conduct the liquid application from the other side of the plant. It will reduce the vehicle movement by half leading to saving of energy, time, and cost. However, the coverage should be sufficient enough on both sides to eliminate the crop pests effectively. In the meantime, more studies are necessary using different nozzle tips that produce fine and medium droplets, different boom angles, more nozzle bodies configurations, and proper placement of the tank to understand their effect on coverage. This research will help improve and provide uniform spray coverage at all locations through a single vehicle pass.

Conclusions

This study quantified the spray coverage at different plant locations under two separate emitter mounting configurations, two application rates, and two sprayer movement strategies. This research aimed to evaluate the performance of a robotic spraying system developed especially for row crops. The test was conducted in a greenhouse environment simulating the actual crop canopy structure with the minimum effect of external factors such as wind speed and temperature. Water-sensitive papers were analyzed using the image processing toolbox in MATLAB to quantify the spray coverage. The spray coverage was higher in the top canopy height followed by medium and low under 0° nozzle orientation. However, it was higher in the medium canopy region followed by top and bottom in 45° emitter orientation. The overall coverage was better while using 45°configurations as compared to 0°. As expected, the double pass strategy provided significantly higher mean coverage at all plant heights and all eight configurations. In the dual-pass method, both 0° and 45° provided higher spray coverage in the 15 GPA application rate compared to 12 GPA. In the lateral canopy regions, the spray deposition was much higher near the stalk compared to the middle of the plant leaves in all test case scenarios. The penetration data shows up to 56% of the total coverage on the leaves present at the other side of the stalk, suggesting the capability of the spraying system to penetrate the canopies and deposit comparable spray droplets on both sides.

Chapter 4 - Conclusions

Summary of Findings

In this research, a robotic platform capable of maneuvering within the row crops was developed that allows easy integration of other systems to perform specific tasks. A low-pressure spraying system was designed, fabricated, and integrated into the mobile platform to conduct the chemical application. The liquid application system was equipped with six PWM-based solenoids, and in-house tests were conducted to validate the performance. The test results indicate that the sprayer maintained a uniform manifold and nozzle pressure within ±5% of the target irrespective of the duty cycle and number of active nozzles. The 1000 Hz pressure and control signal data show proper control system operation and solenoids actuation. Further, two separate studies to check the pressure variation between the two booms and the three nozzles in a single tube show no significant difference suggesting a proper nozzle output flowrate.

The developed system was then used to quantify the spray coverage in different locations in the plant. The test was conducted in a greenhouse environment simulating the real row-crop scenarios. It was found that the coverage was high in top canopy height followed by medium and lower under 0° nozzle orientation and higher in medium followed by top and bottom in 45°. Overall coverage was better from 45° orientation. Along the lateral canopy region, coverage was higher near the corn stalk than in the leaves' middle. The sprayer was able to conduct chemical application with sufficient throw, as suggested by the penetration data. Also, the dual-pass strategy provided superior spray coverage compared to the single-pass, and the 15 GPA application rate provided better coverage in all dual-pass strategies. Further field studies will be conducted in sorghum crop incorporating the findings from this research.

Implications

The successful implementation of a small robotic system in a typical row crop field can reduce chemical usage, decrease the negative environmental impacts, and effectively manage insects. It is possible as this kind of system can move very near to the crop canopy, can closely detect pests, and conduct high-resolution spray applications. The use of pulse width modulated nozzle control solenoid in the developed system offers individual nozzle control capability, which can be utilized to perform the site-specific application. Also, PWM-based systems' ability to maintain consistent application pressure leads to uniform droplet size, less drift, more foliage penetration, and maximum coverage. The modularity of this robotic spraying system makes it a multipurpose spraying solution for different agricultural environments such as open fields, row crops, greenhouse, poly-tunnel, and urban Ag.

The second part of this research provided some valuable information on as applied spray coverage. Understanding where the product is getting deposited under different configurations helps select the appropriate emitters, application rates, and application strategies. It also provides information about the possible design improvement that will ultimately help in improving the system performance. All these findings can help growers find efficient solutions to effectively manage the pests, maximize the crop yield and increase their profitability.

Future Work

The primary goal of this project was to develop a robotic system that can autonomously detect the pest and conduct site-specific chemical applications to precisely manage the insects. The general workflow of this system should include autonomous driving of the vehicle carrying liquid application and all other sub-systems; computer vision to detect the crop pest and simultaneously provide the spray decision feedback to the spraying system; sprayer to conduct site-specific applications based on the inputs from the computer vision, GPS, or platform position. Hence, integrating computer vision and autonomous path planning is our next step in developing this system further. The hardware and software of the developed rover and sprayer allow easy integration of computer vision and path planning to provide decision feedback to the liquid application system. The architecture of the future system would look something like below:

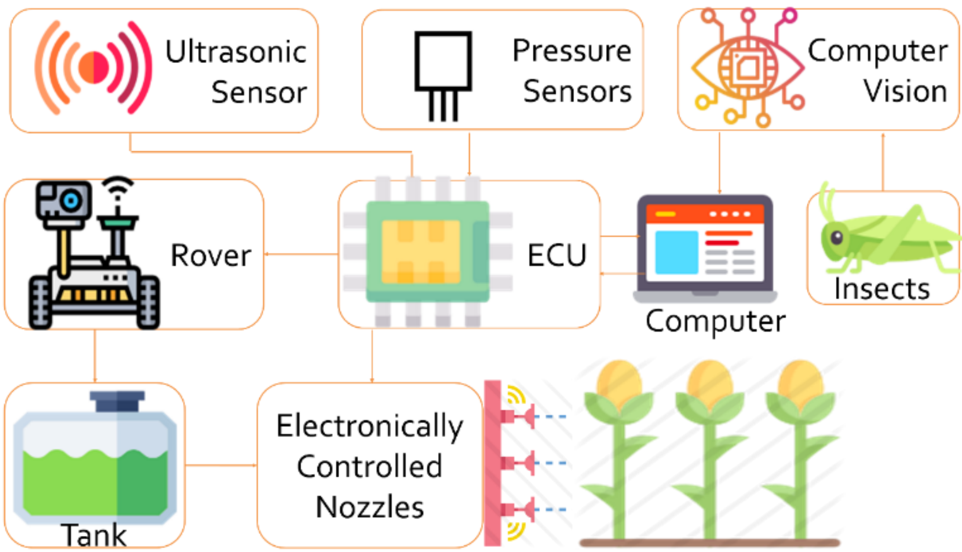


Figure 4.1: Future Spraying System Architecture

Further studies should focus on aphid detection, rover navigation, and spray localization accuracy determination of the system in actual field conditions. Field tests could provide further information on the chemical savings compared to the traditional spraying system and its long-term economic impact on the rural farming community. Assessment of the positive environmental impact of this system could be another vital area of study.

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