Development of Machine Vision Node on Standardized Controller Area Network of a Self-Propelled Boom Sprayer to Perform Site-Specific Pesticide Application

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Dalhousie University is located in Mi’kma’ki,

the ancestral and unceded territory of the Mi’kmaq.

We are all Treaty people.

DEDICATION

This MSc thesis dissertation is dedicated to my girl friend ***Ilakkiya Thirugnanasambandam*** *and my loving parents,* ***Natarajan*** *and* ***Ruckmani,*** *and my caring sister* ***Krithika Natarajan*** *and her son* ***Takshiv*** *who have been an amazing source of support and encouragement. I am thankful for having you all in my life. I would like to thank* ***my families and friends*** *for continually supporting me to accomplish my goals.*

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ABSTRACT

Pesticides are applied by commercial sprayers to control weeds and insects, which commonly develop in patches. Several boom sprayers are equipped with ISOBUS communication links which is a common tendency to integrate different devices and improve the robustness and efficiency of agriculture machineries. The ISOBUS uses CAN-bus as a data link protocol to perform the communication. Machine vision systems (MVS) and real-time response spraying have the potential to limit pesticide use by only spraying on infested areas. However, difficulties arise with integrating MVS with sprayers. The goal of this study is to develop a machine vision node (MVN) for MV-based site-specific spraying on ISOBUS-compatible sprayers. The MVN acts as an ECU which reads and sends the detected information from the MVS to control nozzles. The sprayer apparatus consists of a virtual terminal, a hydraulic unit, a nozzle control unit, a nozzle electronic switch, and six nozzles. A communication algorithm was developed on MVN to read the detected results from the MVS and send respective communication messages via serial communication to the sprayer. The developed algorithm was tested and evaluated with static (small apparatus including six nozzles) and commercial ISOBUS-compatible sprayers to control each nozzle. The results show that correct spraying commands were sent to nozzles (64 combinations) without data loss between the MVS and sprayer. Overall, the developed system resulted in a timely decision (10 ms) for site-specific spraying which may enable real-time spot spraying using machine vision.

Keywords: Precision Agriculture, ISOBUS, CAN-bus, Machine vision node, Machine vision system, Site-specific spraying.

LIST OF ABBREVIATIONS USED

AC - Alternative current
ACK – Acknowledgement
ACM – Address claim mechanism
AEF - Agricultural industry electronics foundation
AFS - Advanced farming system
AIC - Air induction
AIES - Applied intelligent engineering systems
B - Bytes
BUS - Binary unit system
CAN - Controller Area Network
CiA - CAN in automotive
CPB - Colorado Potato Beetles
CRC -Cycle redundancy check
CSV- Comma-separated value
D – Data
DA - Destination address
DC - Direct current
DEC - Decimal
DIN - Deutsche Institute für Normung (DIN) 9684
DLC – Data length code
DP- Data Page
ECU - Electronic control unit
EOF – End of the frame
ETP – Extended transport protocol
FAO - Food and Agriculture Organization
GE - Group extension

GPS- Geographical positioning system

GUI - Graphical user interface

HEX - Hexadecimal

ID - Identifier bitLBS - Landwirtschaftliches BUS system

MISO - Master-in-Slave-out,

MOSI - Master-out-Slave-in

MVN - Machine vision node

MV - Machine vision

MVS - Machine vision system

PDU - Protocol data unit

PGN - Parameter group number

PG - Parameter group

PF - Protocol data unit format

PS - Protocol data unit specific

R- Reserved

RCS - Raven Console switches

RPi - Raspberry Pi microprocessor

RTR - Remote transmission request

RX - Receiver

SA - Source address

SAE - Society of Automotive Engineering J1939

SCK - Serial clock

SOF - Start of frame

SPI - Serial peripheral interface

SS - Slave select

TP - Transport protocol

TX - Transmitter

UART - Universal asynchronous receiver and transmitter

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CHAPTER 1 INTRODUCTION

1.1 Literature review

Potato (*Solanum tuberosum*) is the fourth most consumed crop globally after rice, maize, and wheat (Zarzecka et al., 2020) with a harvest area of 1.3 million ha and annual production of 359 million tonnes (FAO, 2020). Vegetation propagation of potatoes exposes the crop plant to a variety of hazardous elements such as (weeds, pests, and fungal diseases) (Gugała et al., 2018). In Canada, potato is one of the major agricultural crops contributing to $1.5 billion in farm and $2.6 billion in export value with a production of 1.5 % (Government of Canada, 2021). In 2021, over 5.7 million metric tonnes of potatoes were produced by Canadian potato producers (Government of Canada, 2021). By area, the Prairies of British Columbia account for 42% of Canadian output, followed by the Atlantic region accounts for 36%, and the Central region with 22% (Government of Canada, 2021). The top generating provinces by volume were Prince Edward Island (23%), Manitoba (20%), Alberta (20%), New Brunswick (15%), Quebec (13%), and Ontario (7%). The average yield of potatoes in Canada is 40 tonnes per hectare (Government of Canada, 2021).

The United Nations estimates the world population to increase from 7.8 billion at present to 10.9 billion by the end of this century (De Wrachien et al., 2021). The increasing population and shrinkage of agricultural lands highlight the need for more crop production to meet food requirements. In agricultural fields, various diseases in crops may pose a serious threat to crop yield and national food security. As a result, the development of crop protection techniques like removing weeds and eliminating insect damage is critical in preventing yield loss to meet the growing demand (Shin et al., 2020).

Weed, disease infestation, and insect damage are significant agricultural crop production issues. Weeds are unwanted plants growing with a crop, which can reduce crop production by competing for the essential elements of the plants like water, nutrients, and sunlight (Ferreira et al., 2017). Lambsquarters (*Chenopodium album*), for instance, is a widespread weed in Atlantic Canada's potato fields and significantly reduces potato yields (Hadi & Noormohamadi, 2012). The geographical distribution of this weed inside potato fields necessitates the use of intelligent technologies to apply herbicides site-specifically. Disease infestation and insect damage might cause an adverse effect on the quantity and quality of the produce (Hong et al., 2012). Early blight, caused by *Alternaria solani* Sorauer, is a common disease that damages potato leaves and tubers found all over the world. It is resistant to young plants, while adult plants are considerably more prone to it. Early blight has been reported to have caused yield losses of 20% to 30% (Zhu et al., 2017).

The CPB, *Leptinotarsa decemlineata* is the most devastating insect pest in potatoes worldwide. Globally, annual yield losses from CPB range between 30 and 50%, and in certain areas, there is no economic yield (Zhu et al., 2012). CPB larvae and adults feed on green foliage and tubers, harming potato crops. To improve the yield and fulfill food requirements, agrochemical use in potato fields has been growing at a rapid pace, posing threats to the sustainability of the agricultural ecosystem (Zhou et al., 2012). Still, most of the machinery used to spray agrochemicals uniformly apply the products in the field without considering the spatial and temporal variations of weed, disease, and bare soil within fields (Sharma et al., 2019).

Annually, In Canada, 35 million kg of pesticides are used in agricultural fields (Sharma et al., 2019). Glyphosate is a widely used herbicide in Canada and plays an important role in weed management in agriculture (Government of Canada, 2021). The use of agrochemicals like herbicides and insecticides has contributed to weed control and the prevention of biotic stresses such as diseases and insect infestation, which has justified their use so far. They provide a convenient way to control weeds and insects, as 30% to 35% of crop loss can be avoided by using herbicides and insecticides to prevent harmful insects and diseases (Berenstein, 2019).

However, uniform application of pesticides (herbicides and insecticides) results in unnecessary application in areas of low or no weed or insect infestation causing environmental problems such as soil and groundwater pollution (Berenstein, 2019). If pesticides could be efficiently applied in a spatially varying manner based on weed population and insect distribution, fewer pesticides would be used, and pesticide absorption, adsorption, erosion, runoff, and leaching would be drastically reduced (Zhao et al., 2022). The US Environmental Protection Agency estimates that every year, over 2.5 million tons of pesticides are used worldwide with a purchase of $20 billion (Pimentel & Burgess, 2014). Agriculture accounts for nearly 75% of pesticides used annually in the USA and Canada (Pimentel & Burgess, 2014).

Repeated and non-optimal use of pesticides has resulted in herbicide resistance to weeds, excessive waste, residues in food, and environmental pollution, and also affects the quality and safety of agricultural products (Zhao et al., 2022). To reduce these impacts and optimize the use of pesticides in a site-specific manner, precision agriculture has been used (Zhao et al., 2022). As a result, there are two possible ways to reduce the volume of pesticides applied; 1) reducing the number of spraying applications during the cropping period, which can compromise crop yield, 2) restricting the treated area, which is the basic principle of site-specific pesticide spraying using precision agriculture techniques (Zanin et al., 2022).

1.2 Precision Agriculture

Precision agriculture is a management strategy that collects, processes, and analyses temporal, spatial, and individual data and combines it with other information to support management decisions based on estimated variability in order to improve resource use efficiency, productivity, quality, profitability, and sustainability of agricultural production (International Society of Precision Agriculture, 2021). Precision agriculture promotes improved management of agricultural production through the recognition that the productivity potential of agricultural land varies considerably, even over very short distances. Band and spot spraying treatments were designed to decrease waste and pollution caused by off-target losses (Monteiro et al., 2021).

Band spraying application, the agrochemical is applied only to the selected region which reduces the over usage of chemicals. Researchers (Netland et al. 2007; Niazmand et al. 2008) tested band spraying in cabbage and corn fields. Spot application is relatively a development in precision agriculture. Brown et al. (2008) tested a spot-application system, reporting reduced ground deposition by 41% and chemical runoff by 44% in orchards. They also reported that the smart sprayers reduced the input costs and manual labor in addition to enhancing the food quality. Though the research projects across North America have focused on the development of real-time spot applications for other crops, little focus has been given to potato production (Zanin et al., 2022).

1.3 Variable rate application spray technologies

Variable rate application is an important aspect of precision agriculture that provides economic benefits to the grower while reducing the application of pesticides (Katz et al., 2022). It uses field spatial information management variables to optimize agronomic inputs. Instead of spraying the entire field, variable rate application tries to limit the environmental effects by just treating weeds and insects in specified areas of the field. For site-specific spraying, the application rate of the sprayer is based on nozzle control. There are a variety of variable rate application technologies available that can be used with or without a Geographical positioning system (GPS). The two basic approaches for variable rate application are map-based and sensor-based.

1.3.1 Map-based variable rate application

Map-based variable rate spraying adjusts the application rate based on a prescription map, which is an electronic data file containing specific information about input rates to be applied in every zone of a field. The map-based method uses maps of previously measured items and can be implemented using several different strategies. The farmer and consultant have devised strategies for varying the inputs based on (1) soil type, (2) soil color and texture, (3) topography (high ground, low ground), (4) crop yield, (5) field scouting data, remotely sensed images (Hong et al., 2012).

The prescription map-based approach uses a controller to adjust the target application rate based on the exact field location of the machine using an onboard GPS device and a computer-generated applied map. For example, to develop a prescription map for nutrient variable rate application in a particular field, the map-based method could include the following steps: 1) Dividing the field into zones, 2) performing systematic soil sampling and lab analysis, 3) generating site-specific maps of the soil nutrient properties of interest, 4) using an algorithm to develop a site-specific nutrient prescription map based on the zones, 5) using the prescription map to control a fertilizer variable-rate applicator. The positioning system is used during the sampling and application steps to record the location of the sampling points in the field and to apply the prescribed nutrient rates in the appropriate areas of the field (Mooney et al., 2010).

1.3.2 Sensor-based variable rate application

Weeds and insects are usually distributed in patches, where uniform chemical treatment is not efficient from both economical and agronomic perspectives. A method of agrochemical application that depends on the level of weeds and insect infestation could help to improve the situation. However, in practice, precision weeds and insect control require information about the weeds and insect distribution within the field. Therefore, the sensor-based approach is required to avoid manual assessment and labor costs for practical application. In this approach, the applied rate is adjusted through the sensor feed (Steward et al., 2002), which can be MVS) that senses weeds in real-time while herbicides are being applied (Esau et. al, 2018). Data from the sensors is collected, processed, and interpreted by an onboard computer which then sends a signal to control the nozzles of the sprayer (Brown et al., 2008).

Advances in variable rate application control systems have made it possible to get real-time responses of the nozzles to signals received from the sensors. Pulse width modulation was introduced to nozzle control to optimize spraying when the nozzles arrive at new application zones within the field when compensation of flow rate across the boom is necessary when the sprayer turns (Downey et al., 2011; Needham et al., 2012).

1.4 Machine vision system

The management of weeds based on the geographical variability of their development decreases the use of pesticides owing to spraying in areas where the infestation exceeds the economic threshold. Pesticide abuse is associated with at least three major issues: application of pesticides at an insufficient phenological stage, application of herbicides without regard for infestation level, and application of pesticides in weed-free areas (Zhang et al., 2018). The farmer can tackle the first and second difficulties by using technical knowledge; However, strategic planning and tools are required to overcome the third difficulty. Thus, one feasible option would be weed control utilizing precision spraying techniques, which might potentially reduce the number of herbicides administered to the land and the environment (Zanin et al., 2022).

Weed detection involves identifying the weeds between crop rows using MV, which separates weeds from the soil background. Ahmed et al. (2010) used biological morphology algorithms in the field to segment the form and structure of weeds. Weed forms were detected using edge segmentation, and 140 photos yielded a classification accuracy of more than 94%. Most of the research is focused on weeds in crop fields which cause damage and reduce yield. However, for insect identification and discrimination within the field is a challenging task to accurately discriminate insects from plants. The presence of illumination variations, overlapping leaves, and insignificant color differences between weed and crop make this task more challenging. The spatial distribution of weeds, insects, and diseased plant patches within potato fields emphasizes the need to develop a site-specific variable rate sprayer (Kempenaar et al., 2017; Coulibali et al., 2020). Innovations in the development of precision agriculture technologies have enabled Engineers to develop site-specific variable rate sprayers using MV to accurately identify and encounter the targets in real-time within fields variable rate application of herbicides and insecticides (Hong et al., 2012).

Site-specific pesticide spraying requires MV recognition for accurate plant/weed and insect discrimination (including biological morphology, plant reflectance, and visual texture) and in-row removal mechanisms for eliminating weed competition (Slaughter et al., 2008). Slaughter et al. (2008) developed a robotic weed control system, consisting of a detection system using MV, GPS-based guidance, a variable rate control system, and a spray control system. This weed control system included sensors, a processing unit, and a decision support system to control nozzles for targeted agrochemical spraying.

Nowadays, herbicides are the most often used pesticides for site-specific treatment; however, the same approach may be utilized for other pesticides such as fungicides and insecticides (Dammer, 2016; Esker et al., 2018; Huang et al., 2018). In terms of preventative control techniques, site-specific fungicide treatment evaluates the dosage throughout the field surface base on canopy density. Through this technique denser canopies receive a larger dosage of fungicide, assuming that a dense canopy provides a microclimate that is more receptive to disease and contributes considerably to crop yield (Cointe et al., 2016). Studies about site-specific insecticide applications are less prevalent than those about herbicides because the population dynamics of flying insects are very intense. However, for insects, this form of site-specific management is also viable, as long as the treated mapping area is surrounded by a safe zone for proper control (Zanin et al., 2022).

In recent years, MV-based variable-rate application technologies for boom sprayers have been investigated extensively for use in the production of row crops (Liu et al., 2021). Many of the MVS was developed to detect weeds in different cropping systems (Lottes et al., 2017; Gao et al.,2018; Milioto et al., 2018; Zhang et al., 2018) Zhang et al. (2009 and 2010) detected weeds and bare patches in a wild blueberry cropping system using digital color cameras and quick image processing approaches. An MV-guided precision sprayer for small-plant foliar spraying (Slaughter et al., 2008) demonstrated a target deposition efficiency of 2.6 to 3.6 times that of a conventional sprayer, and the non-target deposition was reduced by 72% to 99% (Hong et al., 2012).

In North America, researchers have focused their efforts on developing precision agriculture technologies for crops (Zhang et al., 2010; Zaman et al., 2011; Esau et al., 2018; Zhang et al., 2018; Hussain et al., 2021). This research will be focusing on developing a site-specific pesticide application on insects using a boom sprayer which will enhance the agricultural cropping system.

1.5 Agriculture boom sprayer and its components

To regulate the quality of crops, farms utilize agricultural boom sprayers to apply insecticides, herbicides, and fungicides. They are available in various sizes and capacities such as hand-operated, portable backpack/knapsack sprayers, pull-type, and self-propelled boom sprayers. While considering the mechanized crop production in Canada, the latter two sprayers come to mind (Das et al., 2015). These sprayers are made up of many components that work together to provide the spraying function. Operating the sprayer usually involves chemical application (setting the correct rate of application, turning the application system on and off, checking boom height and flow, periodic checking for plugged nozzles), navigation (covering the field in a parallel pattern), controlling functions (steering, control travel speed, steering the sprayer along the parallel path, boom height control, checking plugged nozzle), scanning the field and displays in the cab, spraying around obstacles, planning parallel patterns through the field, and refilling the sprayer (Das et al., 2015).

The basic components of the boom sprayer include an engine, a cab, a control system, tanks a hydraulic system, and the boom. When evaluating the spraying performance, the boom system is considered a primary element where multiple nozzles and solenoid valves are attached at equidistance on the sprayer. In recent years, most of the sprayers are equipped with multiple electronic control units (ECU) (Figure 1.1) and bus connections as per SAE J1939 standards. Figure 1 shows 9 ECUs connected to each other on 3 busses (CAN-A, ISOBUS, and Tractor CAN-bus).

These ECUs control the working condition of each piece of equipment on the sprayer without any error during spraying or transportation mode. For example, manipulating the switches in the cabin changes the opening and closure of the nozzles on the booms by sending messages over the implement bus (colloquially called ISOBUS). In cabin, a standard ISOBUS connector can use to connect external devices compatible with ISOBUS.

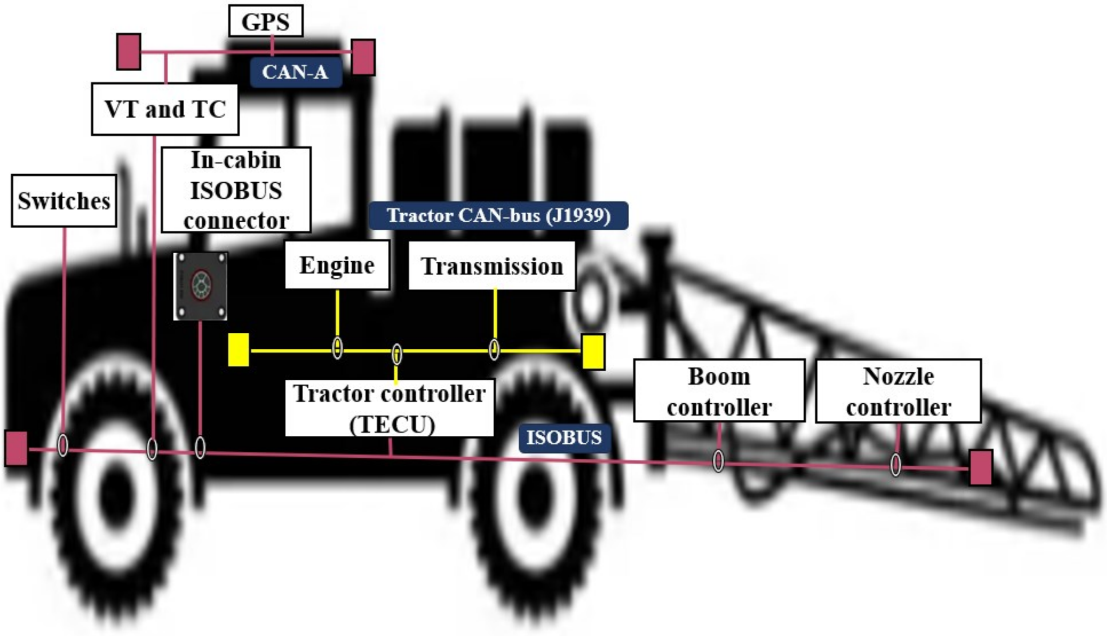


Figure 1.1: The agriculture boom sprayer and its components.

The Task Controller (TC) is a component of ISO 11783 networks used to control implements based on planned tasks received from a Farm Management Information System, (ISO 11783, 2018). The ISOBUS - TC defines TC-Geo and TC-Section control functionality to plan for product applications that vary spatially, which simplifies the treatment of management zones. Automatic section control is a technology that prevents overlap treatment by turning off boom sections made up of nozzles or rows as they approach an area that has already been treated (ISO 11783, 2018).

The nozzle controller and boom controller are mounted at the rear end of the sprayer. The nozzle controller activates the solenoid valves via electronic switches inside the tractor cabin to control individual or sections of nozzle operations (open/close). The boom controller operates the hydraulic cylinders to control the boom movement (Up/down and open/close) via electronic switches in the tractor cabin (Figure 1.1). The springs and dampers attached to the boom arm make it flexible to move around while spraying or allowing it to fold up during transport.

1.6 Communication system of the boom sprayer

One issue that arises by including MVS to boom sprayers is the amount and complexity of wiring required to link the new components to the already existing electronic systems on-board. In particular, in wide boom sprayers whose booms might extend to 32 m, there will be a need for a big number of cameras to cover the entire boom. However, communication protocols to minimize the amount of wiring while maintaining high reliability of data transmission do exist and can be the basis for communications schemes optimized for integrating MV into sprayers.

1.6.1 Controller area network

The controller area network (CAN-bus) is a robust standard and serial communication protocol based on bus topology, which efficiently supports distributed real-time control with a very high level of security communication of onboard equipment in trucks and buses (Marx et al., 2016). The CAN-bus protocol was designed at first to be used in vehicle applications, so it is very suitable for use in agricultural tractors and implements. A single cable with two wires is used to link all modules, and extensive error detection and correction allow it to operate reliably in the agricultural environment (Tumenjargal et al., 2013). CAN-bus uses a physical layer comprised of a shielded twisted two-wire system; CAN high (CAN_H, yellow), and CAN low (CAN_L green) ISO 11898 – 2 (1998) (Figure 1.2). The cable, whose impedance is 120 Ω, is terminated at each end by a resistor of this value ISO 11898 -2 (1998). The bit rate of the CAN-bus protocol can reach 1 Mbit/sec, with the maximum bus length being 40 m. A longer bus length can be achieved with a minimum of 10 cm between ECU (Batbayar et al., 2018). The ECU is an embedded device available in automotive and farm vehicles that connects buses and implements control functions (Figure 1.2)

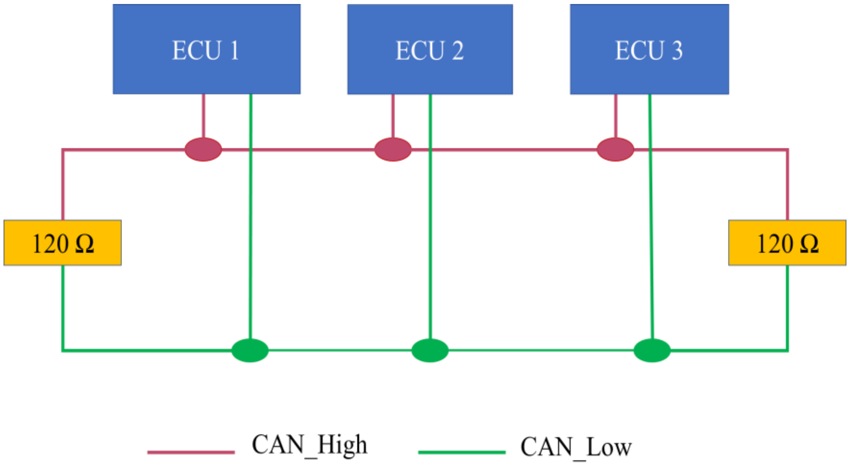


Figure 1.2: Schematic illustration of a CAN-bus topology consisting of three ECU. ECU is an electronic unit that consists of a CAN controller and CAN transceiver.

CAN-bus was adopted as a standard by the SAE (Society of Automotive Engineers), and, later, by the ISO (International Organization for Standardization). The Bosch CAN-bus specification became an ISO standard (ISO 11898) in 1993 (CAN 2.0A) and was extended in 1995 to permit longer device identifiers (CAN 2.0B) (Pereira et al., 2011). The difference between a CAN 2.0A and a CAN 2.0B message is that CAN 2.0B supports both 11-bit and 29-bit identifiers (Figure 1.2) (Paraforos et al., 2019).

In CAN-bus, all messages are referred to as frames. Information sent via CAN-bus must be compliant with defined frame formats of different but limited lengths (Marx et al., 2016) (Figure 1.2). The CAN-bus frame is divided into two main parts which are the arbitration field, and the Data field. The arbitration field on the CAN-Bus data frame consists of CAN 2.0A (11 bits) and CAN 2.0B (29-bits) identifier. The CAN identifier specifies the data in the data field and the address information for the source and destination. The data field contains the signals described as parameters and grouped as PG (Bauer et al., 2019).

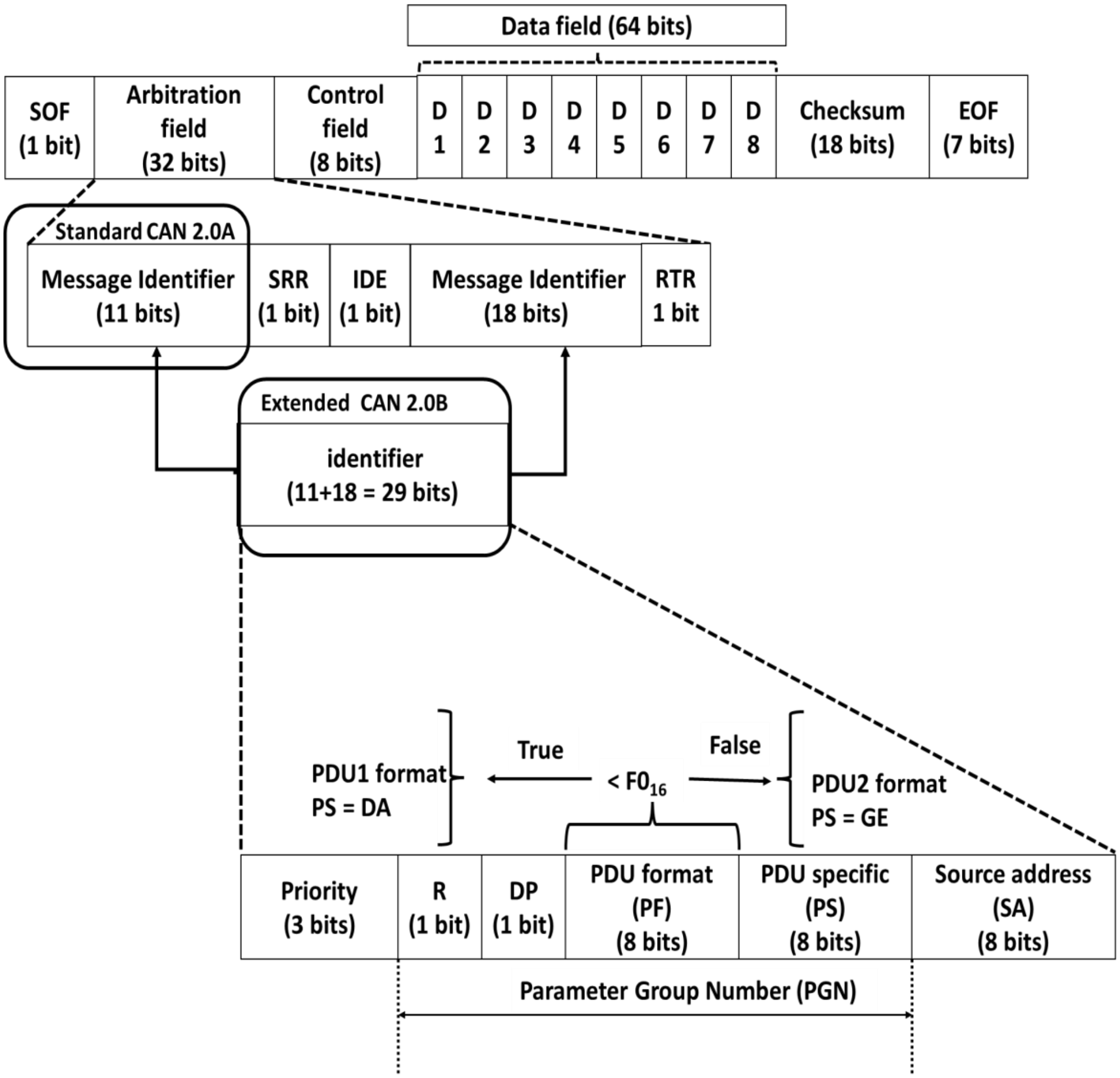


Figure 1.3: CAN-bus data frame consists of CAN 2.0A (11-bits) and CAN 2.0B (29-bits) identifier. The structure of CAN 2.0B 29-bits message identifier was further classified into priority, PGN (R, DP, PF, PS), and SA.

From Figure 1.3 the total number of parameter group numbers (PGNs) is calculated as: (240 + 16*256) *2 = 8672, where 240 is the total number of protocol data units (PDU) - PDU1, 16 is the total number of PDU2, 256 is the total number of GE of PDU2, 2 is DP (either 0 or 1). Each PG is identified by a unique PGN. Since a single CAN-bus frame can only move up to 8 bytes most of the PGs are designed with a length of 8 bytes. Message frame format according to CAN-bus 2.0B allows for the broadcast of prioritized messages between ECUs in a multi-master system (Bauer et al., 2019). This system allows any ECU to broadcast a message to any other ECU under the same protocol (Paraforos et al., 2019).

Messages with varying priorities can be sent using the identifier field regardless of the node source. The ISO 11898 -3 (2016) standard describes how to utilise the identifier and data field bits in the context of a CAN-bus message, as shown in Figure 1.3. During the arbitration, the first three bits of the identification govern message priority, with the highest priority having a value of 0. High-speed control communications, such as the torque control message from the gearbox to the engine, are often prioritized. Lower priority messages are not time-critical, such as road speed. The priority bits are used to optimize message latency for transmission onto the bus only (Paraforos et al., 2019). Every message's priority can be changed from highest to lowest, from 0 to 7. The value 3 is the default for all control-oriented messages. All additional informative, proprietary, request and non-ACK messages have a default value of 6. This allows the priority to be changed in the future when new PGN values are assigned and bus traffic changes.

The PGN is a unique frame identifier in the ISO 11783 standard, which is used to group related data parameters and optimize message transmission. It composes an 18-bit subset of the 29-bit extended CAN ID. The PGN can be broken down into four parts: R (1-bit), DP (1-bit), PDU format (8-bit), and PDU-specific (8-bit). The first 1 bit of the identifier on the PGN is R for future use and is set to 0 for transmitted messages. The next 1 bit of PGN is the DP selector, which increases the number of available PGNs. PGN ensures the messages are delivered to their intended RX and maintains network stability. By grouping the related parameter into PGNs, it is possible to optimize message transmission and reduce network traffic.

The PDU format determines whether the message is transmitted with a DA or as a broadcast message. The PS field is used to address messages and changes according to the PF value. If the PF is between 0 and 239, the message is addressable (PDU1), and the PS field includes the DA. If the PF is between 240 and 255, the message can be broadcast (PDU2), and the PS field includes a GE according to ISO 11898-3 (2016). DA: This field defines the specific address to which the message is being sent. Any other controller or ECU should ignore the message. The global DA requires all controllers or ECUs to listen and respond accordingly as message recipients.

The creation of the PGN is the other purpose of the PF field when it is connected to the DP and R fields. PDU1 messages have a PGN of 10 bits, while PDU2 messages have a PGN of 18 bits due to the addition of the GE - 8 bits field (Pereira et al., 2011). The SA contains the address of the nodes transmitting the message. The address is a specific label assigned to access a given node on the network uniquely. For any given network, every address must be unique. There are a total of 254 different addresses available. No two different nodes (ECUs) can use the same address. The TP and ETP are the two protocols specified by ISO 11783 to carry out data transfers bigger than 8 bytes. TP defines the format of frames, sending, handshaking, and reassembling packets. TP uses two multi-packet broadcast-specific PGs for fragmented transmission of large data (More than 8 bytes). First is the TP connection management message (TP.CM); it contains the connection command, the PGN identifier of the TP message, and information about how to reconstruct the message. The second is the TP data transfer message (TP. DT); it contains sequence numbers in the first byte and 7 bytes of data. The TP is used for data transfer larger than 8 bytes and up to 1785 bytes. The ETP is used for transferring data over 1785 bytes and up to 117,440,512 bytes ISO 11783-6 (2018).

Message communication is supported by the ISO 11783 protocol, including broadcast, point-to-point, and global messages. Broadcast messages are delivered to all ECUs on the network, whereas point-to-point communications are delivered directly between two ECUs. Message filtering is also supported by the ISO 11783 protocol, including SA filtering, message ID filtering, and PG filtering. These filters assist to decrease network data traffic, enhancing overall performance, and lowering the danger of data collisions.

1.6.2 International Society of Organizations (ISOBUS) communication system

For agricultural implements, the trend is to use standardized communication systems under ISO 11783 (Backman et al., 2019). This standard, colloquially called ISOBUS, is a set of definitions, regulations, and processes for connecting and exchanging information between tractor control units and agricultural implements - attempting to apply the concept of "plug and play" between agricultural machinery and equipment (Tumenjargal et al., 2013). ISO 11783 arose from the union of two other standards: LBS / DIN 9684 (Auernhammer, 2001; Pereira et al., 2008) and Society of Automotive Engineering SAE J1939 (Auernhammer and Speckmann, 2006; Pereira et al., 2008) both standards based on protocol CAN-bus (Pereira et al., 2008). ISOBUS can be a suitable solution for the decentralization of the data acquisition system whose communication protocol is based on version 2.0B of CAN-bus ISO 11783 -3 (2018). This standard has been developed to meet the need for electronic communication between tractors and implements, between components within tractors, within implements, and other self-propelled agricultural machines (Yu et al., 2021). Nevertheless, the standard has some flexibility which allows for different interpretations, resulting in probable different implementations that may be incompatible with one another (Siponen et al., 2022).

To prevent this, implement and tractor manufacturers established the Agricultural Industry Electronics Foundation (AEF) in 2008 with the goal of promoting the use of ISOBUS, their implementation of ISO 11783, to improve compatibility between tractors and implements made by various manufacturers. To ensure interoperability amongst ISOBUS products, the AEF has established standards for how ISO 11783 should be read (Siponen et al., 2022). To be marketed as ISOBUS compatible, a product must pass at least one of the AEF's conformance tests. Products that have received AEF certification are marked with the AEF Certified Label and included in the AEF ISOBUS database. The database is primarily intended for end users to conveniently obtain information about available certified ISOBUS devices and their functionality (Siponen et al., 2022).

1.7 Research problem

Although there is a proposed MVS that can detect invaders (insects and weeds) of the potato fields, the communication lag still exists between the MVS and the sprayer. However, these MVS are not necessarily compatible with the sprayers to send the detected information to control the nozzle system. To enable an MV-based site-specific application on sprayers as an after-sale option, the MVS needs to be connected to the sprayer via an

ISOBUS node which is an ECU that receives detection results information from the MV and creates CAN messages compatible with the sprayer. This node will provide a generalized protocol to communicate the results of the MV detection with itself, whereas the CAN messages will be customized to the specific sprayer.

1.8 Research objectives

The goal of this research project is to enable sensor-based site-specific application on boom sprayers for real-time herbicide and insecticide application. This can be achieved by developing the node that will enable integrating third-party MVS as add-ons to sprayers that communicate via ISOBUS. The following are the objectives of this research project that will lead to the research goal:

- Developing software to communicate with proprietary nozzle control units via ISOBUS.
- Embedding the software algorithm in the node, which is a single board computer, and establishing a new communication protocol to communicate between the node and the MVS.
- Testing the node with different MVS in the lab and the field on a static sprayer and a self-propelled boom sprayer.

CHAPTER 2 MATERIALS AND METHODS USED IN LAB AND FIELD

2.1 Introduction

The development of electronic systems has allowed agriculture to enter a new age with real-time data transfer and task monitoring capabilities. The adaptation of electronic systems has provided growers with an improved ability to ensure optimal solutions (Al-Aani et al., 2016). As described in Chapter 1, ISO 11783 can be utilized to design a management system for agricultural implements as it provides reliable transportation of data. In this chapter, the implement busses, used to transport CAN data including ISO 11783 data, were analyzed on the research apparatuses which were a static sprayer and a boom sprayer. The methodology performed on both sprayers was to analyse the implement data and write software to control the sprayers via laptop using CAN messages.

2.2 Lab analysis and evaluation of prototype static sprayer

2.2.1 Static sprayer description

The static sprayer, located at the AIES research laboratory – Banting building, Department of Engineering at Dalhousie University Faculty of Agriculture, Truro, NS, Canada, is a custom-made system (Green Lea Ag Center Inc., Mount Elgin, Ontario, Canada) that resembles an actual boom sprayer for spot application. It consists of a virtual terminal (AFS Pro 700, Raven Industries, Sioux Falls, South Dakota, USA) with raven console switches (RCS) that control the nozzles (6 nozzle switches, rate control switch, and master key). The nozzles used were flat fan AIC Teejet (AIC11004, Spraying Systems Co., Wheaton, IL, USA), whereas the solenoid valves were Raven Hawkeye valves (Raven Industries, Sioux

Fall, SD, USA), used for uniform rate application. The nozzle and solenoid valves were placed at equidistance on the sprayer pipe ~ 300 mm (Figure 2.1). The pump used was a diaphragm pump (2088-343-435, Pentair Inc., Minneapolis, Minnesota, USA). The controller box contains the nozzle control unit (Rate Control Module, Raven Industries, Sioux Fall, SD, USA) is attached to an ISOBUS connector harness (Raven Industries, Sioux Fall, SD, USA) in the controller box (Figure 2.1). The virtual terminal, RCS, and the nozzle control unit interact with each other on the implement bus (i.e., ISOBUS) shown in Figure 2.1

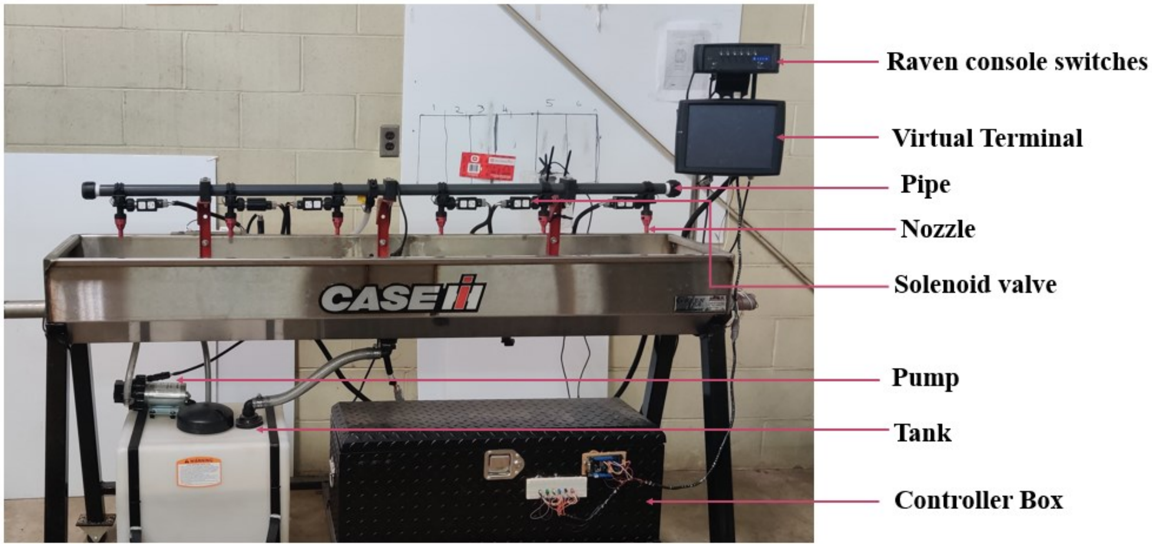


Figure 2.1: Indoor static sprayer setup.

2.2.2 Experimental setup for the communication data collection on a static sprayer

The first step in the work methodology was to collect the sprayer messages on the implement bus via laptop. This was carried out to develop a sprayer control software. An ISOBUS extension was made between the sprayer and laptop by developing communication using a CAN sniffer (CANUSB, Lawicel AB, Tyringe, Sweden) (Figure

2.2). The CAN sniffer is a data sniffer used to collect data from the sprayer. The dongle can be plugged directly into a standard USB port and provides a standard DB-9 male output to CAN-bus systems according to CiA DS102-1 recommendations. It is powered by a USB port as it uses 5 VDC. It consumes a max of 100 mA, but normally not more than 60 mA (this depends on BUS load and eventual CAN-bus cable errors).

Next, software that can communicate with the nozzle control was developed. In the following stages, an MVN was developed to integrate an MVS. The developed MVN was mounted on both the static sprayer and boom sprayer to transfer commands from the MVS to the nozzle system of the sprayer. Analysing of the sprayer data flow was carried out by making a CAN-bus harness (Figure 2.2).

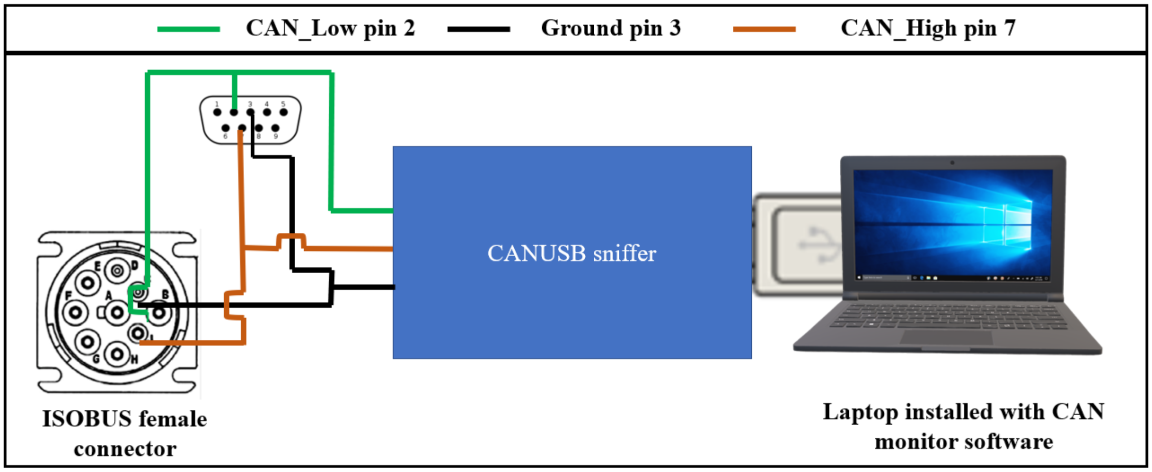


Figure 2.2: ISOBUS harness connection to connect CAN sniffer to the sprayer

The harness was connected to the ISOBUS male connector via the CAN-bus communication system on the static sprayer shown in (Figure 2.3). A CAN monitor software (WG software, Lawicel, Sweden) is an existing method to view the data from the CAN-bus communication system (Figure 2.4). To monitor the flow of CAN-bus data on the static sprayer, the sniffer is useful for sending, receiving, and monitoring data messages from the CAN-bus frame of any parameter (CAN_ID, DLC (Size of data), message, and timestamp). The CAN monitor software was used to find the CAN_ID and data messages on the static sprayer as shown in Figure 2.4 (b) and (c).

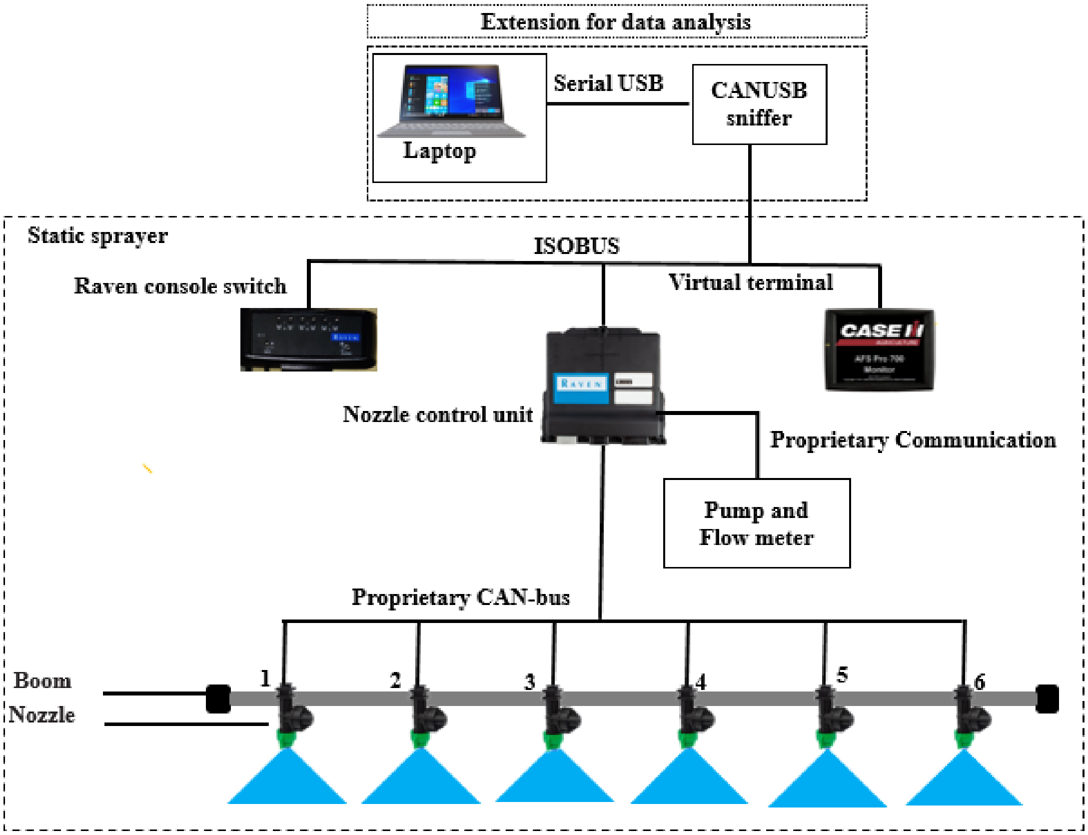
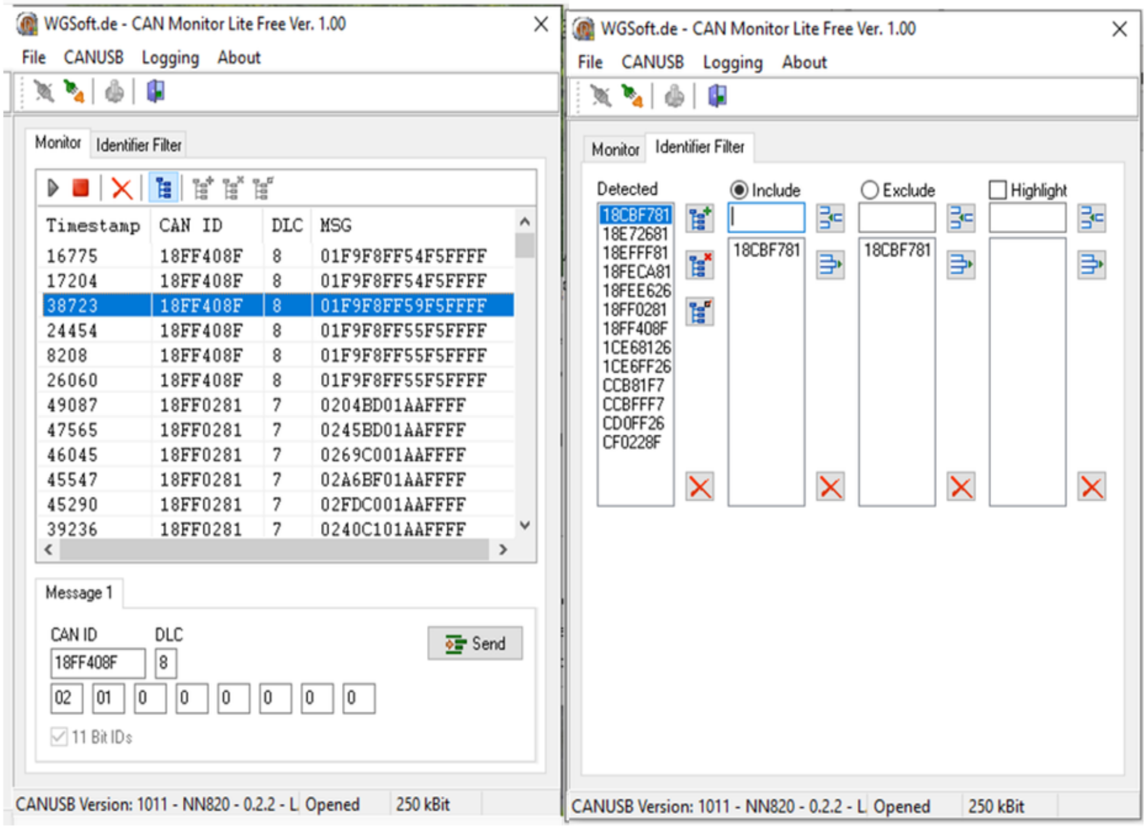


Figure 2.3: Communication between all electronic components on the static sprayer including the extension of data analysis using CAN sniffer and laptop.

2.2.3 Developing CAN-bus connections on the static sprayer

Before monitoring the CAN-bus data, the CAN monitor software needs to be configured as follows: Initially, the CAN-bus bit rate box was set to 250 Kbit/s which is the rate of ISOBUS standard (Figure 2.4 (a)). The software consists of two sections, monitoring, and identifier filter as shown in Figure 2.4 (a) and (b). The monitoring section has four columns that show the timestamp, CAN_ID, DLC, and data messages from the sprayer. The identifier filter section is useful to filter the specific CAN_ID or data message out of the available CAN_ID and messages. All data are in a hexadecimal (HEX) format for the sprayer data flow analysis.



Timestamp	CAN ID	DLC	MSG
16775	18FF408F	8	01F9F8FF54F5FFFF
17204	18FF408F	8	01F9F8FF54F5FFFF
38723	18FF408F	8	01F9F8FF59F5FFFF
24454	18FF408F	8	01F9F8FF55F5FFFF
8208	18FF408F	8	01F9F8FF55F5FFFF
26060	18FF408F	8	01F9F8FF55F5FFFF
49087	18FF0281	7	0204BD01AAFFFF
47565	18FF0281	7	0245BD01AAFFFF
46045	18FF0281	7	0269C001AAFFFF
45547	18FF0281	7	02A6BF01AAFFFF
45290	18FF0281	7	02FDC001AAFFFF
39236	18FF0281	7	0240C101AAFFFF

CAN ID: 18FF408F
DLC: 8
02 01 0 0 0 0 0 0
☑ 11 Bit IDs

CANUSB Version: 1011 - NN820 - 0.2.2 - L Opened 250 kBit

Detected
18CBF781
18E72681
18EFFF81
18FECA81
18FEE626
18FF0281
18FF408F
1CE68126
1CE6FF26
CCB81F7
CCBFFF7
CD0FF26
CF0228F

● Include
18CBF781

○ Exclude
18CBF781

☐ Highlight

CANUSB Version: 1011 - NN820 - 0.2.2 - L Opened 250 kBit

(a) (b)

Figure 2.4: CAN monitor software used to view the data flow of the sprayer (a) Monitoring window (b) Filtering window of CAN monitor software.

From the analysis, 13 CAN_IDs were found, out of which, 7 followed the ISOBUS protocol, 4 were proprietary, and 2 followed the J1939 protocol as mentioned in Table 2.1. As explained in Chapter 1, CAN 2.0B (29-bit identifier) frames consist of an identifier that shows the type of data (PDU1 or PDU 2), the SA (sending ECU), and the DA (receiving ECU) if available. The 13 identifiers of the static sprayer were studied to determine whether the nozzle control unit requires peer-to-peer or broadcast communication messages for nozzle operation. For this purpose, ECU information and address that claim during data transfer are needed.

The ISO 11783 address claiming mechanism is an important part of the ISOBUS protocol. Network management (ISO 11783-5, 2018) is in charge of assigning addresses to ECU during the boot-up (Voss, 2008). No master node in the ISO 11783 network can assign these addresses to ECU devices. Instead, the bus addresses are retrieved using the address claim mechanism. When a new node enters the network, it must first receive a valid address before it can begin communicating. These addresses are assigned with the help of the address-claiming mechanism (Voss, 2008). It consists of two possible scenarios: 1) sending an address claim message and 2) requesting an address claim message. In the ISOBUS network, address conflicts amongst ECUs are handled by the use of a unique device 'NAME', and a valid address for identification purposes (Jichici et al., 2022; Voss, 2008). The ISOBUS protocol uses the J1939 vehicle network procedure to define a 64-bit 'NAME' to uniquely identify each ECU in a network (Pereira et al., 2008). The 'NAME' structure includes the essential information for connecting and initializing ECU on the network (Jichici et al., 2022; Voss, 2008).

The NAME cannot be utilized as the message address as is because the CAN-ID is only 29 bits long and the whole data field in a CAN frame is only 64 bits. Instead, communication uses a one-byte address, which is shorter. When claiming an address, the Name is placed in the CAN data field to identify which ECU wants to claim an address. In the address claim procedure of ISOBUS, there are 256 possible ECU addresses. Valid addresses for ECUs are 0-253, 254 is a null address and 255 is a broadcast address (Murvay and Groza, 2018). The Name structure denotes information such as the manufacturer code, identification number, and function instance, industrial group. The manufacturer code and identification number and industrial group are unique identities issued by the ECU's manufacturer. A function instance indicator is added in cases where multiple ECUs with the same main function share the same network (Pereira et al, 2011).

All ECUs connected to the ISOBUS network will start to receive the address claim message after it has been broadcast. The information in the address claim message will be compared to the information on each ECU (Voss, 2008). Each ECU that receives an address claim will record and check it within its internal address table. The ECU with the lowest 'Name' value will prevail and utilize the address as claimed in the event of an address dispute (Murvay and Groza, 2018). When two or more ECUs attempt to use the same address either a new address must be claimed by the existing ECUs, or they must stop sending data to the network.

The remaining ECUs must either send a cannot claim address message or send another address claimed message with a new address to claim a different address (Voss, 2008). The DA for an address claim is always the global address (255) to address all ECUs in the network as shown in Table 2.1 (0xFF-PDU specific). An ECU, that has not yet claimed an address, must use the NULL address (254- 0xFE) as the SA when sending an address request claimed message (Murvay and Groza, 2018). This allows the other ECUs to determine which address the ECU will use. Finally, if there is an address dispute, the ECU must wait before proceeding with regular communication using the claimed address.

Table 2.1: Analysing of 13 CAN-bus identifiers on the static sprayer

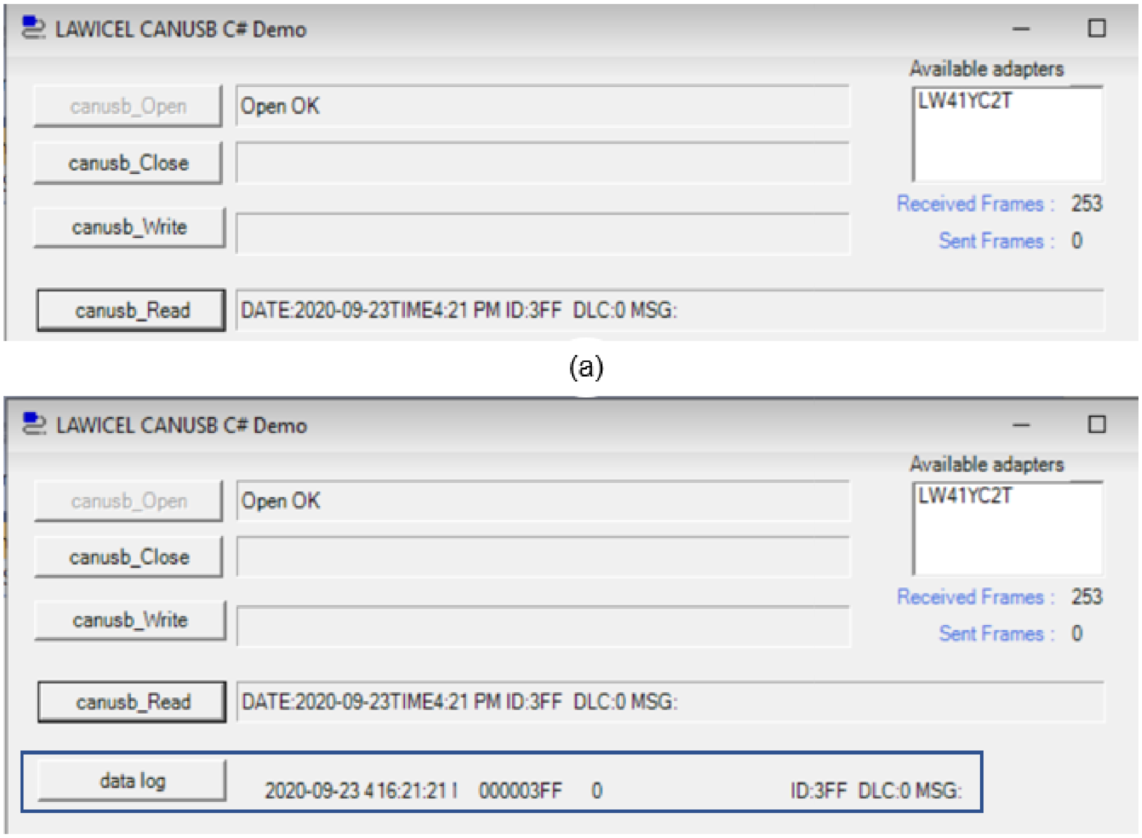
Source ECU	CAN-ID	PGN	PDU	(Destination ECU/ Global address)	Protocol
Nozzle control unit	18EFFF81	61184	1	Claiming address	Proprietary
	18CBF781	51968	1	Task controller	ISO 11783
	18E72681	59136	1	Virtual terminal	ISO 11783
	18FECA81	65226	2	Broadcast	Proprietary
	18FF0281	65282	2	Broadcast	Proprietary
Raven console switch	18FF408F	65344	2	Broadcast	Proprietary
	0CF0228F	61474	2	Broadcast	ISO 11783
Virtual terminal	0CD0FF26	53248	1	Requesting address	J1939
	1CE6FF26	58880	1	Requesting address	ISO 11783
	1CE68126	58880	1	Nozzle control unit	ISO 11783
	18FEE626	65254	2	Broadcast	J1939
Task controller	0CCBFFF7	51968	1	Claiming address	ISO 11783
	0CCB81F7	51968	1	Nozzle control unit	ISO 11783

2.2.4 Modifying the data logging software for the data collection on a static sprayer

The CAN sniffer has data monitoring software (designed by Lawicel) written in visual studio C#. This software allows to view and monitor CAN messages and information via sniffer as shown in Figure 2.5 (a) but without a data logging feature. To log the communication data message the software was modified as shown in Figure 2.5 (b). To allow simultaneous spraying, CAN messages need to be sent the order to open or close each nozzle on the same message. Because each nozzle valve has only two states (open and close), the number of unique messages required to open or close all of the nozzles at the same time was determined by Equation (1), where n is the number of nozzles. As the apparatus consisted of 6 nozzles, there were 64 unique messages requested by the nozzle control unit.

$$\text{Number of switch messages} = 2^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

To collect data, on the static sprayer (Figure 2.3), the nozzle switches were turned on for 5 minutes, at each possible combination of the 64 (Trial and error). The collected data was saved in spreadsheets for further analysis of CAN_ID and data messages. The analysis focused on finding consistent patterns of data at different CAN_IDs to find the messages requested by the nozzle control unit. From the comparison of spreadsheets, the specific CAN_ID and data messages pattern were identified based on changes in message bytes as the spraying nozzles changed. These messages were different in the values of two bytes only in the data field.



Open OK

LW41YC2T

Received Frames : 253

Sent Frames : 0

DATE:2020-09-23TIME4:21 PM ID:3FF DLC:0 MSG:

(a)

Open OK

LW41YC2T

Received Frames : 253

Sent Frames : 0

DATE:2020-09-23TIME4:21 PM ID:3FF DLC:0 MSG:

2020-09-23 4 16:21:21 I 000003FF 0 ID:3FF DLC:0 MSG:

(b)

Figure 2.5: (a) Lawicel C# GUI. (b) Modified data logging software using data logging button inclusion.

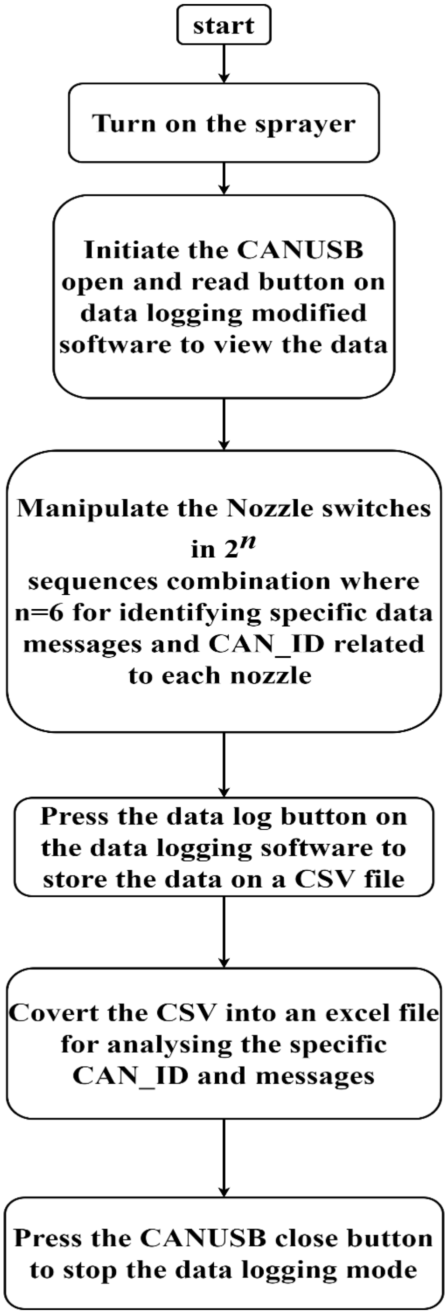


Figure 2.6: Flow of data collection from the implement bus using CAN sniffer.

Based on the identification a flowchart was developed to control the nozzle of the sprayer as shown in Figure 2.6. From the analysis, it was found that the nozzle control messages were broadcast by the RCS based on changes in the 5th and 6th bytes of the data field. In the following step, a laptop sprayer control software was written in C# software to enable controlling the nozzles via the laptop.

2.3 Field analysis and evaluation of boom sprayer

Field experimentation was conducted at McCain Farms of the Future (Florenceville, New Brunswick, Canada). Pesticide spray application procedures were performed as normally conducted by on-farm staff, with minimal interference during data collection. Precision spraying technologies utilized during field operations included: automatic boom section control based on previously defined field boundary maps, and auto-guidance technologies, both of which utilized a local real-time kinematic GPS correction network.

The boom sprayer (Figure 2.7) was Patriot 3340 (CASE IH, Racine, Wisconsin, USA). The sprayer boom consisted of 62 equally spaced nozzles, set at 0.5 m spacing, spanning a total width of 30.5 m. The sprayer automatic section control system was divided into six boom sub-sections. A uniform set of Teejet AIC11004 nozzles were used across the width of a boom. The same solenoid valves mounted on the static sprayer were used for uniform rate application. The nozzle control unit which regulates the actuation of 62 solenoid values and the boom control unit which controls the action of the boom (folding and unfolding) were located at the back end of the boom sprayer. The nozzle section control and boom control had separate switches inside the cabin of the tractor.

Figure 2.7: Case IH patriot 3340 sprayer.

2.3.1 Data collection for nozzle control in the boom sprayer

The ISOBUS extension harness was modified with two-channel monitoring capabilities which enabled CAN-bus to record the CAN_ID and CAN-bus messages on the implement bus. A Multiple DB-9 pin connector (Male and female DB-9 connector) with CAN-bus wiring was used to collect data. A similar connection (Figure 2.2) was established between the ISOBUS extension harness and the in-cab ISOBUS male diagnostic port. The sniffer was connected to the laptop which had the modified data logging software. From the analysis, 22 CAN_IDs were found, out of which, 13 were identical to the ones found in the static sprayer in Table 2.1. The remaining 9 CAN_IDs included 4-ISO 11783, 2- J1939, and 3 proprietaries as shown in Table 2.2.

Table 2.2: Analysis of 22 CAN-bus identifiers on the boom sprayer.

Source ECU	CAN-ID	PGN	PDU	(Destination ECU/ Global address)	Protocol
Raven console switch	0x0CE7FF8F	59136	1	Claiming address	ISO 11783
	0x18E7268F	59136	1	Virtual terminal	ISO 11783
Nozzle control unit	0x18ECFF81	60416	1	Claiming address	J1939
	0x1CEB2681	60160	1	Virtual terminal	J1939
	0x18EF8881	61184	1	Not investigated	Proprietary
Tractor ECU	0x18E72690	59136	1	Virtual terminal	ISO 11783
	0x14FF3290	65330	2	Broadcast	Proprietary
Not investigated	0x18E72688	59136	1	Virtual terminal	ISO 11783
	0x18EF8188	61184	1	Nozzle control unit	Proprietary

2.4 Conclusion

The developed Lawicel CAN monitor software collects all the CAN-bus message information for both static and boom sprayers. All the data collected using this software were decoded of the messages of various parameters of the sprayer. All the conversion of the HEX data engineering unit was performed using Microsoft excel based on SAE and ISOBUS database documents. With the aid of the feature of the HEX2DEC conversion tool, each CAN_ID is converted one at a time. And the nozzle controlling CAN_ID and messages were extracted and analyzed for the selected message data. From the analysis, this study summarizes that the modified data logging software is one of the efficient tools for analyzing the sprayer data flow. The collected CAN_ID data and messages were compared with the ISOBUS directory to know the specific information. In the following chapters, the identified CAN_ID with the messages was used to develop a GUI-based MVN to control each nozzle of the sprayer.

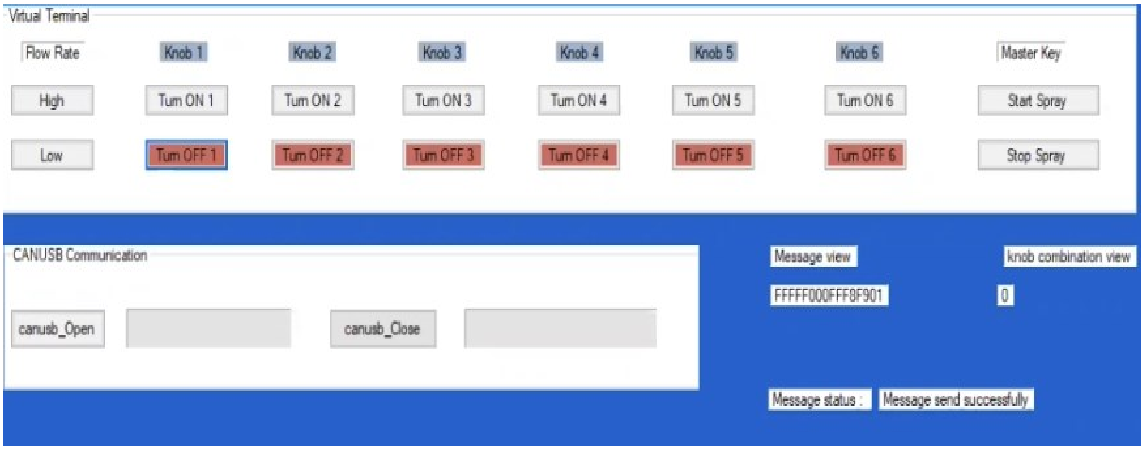
CHAPTER 3 GRAPHICAL USER INTERFACE LAPTOP-BASED AND MICROCONTROLLER NOZZLE CONTROL SOFTWARE

3.1 Introduction

This chapter summarizes the electronics used to develop a GUI laptop-based and microcontroller-based nozzle control software. The hardware used for developing the software systems are a laptop (Dell Inc., Round Rock, Texas, USA), a Mega Microcontroller (Arduino Inc., Somerville, Massachusetts, USA), a CAN-bus shield (CAN-Bus Shield V2, Seeed Studio, Shenzhen, China), as well as the CAN sniffer. The software platforms used were Visual Studio C# and Arduino IDE. The proposed software was communicated with the sprayer via a serial communication protocol. The performance of the proposed system was tested and evaluated in both lab and field environments.

3.2 Development of GUI laptop-based software

Based on data flow analysis, a GUI sprayer control software was written in visual studio C# based on the developed flowchart algorithm (Figure 2.6) to open and close the nozzles. The software (Figure 3.1) includes 4 information tabs: CAN communication (CAN-bus open, close), Message view (respective message to open and close the nozzle), nozzle combinations view (64 combinations), and message status (successful or failed) for monitoring the CAN-bus communication system between the sprayer and laptop.



Message view: FFFFF000FFF8F901

knob combination view: 0

Message status : Message send successfully

Figure 3.1: Laptop sprayer control software for controlling the nozzle of the sprayer

3.2.1 Performance and evaluation of the developed software

The demonstration test trial of the software was carried out using both the static sprayer and the boom sprayer. At the boom sprayer, the trial was conducted under stationary conditions as well as running at an idle. The software consists of a button configuration to switch on (green) and off (red) each nozzle. Figure 3.2 shows a situation when the software was able to open a specific nozzle on the static sprayer. The user can manipulate the virtual switches on the developed laptop software to control each nozzle individually or in combinations. The developed system provided 100 % consistent results with proper nozzle operation when multiple replicate measurements were conducted.


Figure 3.2: Testing the laptop nozzle control software opening Nozzle 2 (Second from left) of the static sprayer.

3.3 Microcontroller nozzle control system using Arduino

The Developed ECU system consists of the Mega microcontroller, CAN-ShieldV1.2 embedded with MCP2515 a CAN-bus controller, and an MCP2551 CAN-bus transceiver which is assigned for J1939 and ISOBUS vehicles.

3.3.1 CAN-bus shield

The CAN-bus shield (Figure 3.3) is equipped with an MCP2515 microchip CAN-Bus controller with SPI interface and an MCP 2551 CAN-bus transceiver, allowing the Arduino to make CAN-bus compatibility to communicate through sending and receiving CAN-bus messages. The CAN-bus shield can implement CAN 2.0 at up to 1 Mb/s and SPI interface up to 10 MHz. It possesses two receive buffers with prioritized messages storage. It has LED indicators that consist of power, TX blink when data is sent, RX when data is coming, and INT data interrupt.

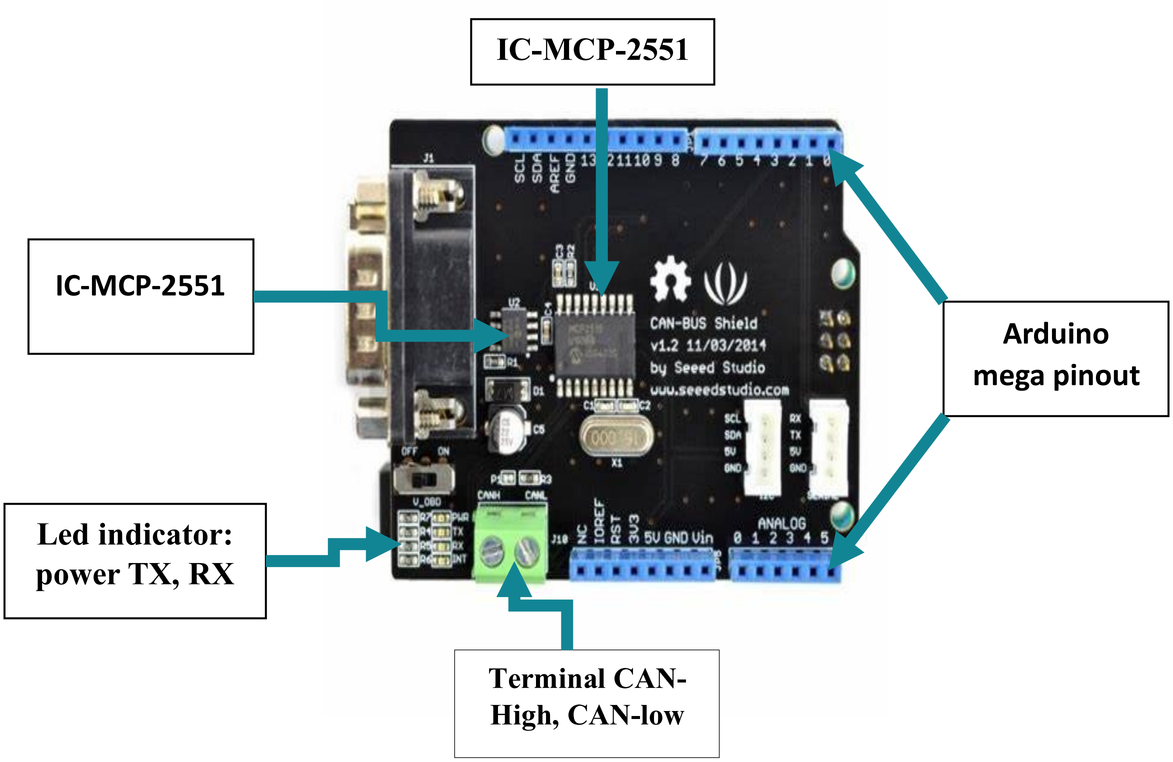


Figure 3.3: Main components of the CAN-bus shield V 1.2 microprocessor.

The shield is compatible with Arduino UNO and Mega boards by interfacing via SPI, which is a synchronous, full duplex master-slave-based interface. The data from the master or the slave is synchronized on the rising or falling clock edge. Both master and slave can transmit data at the same time. Table 3.1 shows the pin configuration for the MEGA and CAN-bus shields.

Table 3.1: Pin configuration for Arduino mega 2560 with the CAN-bus shield

Mega pin	Shield pin	SPI description
50	12	MISO
51	11	MOSI
52	13	SCK

The electronic connection between the sprayer and microcontroller was established by connecting the developed microcontroller (Arduino mega and CAN-bus shield). This connection allows the data to flow between the microcontroller and the sprayer via the implement bus. The CAN sniffer was interfaced and used to collect the data transferred while controlling the sprayer using the developed software systems.

3.3.2 Software used for developing the microcontroller interface

Arduino IDE was used as a platform to flash the developed code into the developed embedded device. The CAN-bus shield was connected to the laptop which powered the Microcontroller. The SPI library and MCP2515 CAN-bus library were included in the Arduino IDE platform using a C++ program for configuring the CAN-bus shield with Arduino mega. The software was used for the development of microcontroller software for the nozzle control system on the static sprayer using electronic switches. All the developed codes are uploaded in Arduino which can interact and communicates with both an indoor static sprayer and outdoor boom sprayers via the shield.

An electronic push button switch was used as a replacement for RCS and a developed algorithm was embedded in the microcontroller to act as external physical control of the static sprayer. This system paved a pathway for the control of the sprayer via the MV. Six electronic push buttons (Figure 3.4) were added to the microcontroller so that physical rather than virtual buttons can control the nozzles.

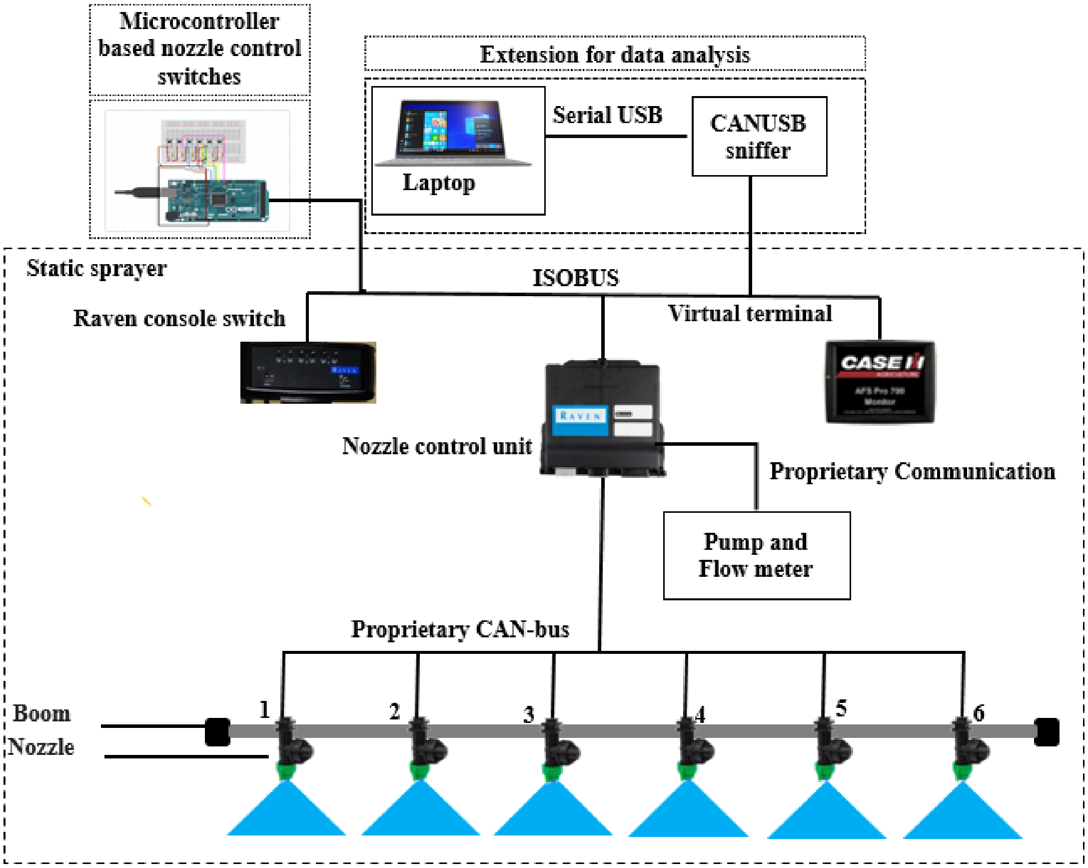


Figure 3.4: Communication between all electronic components on the static sprayer including the microcontroller-based nozzle switches.

3.4 Testing microcontroller software for nozzle control system on the static sprayer

The demonstration test trial for the developed microcontroller-based nozzle control software system was carried out. The static sprayer and boom sprayer were used as platforms for the trial test. For the boom sprayer, the test trials were conducted under a tractor stationary stage and running at an idling speed condition. These trials were conducted for verifying the developed microcontroller-based nozzle control software system to control the individual nozzle or section of the sprayers. The developed microcontroller-based program was connected to the ISOBUS cabin connector. Based on the buttons pressed, the coded embedded in the microcontroller was able to send the correct messages via the CAN-bus shield to control the respective nozzle of the sprayer. From the result, the developed software can communicate with proprietary nozzle control units via ISOBUS.

CHAPTER 4 MACHINE VISION NODE DEVELOPMENT FOR SITE-SPECIFIC APPLICATION

4.1 Introduction

This chapter summarizes the assembly of the MVN prototype using the hardware and software developed in the previous chapters. Also, it summarizes the development of an indoor MVS deployed on the static sprayer to test and validate the MVN before testing with an MVS developed by Resson Aerospace Technology in the field condition.

4.2 Development of an MVN prototype for a static sprayer

The MVN and MVS consist of a Raspberry Pi (RPi) camera (RPi, CAM V2 (RGB), Raspberry Pi, Cambridge, UK), an RPi board (Model 4, Raspberry Pi, Cambridge, UK), a mega Microcontroller (Arduino Inc., Somerville, Massachusetts, USA), one CAN-bus shield, and the ISOBUS extension connector. The environments used in this chapter are Arduino IDE and Python. The proposed hardware and software were communicated with the sprayer via a universal serial communication protocol. The performance of the proposed system was tested and evaluated in both lab and field environments.

4.2.1 Design of indoor MVS

In this study, I designed an indoor MVS (consisting of an RPi camera and RPi board) which would detect color and generate specific string information based on detection (Figure 4.2). The RPi camera module version 2.1, whose resolution is 8 megapixels, can be directly connected to the RPi board via a camera serial interface connector using a camera ribbon cable. The camera operates at a visible spectral range of 400 to 700 nm. The designed system was tested on the static sprayer to validate the MVN performance in terms of handling machine vision detection results in data in preparation for use by third-party machine vision systems designed to specifically detect Colorado potato beetles. An RPi real-time detection code was written in Python with the necessary Open CV and camera library to develop detection string information similar to the MVS detection in real-time field operation.

4.2.2 Deployment of indoor MVS

The indoor MVS was mounted on the static sprayer facing wall board (Figure 4.1). The wall board was segregated into six rectangles based on a field of view which represents one camera for six nozzles of the static sprayer. Software written in Python was integrated into the Raspberry Pi board to continuously grab image frames (containing the field of view) from a real-time video, dividing each of them into 6 regions, and treating each region as a separate camera. The Python program embedded in the indoor MVS detects color and sends 64 different unique detection messages depending on the numbers and locations of color spots appearing in the field of view of the camera. The MVS was configured to convey detection information from each location separately to simulate an outside real-life situation in which numerous cameras were mounted.

To send the particular message for each nozzle, the CAN-bus message needed to be stitched using an arithmetic operation in the MVN. C++ programming was used to develop the arithmetic operation under the Arduino software platform. Figure 4.1 depicts the communication connection between the indoor MVS and the sprayer. The python script is written in the format as when an anomaly (color) is identified in any of the segregated regions, the program generates a detection string that includes the identifying number of the region or camera (the camera ID), the type of pest, and the time when it was discovered, as shown in Figure 4.2.

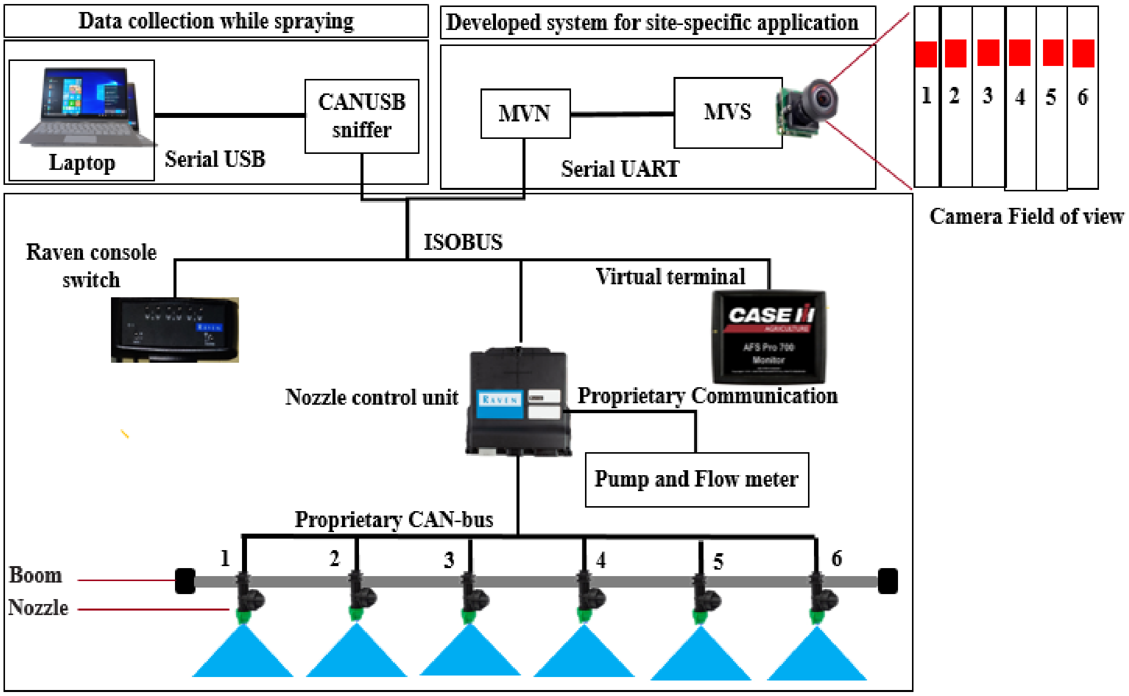


Figure 4.1: Schematic view of the developed MVS and MVN mounting view on the static sprayer.

SOF [1]	Camera ID [8]	Pest ID [8]	Detection time	EOF [1]

Figure 4.2: Data frame represents the string format used in the MVS. Each number in bit format is sent from the MVS to MVN at each time of detection.

4.2.3 UART communication between MVS and MVN

Universal asynchronous receiver and transmitter (UART) is a serial communication protocol that was used to transfer data from MVS to MVN. UART is a two-wire communication where one wire act as transmitting data (called TX pin) and the other is for receiving data (called RX pin) (Kashyap & Ravi, 2020). UART has a buffer for temporarily storing data from high-speed transmission. Data is converted into packets for UART to deliver data or to reconstruct data from packets it receives. The transmitting device transforms the data bytes to bits before the UART device may transfer data. The UART device first converts the data into bits and then divides them into packets for transmission. A start bit, a data frame, a parity bit, and the stop bits are included in each packet. After preparing the packet, the UART circuit then sends it out via the TX pin (Kashyap & Ravi, 2020).

The UART receiving device verifies the received packet for faults by computing the number of 1s and comparing it to the value of the parity bit present in the packet. If there are no mistakes during transmission, it will proceed to strip the start, stop, and parity bits to obtain the data frame. It may need to receive numerous packets before it can reconstruct the entire data byte from the data frames. After reconstructing the byte, it is saved in the UART buffer (Kashyap & Ravi, 2020). The parity bit is used by the UART device that is receiving data to assess if there was a data loss during transmission which happens when a bit changed its state while being transmitted (Gupta et al., 2020).

Baud rate is the number of bits per second (bps) a UART device can transmit/receive. The same baud rate needs to be set on both UART devices to have the proper transmission of data. Common values for the baud rate are 9600, 1200, 2400, 4800, 19200, 38400, 57600, and 115200 bps. The parity bit, which is a bit appended to the sent data, informs the recipient if the data transmission's number of ones is odd or even. The parity bit can be adjusted to either an odd or an even value. If the data contains an even number of ones, the parity bit is set to 1. Otherwise, the parity bit is set to 0. To indicate the conclusion of a transmission of a group of bits (known as a packet), UART devices can utilize zero, or one-stop bits (Gupta et al., 2020).

4.3 Software development for MVN

The software development of the MVN includes developing an ECU that replaces the laptop sprayer control software. The MVN is a hardware (CAN-bus shield stacked on Arduino mega) that needs software to read detection results as a signal from the indoor MVS and transfer them as a CAN-bus message to the sprayer. The communication protocol was established, by writing the software on the MVN that should resemble the developed algorithm used for developing laptop sprayer control software. Then the developed MVN will read the detected information from the MVS and generate and transfer the CAN-bus message to the nozzle system of the static sprayer.

The UART communication was connected between indoor MVS and Arduino mega as shown in Figure 4.3 (for pin configuration Table 3.1). The baud rate for data transfer is set to 115200 kbps. The Arduino mega was programmed to read the detected signal from both indoor and outdoor MVS and convert it into a respective CAN-bus message to control each nozzle.

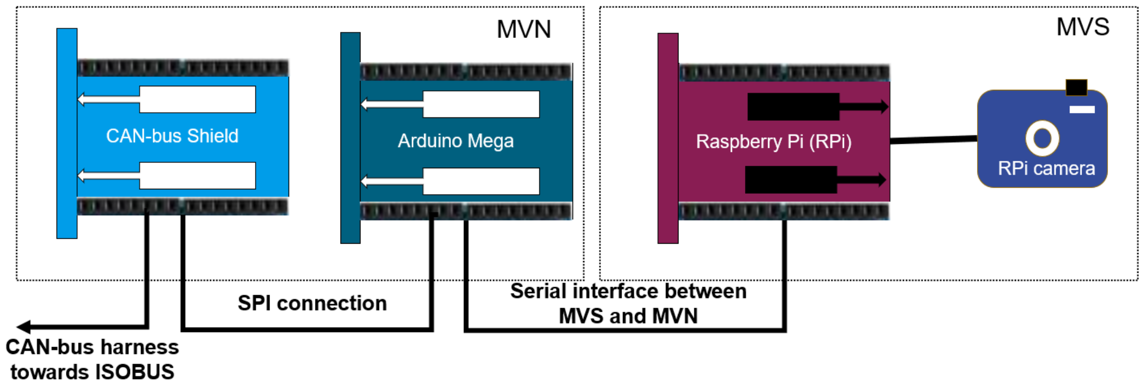


Figure 4.3: The CAN-bus shield stacked over the mega board to provide SPI communication based on pin assignment. The serial interface and CAN-bus harness provide the hardware interface of the MVN to the MVS and sprayer respectively.

4.4 Developed MVN algorithm

To communicate between the indoor MVS and the nozzle of the sprayer, the communication data message to open or close each nozzle should be sent simultaneously over the ISOBUS which was achieved by sending the detected string format of Figure 4.2. This arrangement resembles a situation when multiple MVS would be mounted on the boom sprayer with individual processing images and detection.

In CAN-bus Protocol, nodes communicate information through messages known as frames as shown in Figure 1.3. In the CAN-bus protocol, the data field carries specific information based on the developer protocol. From the analysis, the specific CAN_ID that controls the nozzle was listed in Tables 2.1 and 2.2. based on which the algorithm was developed. The Algorithm was divided into two processes, the first reads the detection string format within a fixed detection time (~10 ms) from the MVS to create a nozzle-opening array of six binary numbers whether it is detected (1) or not (0) for each camera ID. Once the detection time is reached the second prepares one CAN message that carries information to concurrently open the nozzles corresponding to the location of detection regions.

Arduino mega receives the detection string from MVS through the UART serial protocol at a frequency of 0.5 Hz (one message every 2 ms). For the static and boom sprayer, the 64 unique messages are calculated based on the two bytes (5th and 6th) of the data field of the same arbitration field in CAN-bus communication (Figures 1.3 and 4.2). The code was written in an arithmetic statement to activate the specific nozzles accordingly. The equations below show the calculation of the 5th, and 6th bytes to update the CAN-bus message and broadcast it on the ISOBUS to be received by the nozzle control unit.

For the static sprayer, the 5th byte on the CAN message carries information about the first 4 nozzles whereas, the 6th byte carries information on the other 2 nozzles.

$$D5 = (A\,[0] \times 0xB_1 + A\,[1] \times 0xB_2 + A\,[2] \times 0xB_3 + A\,[3] \times 0xB_4) \quad (4.1)$$

$$D6 = (A\,[4] \times 0xB_5 + A\,[5] \times 0xB_6) + F0 \quad (4.2)$$

For the boom sprayer, the 5th byte on the CAN message carries information about the first 3 nozzles section whereas, the 6th byte carries information about the other 3 nozzles section.

$$D5 = (A\,[0] \times 0xC_1 + A\,[1] \times 0xC_2 + A\,[2] \times 0xC_3) \quad (4.3)$$

$$D6 = (A\,[3] \times 0xC_4 + A\,[4] \times 0xC_5 + A\,[5] \times 0xC_6) \quad (4.4)$$

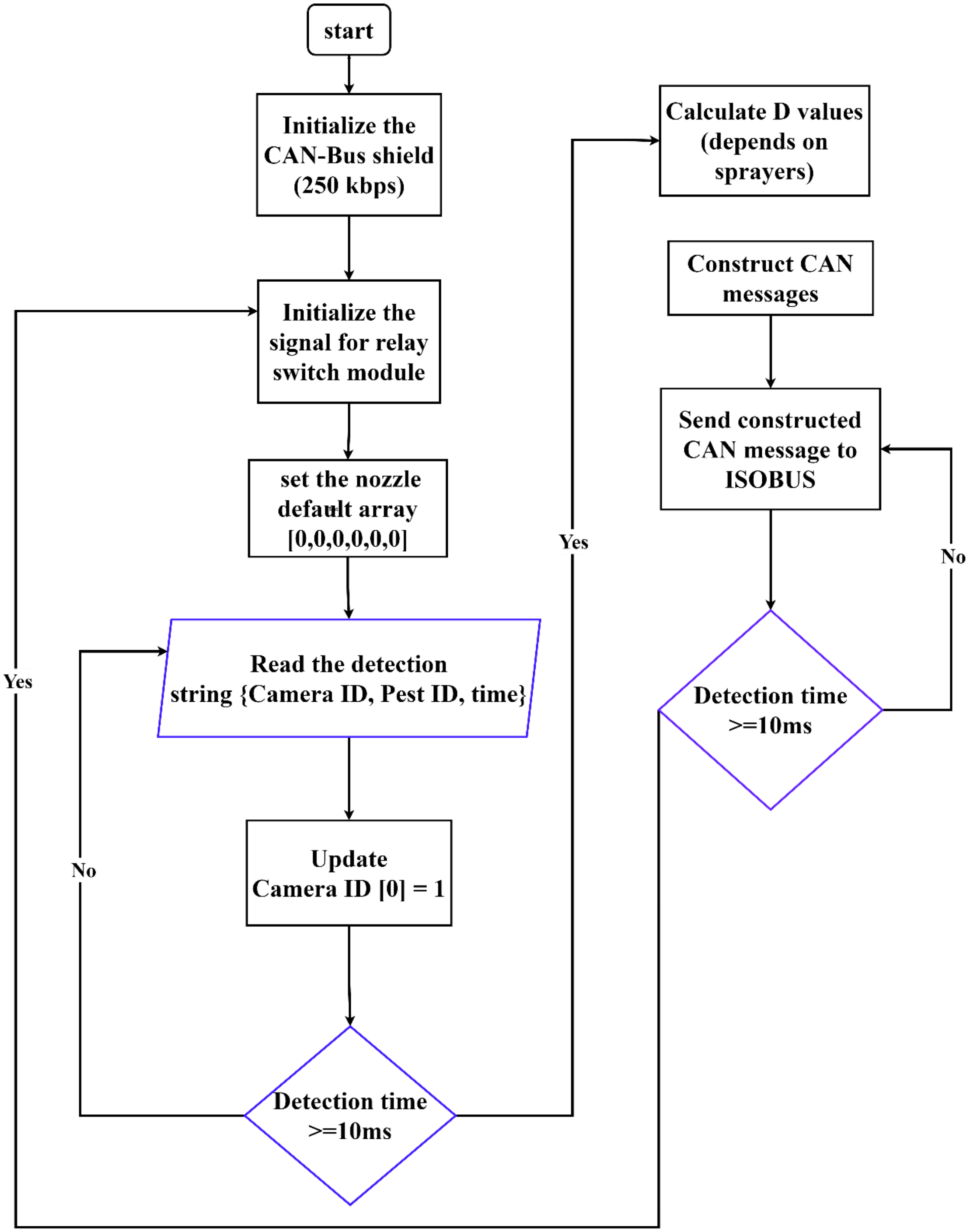


Figure 4.4: Flowchart of the algorithm used in an MVN to convert MVS signal into CAN-bus message to control each nozzle or section of the static and boom sprayer which resembles the message from the RCS to the nozzles.

where the nozzle default array is denoted as A represents the nozzle number [1,2,3,4,5,6]. 0x represents HEX numbers. B_n and C_n are proprietary nozzle constants understandable by the nozzle control unit. The constant values were: 1 for B_1, B_5, and C_4; 4 for B_2, B_6, C_1, and C_5; 10 for B_3, C_2, and C_6 and 40 for B_4 and C_3. Using Equations (4.1, 4.2,4,3, and 4.4), the developed algorithm calculates D5 and D6 before constructing the entire CAN frame and broadcasting it on the ISOBUS to be received by the nozzle control unit. Figure 4.4 describes the algorithm used to develop an MVN for the sprayer.

4.5 Results and discussion

The developed MVN and indoor MVS were evaluated and tested on the static sprayer to see the performance of nozzle control before the MVN was tested with the multiple cameras in field conditions. Testing and evaluation were conducted on July 29, 2021, under lab conditions, where I tested the 64 possible combinations to open and close the nozzles concurrently. Color cubes were placed before the developed MVS which the camera field of view specifical covered the segregated square box. The developed algorithm changed the values of the nozzle status array for a proprietary control unit with six nozzles in response to all possible combinations of simultaneous spraying, and it created two equations to condense all possible combinations into two bytes.

The sprayer had a 100% response without any data loss. The results show that the developed MVN is capable to read and construct the CAN-bus message based on string format from the MVS to control both static and boom sprayers without any human interference. While testing with the static sprayer the developed MVN did not lose any data either from the MVN or the original electronic components of the ISOBUS. These results suggest that the developed MVN is compatible and able to detect and convert the string information into respective CAN-bus data messages to control the nozzle of the sprayer.

4.6 Conclusion

In conclusion, the developed algorithm on both MVS and MVN is capable to control 64 combinations of the nozzle or section of the boom sprayer within a 10 ms deliberate delay. Though the hardware and software of the developed system are affordable there are some general limitations in the electronic system. These hardware limitations could be overcome by upgrading the hardware components that are compatible with ISOBUS. The embedded software algorithm in MVN establishes a new communication protocol to communicate between the MVN and the MVS. The developed MVN provides proper communication between the MVS and the sprayer to open and close the respective nozzle based on the detection results. This developed code and algorithm can integrate and communicate with the new modern boom sprayer which has ISOBUS and CAN-bus communication systems that can be plugged and played.

CHAPTER 5 PERFORMANCE EVALUATION OF THE MACHINE VISION NODE PROTOTYPE

5.1 Introduction

This chapter evaluates the performance of the developed MVN with the MVS to perform site-specific applications. The evaluation and testing are expected to get the proper outcome that the developed MVN is capable to read the detected information from the MVS and sending the respective CAN-bus message to open/close respective nozzles or sections on the static and boom sprayer for spot-specific applications. The experimental tests were conducted in both laboratory (static) and field (boom sprayer) conditions. During this testing and evaluation on both small and large scales, water is used as an agrochemical for safety purposes.

5.2 Dual running of the nozzle using RCS or MVN

On the ISOBUS of a static sprayer, the nozzle control unit receives broadcast messages from the MVN and the RCS simultaneously once the MVN gets connected. Even when the switches of the RCS are unchanged, it will send messages to close the nozzles every 100 ms, which will contradict any opening message that might be sent by the MVS via the MVN. To overcome this issue a 5V relay module switch was integrated (Figure 5.1) so that the RCS gets shut off once the MVN is connected and vice versa. Then, the developed MVN and MVS were tested in lab conditions on the static sprayer.

Two experimental tests were conducted on the static sprayer continuously to analyze the performance of the developed systems. 1) Testing the MVN with a relay switch module. 2) Testing the MVN without a relay switch module. The UART interface at the MVN can receive one message from MVS within 2.0 ms, meaning that 5 messages can be received within the defined 10 ms. The relay switch can be triggered through the MVN. A C++ code was embedded in the MVN memory to trigger the non-contact signal that disconnects the simultaneous connection of MVN and RCS on the static sprayer as shown in Figure 5.1.

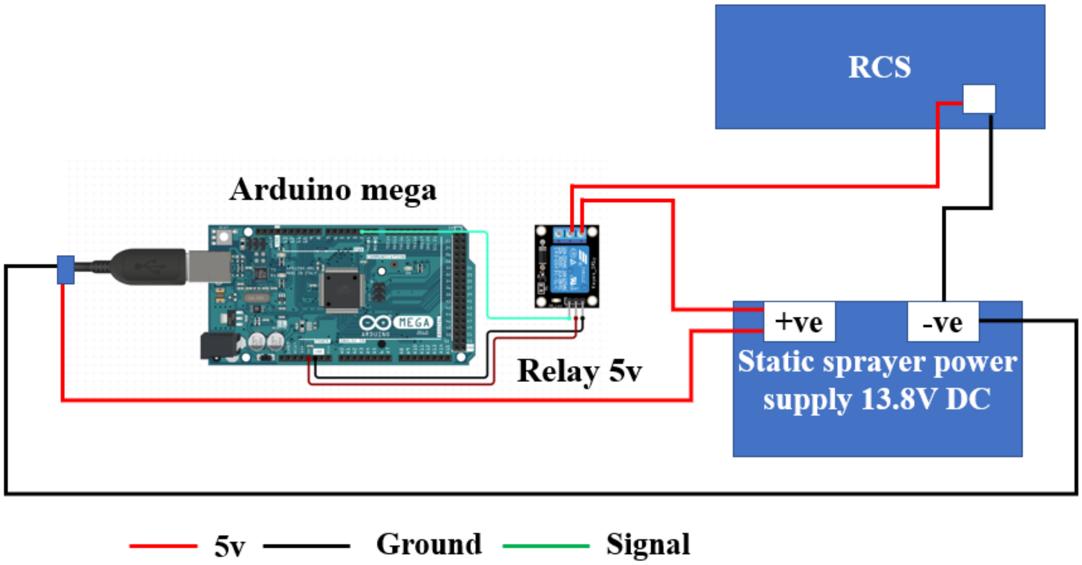


Figure 5.1: Electrical harness diagram showing the relay module switch implementation on RCS of the static sprayer.

The test trial was conducted in two different ways (with/without the relay module switch). With the help of the relay module switch the nozzles received the respective CAN-bus message without any interruption from the RCS. On the other hand, once the MVN gets disconnected, the console restarts seamlessly which allows for dual operation of the static sprayer. To verify the performance of the spraying all possible combinations (64) were conducted. The results showed that the developed algorithm was able to communicate with proprietary nozzle control units via ISOBUS.

5.3 Testing of MVN with outdoor MVS on the boom sprayer

To make the experiments as practical as possible, the McCain Farms of the Future (53, Waugh Road, Riverbank, New. Brunswick) and McCain Research Farm (46° 28' 7.8996" N and 67° 40' 52.8348" W, NB, E7L 3A7, Canada) were selected to test the developed MVN under field conditions. Preliminary test trials (Table 5.1) were conducted on August 3rd, 2021, at the McCain Farms of the Future by sending the respective CAN messages to control Sections 3 and 4 on MVN via ISOBUS to the nozzle control unit. Spraying data was logged using the sniffer and data were stored in an excel spreadsheet under sprayer idle conditions to ensure the compatibility of MVN before it connects to outdoor MVS.

The visual observations during the preliminary tests to ensure communication between the MVN and the sprayer. Table 5.1 shows that the scenario of the master key switched ON and the 6 section control switches turned OFF (Figure 5.2) was preferred as it controlled only Sections 3 & 4. In the other scenario, all the sections of the boom were getting triggered despite not sending commands from the MVN. This probably was caused by not being able to implement the RCS cut-off relay (Section 5.1) on the actual boom sprayer. On the following day (August 4th, 2021), a demonstration test trial was conducted at McCain Research Farm using the first scenario of switch settings. The demonstration test trial took place in an area at the farm that had the visible distribution of Colorado potato beetle, which looks as shown in Figure 5.3.

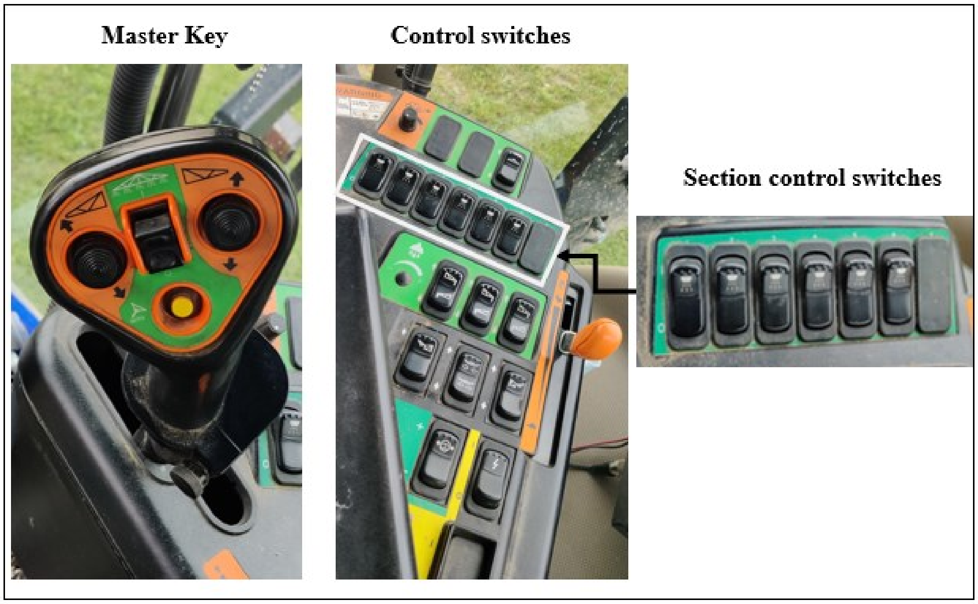


Figure 5.2: Tractor cabin view showing the master key and section control switches

Table 5.1: Scenarios of nozzle switches status during the preliminary test trials

Scenario	Master switch	Section switches	Observation
1	ON	OFF	Consistent opening of Sections 3 & 4
2	ON	ON	Inconsistent nozzle opening across the boom

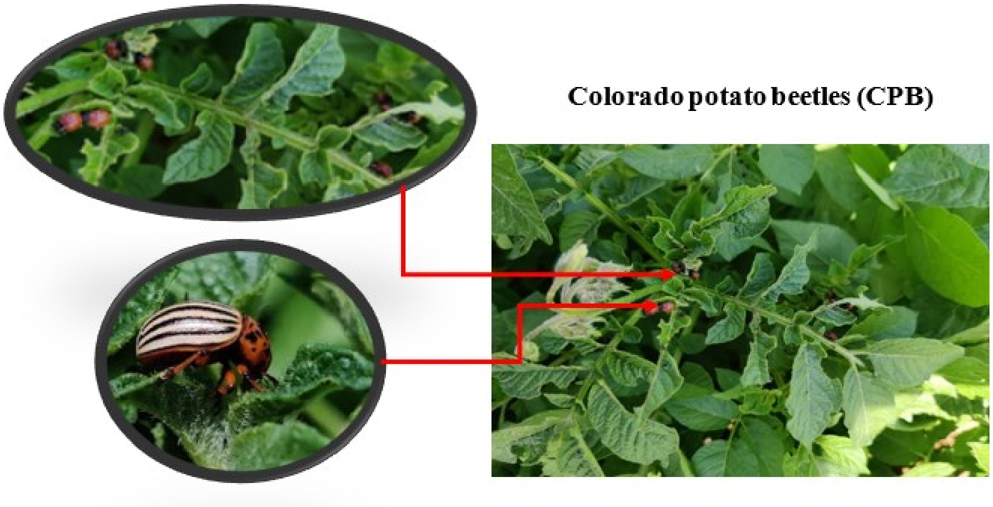


Figure 5.3: The distinct spread of CPB in the potato field

The boom sprayer used in these trials was Patriot 3340. The sprayer is similar to the static sprayer in terms of the electronics, consisting of an AFS Pro 700 virtual terminal, a switch console, and 6 sections of nozzles (which had either 9 or 13 nozzles) with solenoid values at equal distance spacing (610 mm), hydraulic unit, 3786-liter stainless steel product tanks.

During the trials, an outdoor MVS (consisting of two cameras) developed by Resson Aerospace Technology (Fredericton, NB, Canada) was mounted on Section 3 (consists of 9 nozzles) and Section 4 (consists of 9 nozzles) of the sprayer to view the real-time site-specific spraying as shown in Figure 5.4. The outdoor MVS sent detection information via the UART port to the developed MVN as per the design requirement of the MVN. Then the MVN was able to generate the respective CAN-bus message to open/close the sections. Outdoor MVS acts as the indoor MVS used in the lab.

Figure 5.4: Cameras of outdoor MVS mounted on CASE IH Patriot 3340 sprayer.

The MVN was interfaced with the sprayer via the in-cabin ISOBUS connector (HD10-9-1939, Deutsch, J1939-TE connectivity Ltd, Schaffhausen, Switzerland) (Figure 2.2). The spraying data were collected via the CAN sniffer to evaluate the efficiency and performance of the developed MVN. During the test trial, the sprayer was aimed to run at

9 mph (4.0 m/s) by the operator. The flow rate (3.10 litres / min) and pressure (414 to 483 kPa) of the spray were pre-set by the operator as shown in Figure 5.4.

At a rate of every 1.8 to 2.0 ms the serial interface receives one message from MVS. In 10 ms, 5 data frames could be generated with a single message size of 98 bits. The baud rate of data transfer could be increased by more than 49 Kbps when MVS sends detected information within 2.0 ms. Conversely, the developed MVN creates one CAN message of size 130 bits and sends it to the implement interface every 10 ms. This in turn provides ~13kbits per second of information added to the bus every second which gives 5.2% of data added in the CAN-bus capacity of 250 kbps. No data loss occurred during the test trial conducted in the field condition. The MVN provided consistent results with proper nozzle operation when two test trials were conducted.

5.4 Results and Discussion

The demonstration test trial consisted of two passes by the sprayer, each of which lasted for 12 minutes. The cameras of the outdoor MVS attached to the boom section were expected to sense the insects and send the detected information to the MVN based on the UART protocol developed in Chapter 4.

To determine the occurrence of spraying on Colorado potato beetles, visual observation was conducted to find the distance between the location of the beetles and the sprayed area. From this observation, it was found that there was roughly a distance of 4 m between the beetle and the sprayed area. This distance indicates while the outdoor MVS was able to detect the beetle and the commands were sent to the nozzle control unit of the sprayer via the MVN, the delays in spraying that resulted in mishitting the target (the beetles) could be associated with image processing delays, data transfer delays, or actuation delays. However, the MVN was responsible of 2% of the delays. This was estimated by considering the speed of the tractor (4 m/s) and the distance between the target and the droplets (4 m), taking into account that the MVN takes 20 ms to manage the data between the UART and CAN interfaces.

5.5 Conclusion

The MVN provides the possibility to control each nozzle/section without adding wiring to the sprayer or nozzle control system. The standardized communication based on CAN-bus communication enables us to integrate the developed system for sensor–based spraying applications. The developed algorithm is robust and written in the arithmetic operation format to help the MVN to frame the respective CAN-bus message to control each nozzle/section of the sprayer. All 64 possible combinations of nozzle control were tested and evaluated in both sprayers with simultaneous data collection during the testing.

The developed MVN is robust which can make it easily deployed to different MVSs. The MVN acts as a bridge between MVS and the sprayer via ISOBUS which implies a plug-and-play installation without any additional cables on the nozzle control system. This communication protocol suggests that the MVS of multiple cameras can be mounted to detect insects on the boom of the sprayer and controlled through the MVN. This shows that the ISOBUS-equipped sprayer can be converted into the sensor–based spraying with the help of the MVN. The conducted test results to control each section of the sprayer via ISOBUS is a powerful way to add new components to enable site-specific spraying as it has the potential to save the cost of agrochemicals which help to protect human health and the environment.

CHAPTER 6 CONCLUSION

6.1 Summary and future direction

In this thesis, I presented my design and implementation of an MVN which can transfer information on detection from any MVS to the sprayer. The retrofit system developed in this study is an efficient way to add extra components to enable sensor-based spraying through the nozzle control unit communication over ISOBUS. Although there aren't any ISO 11783 protocols that are currently standardized for controlling individual nozzles, proprietary CAN messages can be sent over the implement bus to control the nozzles.

The developed software was capable of controlling each nozzle and section of the static and boom sprayer, respectively. Therefore, these hardware and software could be used to develop an MVN for the sprayer to transfer the detected targets (insects) and site-specific application of agrochemicals at correct targets reliably to reduce the cost of production and protect the environment. It is worth noting that CAN-bus communication provided a unique solution to common issues in measuring, monitoring, and controlling agricultural machinery. This approach has the benefit of sectioning the development of machine vision-based individual nozzle control, allowing machine vision developers for pest detection to focus on the accuracy of detection while leaving the nozzle operation to the MVN.

This will expedite the implementation of various MVS on ISOBUS in the direction of the eventual full standardization of the work of individual nozzle spraying. The algorithm developed on the MVN promotes the stability of data transfer between the two processors that run simultaneously with a user-defined time of 10 ms. The CAN-bus shield and its library can be employed alternatively on a single-board computer such as RPi with multi-threading which could reduce the hardware of the MVN.

The MVN with its developed algorithm will act as a communication platform and be more widely used in every aspect of precision agriculture to solve the current agriculture problem. The MVN is developed to read messages from multiple cameras. For decades, ISO 11783 (ISOBUS) has been the de facto standard for tractors and implements of many brands. As the computerization and sophistication of agriculture equipment continue to advance, the AEF set its sight on a tractor implement management which would provide for closure integration between the tractor and add-on components regardless of manufacture.

In the future, the developed MVN can be upgraded to meet the requirements of the AEF standard library which would potentially provide standardized communication for machine vision systems via the implement bus. This might contribute to the increase in the efficiency of agricultural inputs which would provide valuable insights for growers for decision-making and also rapid development in agriculture automation.

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Appendix

- Publication: Al-Mallahi, A., Natarajan, M., & Shirzadifar, A. (2023). Development of robust communication algorithm between MV and boom sprayer for spot application via ISO 11783. Smart Agricultural Technology, 4, 100212. https://doi.org/10.1016/j.atech.2023.100212
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- CANUSB sniffer and driver used in this thesis – https://www.canusb.com/support/canusb-support/ CAN-monitor software – https://www.wgsoft.de/can-monitor-canusb
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