ROBS4CROPS

D2.2 Technical report on the new spraying and weeding implement features and capabilities

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101016807

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Work Package	WP2
Delivery Date (DoA)	31 Dec 2022
Actual Delivery Date	23 Dec 2022
Abstract:	This technical report contains an overview of the technical advances and new capabilities from all smart implements for both spraying and weeding cases. The French weeder is equipped with rotary potentiometers to measure rotation of tools in tool carrier. The Dutch weeder is equipped with RGB cameras to measure the quality of weeding. Both spraying units that were used in the Greek and Spanish pilot cases are equipped with RGBD cameras and GPS that are generating spraying commands. Those commands are sent using middleware to the Spraying Unit using ISOBUS. The total spraying performance was evaluated using water sensitive papers. All further work that needs to be done in both cases will be described in the end of this technical report.

Document Revision History			
Date	Version	Author/Contributor/ Reviewer	Summary of main changes
23 December 2022	1	Giannis Avgoustakis & Nikos Mylonas (AUA)	Initial version

Dissemination Level		
PU	Public	Yes
PP	Restricted to other programme participants (including the EC Services)	NO
RE	Restricted to a group specified by the consortium (including the EC Services)	NO
CO	Confidential, only for members of the consortium (including the EC)	No

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Funding Scheme: Innovation Action (IA) ● Topic: H2020-ICT-46-2020

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List of Abbreviations and Acronyms	
FC	Farming Controller
ROS	Robot Operating System
TCP/IP	Transmission Control Protocol / Internet Protocol
LSP	Large Scale Pilot
GPS	Global Positioning System
ECU	Electronic Control Unit
TECU	Tractor Electronic Unit
DBC	Database Container file
TC	Task Controller
UC	Universal Terminal
WSP	Water Sensitive Papers

1 Introduction

This document describes the technical advances and new capabilities for the smart weeder and sprayer relative to the original implementation described in D2.1 "Specifications of the sensor and control systems to equip the implements". This technical report includes a scheme of all the peripherals attached in both implements, in addition to the functionalities and capabilities that are included in the weeding and sprayer implements.

2 Description of the Use Case

Robots for protecting crops (ROBS4CROPS) is a 4-year EU-funded project that will accelerate high-tech robotics and automated technologies to be integrated in the European food and farm industry. Building upon the existing agricultural machinery, standards and best practices, this project will deliver a flexible and modular, fully autonomous system ready for large-scale commercial trials. The trials will be conducted in partnership with commercial farms and businesses in Greece, Spain, France and the Netherlands.

The main technical target of ROBS4CROPS project is the development of a robust robotic system able to perform spraying and weeding tasks. The modularity proposed consists of four different vehicles, two robots and two retrofit tractors, and four different implements (two weeders and two sprayers).

In this technical document, we will describe the sensors that are installed in the weeder and sprayers to make them "smart": i.e., make them able to assess whether the implement is working well, and report this information to the robotic system as a whole. For the sake of simplicity, we are presenting first all technical supplies categorized based on **spraying** and **weeding** use cases. Those two categories will be further categorized based on the implement **carrier platform** (Robotic Platform and Retrofitted Tractor) in the case of Spraying and in **pilot's location** in the Weeding case. For each category there is a description of the use case, an overall architecture scheme and the Hardware/Sensor Specification Table that will be equipped in the implements.

3 Weeding Implement

3.1 Technical Overview

As previously described in ROBS4CROPS Deliverable 2.1, two mechanical weeding units will be utilized, one in France and one in the Netherlands.

These units are essentially identical in design. A powerful/performance PC is used to run both the Middleware and Analytics, which communicate with each other using internal sockets. The PC also uses a CAN-bus connection to communicate with the robots and a 5G/Ethernet connection to communicate with the Farming Controller. The technical overview of both mechanical weeders is depicted in the schematic presented in Deliverable 2.1.

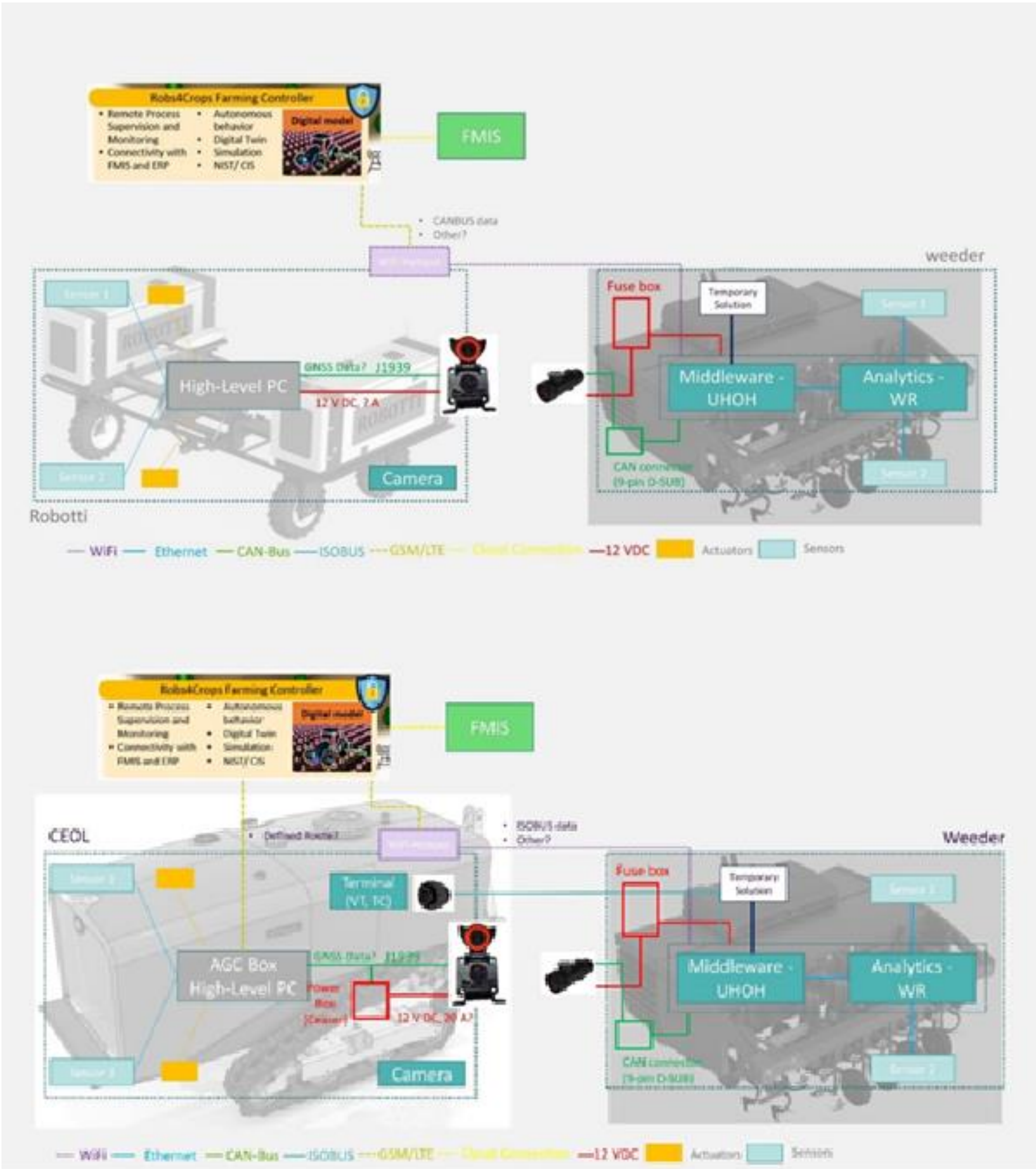

Figure 1. Overall Architecture Scheme for the Weeder using the Robotti robot in the Netherlands (top) and Ceol robot in France (bottom).

3.2 Functionalities and Capabilities

While the two units for weeding in principle work the same, they use different mechanisms to get information about weeding quality.

3.2.1 Weeding implement in LSP1(France)

3.3.3.1 System Design

In France, after consulting with farmer representatives from TERRENA, it was determined that it would not be feasible to use cameras to assess the quality of the weeding implement's work. Therefore, a different approach was taken, utilizing various sensors to track the movement of the cutter, disks and other aspects of the implement's operation. There are two types of sensors we use: ZF gear tooth speed sensor GS100701 that measures the presence of magnetic field (Hall effect sensor) and Joy-it COM-KY040RE which measures the change on voltage (rotary potentiometer). All the sensors are connected to the microcontroller of the computer (a Teensy 4.1 with a 600 MHz Cortex-M7) which has analog inputs and can support up to 8 different sensors. Then the data is sent to the computer, which processes it using an algorithm (described later) to determine the quality of the weeding.

3.3.3.2 Tools

3.3.3.2.1 Finger Weeder

The Finger Weeder is a tool designed for use in weeding operations. It is mounted on a tool carrier at a 90-degree angle and rotates as the tractor or robot moves. Due to its constant contact with the ground, the Finger Weeder is prone to being clogged with weeds and crop residues, which reduces its effectiveness in weeding. It is important to identify blockages as soon as possible in order to take corrective action, such as stopping the tractor or robot to alert the farmer or engaging the hitch to release the blockage.

This tool consists of plastic fingers attached to a metallic plate that rotates. Two types of sensors could potentially be used for this purpose: a rotary potentiometer or a Hall effect sensor. However, the rotary encoder was deemed unsuitable due to the difficulties in accessing the rotation axis for mounting purposes. Additionally, the metallic nature of the finger holder provided an opportunity to utilize a Hall effect sensor instead. Thus, the sensor is mounted at the base of the tool where a metal part is extruded out of the plastic, making a perfect opportunity to sense that specific spot every rotation.

3.3.3.2.2 Rotary hoe

The Rotary Hoe is a tool designed for hoeing rather than weeding and is constructed entirely of metal. It is mounted in a similar position as the Finger Weeder and relies on the inertia of the tractor or robot to rotate. Despite these differences, the Rotary Hoe shares many similarities with the Finger Weeder, and as such, the same sensor is used for both tools.

The all-metal construction of the Rotary Hoe posed a challenge when mounting the Hall effect sensor, as the sensor requires a break or non-continuous metal material to function properly. To address this issue, the sensor was mounted at the top or end of the rotary hoe, where a toothed shape provided the necessary break in the metal for the sensor to detect the presence and absence of metal. This allowed the sensor to function effectively on the Rotary Hoe.

3.3.3.2.3 Cutter

In contrast to the Finger Weeder and Rotary Hoe, the Cutter tool does not have an indefinite rotation mechanism. Instead, it is designed to swing through a specific arc in order to cut the roots of grass and other weeds below the soil surface. This swinging mechanism is connected to a mechanical sensor that detects the presence of vines. When a vine is detected, the mechanism is retracted until the tool passes the vine, at which point it releases the cutter to cut the grass between two adjacent vines.

However, if the sensing mechanism of the Cutter tool becomes broken or fails to function correctly, the cutter will be forced into a fixed position. If this position is open, it can potentially damage the roots of the trees. To prevent this, it is critical to detect any issues with the sensing mechanism. To do so, a rotary potentiometer is used. This potentiometer is physically attached to the axis where the mechanical vineyard trunk sensor is mounted, allowing it to detect each swing of the Cutter tool. This helps ensure the proper functioning of the tool and prevent damage to the vineyard trees.

3.3.3.2.4 Depth check

The final measurement to be considered is the distance of the tool carrier from the ground. While this has not yet been fully implemented, it is important to understand the impact of this distance on the overall system. It is known that the cutter tool should be located approximately five cm under the ground in order to efficiently remove grass. However, if the tool carrier is tilted to one side more than the other, the efficiency of the cutter may be reduced. Further analysis is needed to determine the importance of this measurement and how it should be incorporated into the system.

The distance of the tool carrier from the ground is measured using a rotary potentiometer. This potentiometer is connected to a spring-actuated mechanism, which in turn is connected to an extended metal piece that touches the ground (as shown in Figure 3c). If the distance between the tool carrier and the ground decreases, the spring mechanism is pulled through the metal piece, and vice versa. The movement of the spring mechanism is captured by a custom-built tool (Figure 3c), which houses the rotary potentiometer. This allows the system to accurately measure and track the distance of the tool carrier from the ground.

Figure 2. Depth check tool: a) An illustration of how slope shifts the wheels. b) CEOL robot shifted due to the slope and the cutter won't work in one side. c) A custom build tool to detect the distance and in the red square is the rotary encoder.

3.3.3.3 Algorithm (Heartbeat Check)

The Heartbeat Check is a finite state machine implemented in Python that is used to monitor the status of sensors. The algorithm is designed to check for the "heartbeat" of each sensor every 100 milliseconds. If a sensor exhibits irregular behaviour, a secondary timer is set to track the duration of the irregularity. This immediately affects the "quality" parameter, indicating that there may be an issue. If the "heartbeat" of a specific tool is not detected for a predetermined amount of time, the algorithm begins logging GPS data to determine the distance travelled by the robot and the duration of the sensor inactivity. Depending on the tool, this can have a significant impact on the "quality" parameter. If the sensor is not detected for a predetermined amount of time, an "error" signal is sent over the BUS to the CEOL Robot, causing it to stop all operations. The camera feed is then immediately sent to the Farming Controller so that the farmer can determine if the error is a true positive or a false positive. The "heartbeat" value is calculated based on the sensor type, the probability of the sensor experiencing irregularities (as determined from the sensor manufacturer's website), and the priority of the sensor (in the event that multiple sensors are connected). This value is directly linked to the quality of the weeding.

The Heartbeat design is built in a such way that allows for the integration of additional functionality in the future, such as the use of artificial intelligence to assess weeding or tool damage.

To facilitate communication with the middleware, the Python-CAN library is used, which includes built-in functions for interacting with the Vector Canoe Software and connecting to the virtual CAN. Each message is constructed according to the ISOBUS/J1939 standards. The data collected from the external sensors on the weeding machine is processed by the Analytics software using the algorithm described above. The results are simplified for presentation purposes. The Heartbeat occurs every 100 milliseconds, so the figures presented below are approximations of the values.

For proper functionality, four main distinct patterns have been identified (which are coded in the state machine) and are presented below:

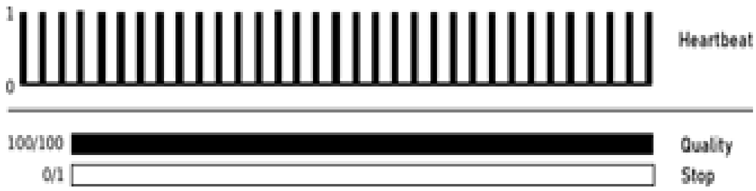

Figure 3*. Regular sensor heartbeat, maximum quality, no stop signal.*

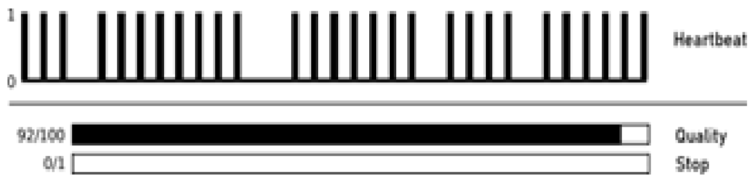

Figure 4. Irregular sensor heartbeat, quality is impacted slightly but stop is never triggered.

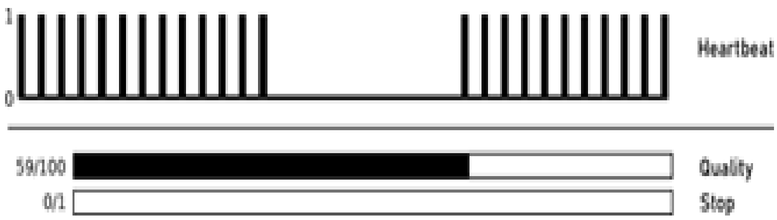

Figure 5. Abrupt sensor heartbeat for long period of time, quality is significantly impacted, stop almost triggered.

Figure 6. Sensor heartbeat stopped, quality is downgraded to minimum, and stop signal is send to CEOL Robot.

As shown in Figures 4-7, the Heartbeat has a direct impact on the quality of the weeding. When the Heartbeat is regular (Figure 4), the quality is 100%. This message is constantly relayed to the Middleware and the Farming Controller. When the disks stop spinning or exhibit irregular behaviour (usually due to wet soil), an irregular pattern is sent (Figure 5), which indicates that slippage is occurring and slightly decreases the quality, as the tool is still functioning within its design parameters. In case three (Figure 6), there is a significant disruption in the signal. This pattern typically indicates that the disks have become blocked for a period, and then the blockage falls away and the tool returns to normal functioning. In this case, the stop signal is almost triggered. In the final case (Figure 7), when the heartbeat is completely stopped, the quality parameter is downgraded to 10% and the STOP flag is triggered. Simulated data was used during the measurement process to test the algorithm described above, so it is possible that the sensor system may fail under field conditions.

3.3.2 Weeding implement in LSP4(The Netherlands)

3.3.2.1 System design

The LSP4 Robotti Robot in the Netherlands uses cameras to evaluate the performance of its weeding implement. These cameras are mounted at the front and back of the vehicle, and the timing and speed of the vehicle or the GPS coordinates are used to synchronize the images captured by the two cameras. A simple model is then applied to detect the presence of plants in the images. If plants are not present in the image captured by the rear camera, it can be inferred that the weeding implement is damaging the plants, resulting in low weeding quality.

In general, the implementation of the weeding system in the Netherlands is simpler than that in France. The system in the Netherlands relies solely on cameras to estimate the quality of the weeding and only uses a single computer for analytics, while the system in France employs different sensors connected to a microcontroller. However, the analytics and algorithm used to report the quality in the Netherlands are more complex, as they require the use of advanced image processing techniques to extract meaningful data and representation from the cameras (described below in algorithm section).

3.3.2.2 Tools

As specified above, in this case only cameras are used. The cameras we opted to use are OAK-D-PoE cameras. The OAK-D Power-over-Ethernet (PoE) device is designed for use in rugged environments and is equipped with an IP67-rated casing to protect against weather and dust contamination. It utilizes PoE technology for both communication and power and is compliant with 802.3af Class 3 standards, offering 1000BASE-T speeds and a micro-SD card connector. In addition, the OAK-D-PoE baseboard features three on-board cameras that enable stereo and RGB vision, enabling depth perception **and on-device artificial intelligence (AI) processing**.

Figure 7. OAK-D camera attached to the holder

This camera communicates to with the host with so called DepthAPI. This API allows users to connect to, configure and communicate with OAK devices. It supports both Python API and C++ API.

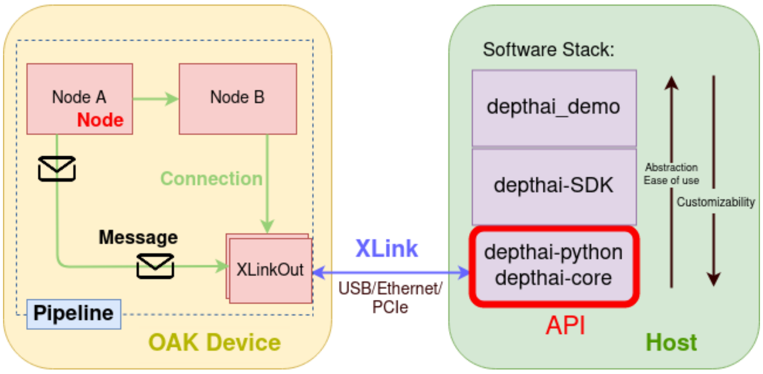

Figure 8 OAK-D camera – Analytics communication

- Host side the computer (analytics) to which an OAK device is connected.
- Device side is the OAK device itself.
- Pipeline is a complete workflow on the device side, consisting of nodes and connections between them.
- Node is a single functionality of the DepthAPI. Nodes have inputs or outputs and have configurable properties (like resolution on the camera node).
- Connection is a link between one node's output and another one's input. In order to define the pipeline dataflow, the connections define where to send messages in order to achieve an expected result
- XLink is a protocol that is capable to exchange data between device and host. XLinkIn node allows sending the data from the host to a device, while XLinkOut does the opposite.
- Messages are transferred between nodes, as defined by a connection.

Here is the basic node configuration to run the neural network inside the camera and streaming the output of both RGB and Depth to the analytics PC:

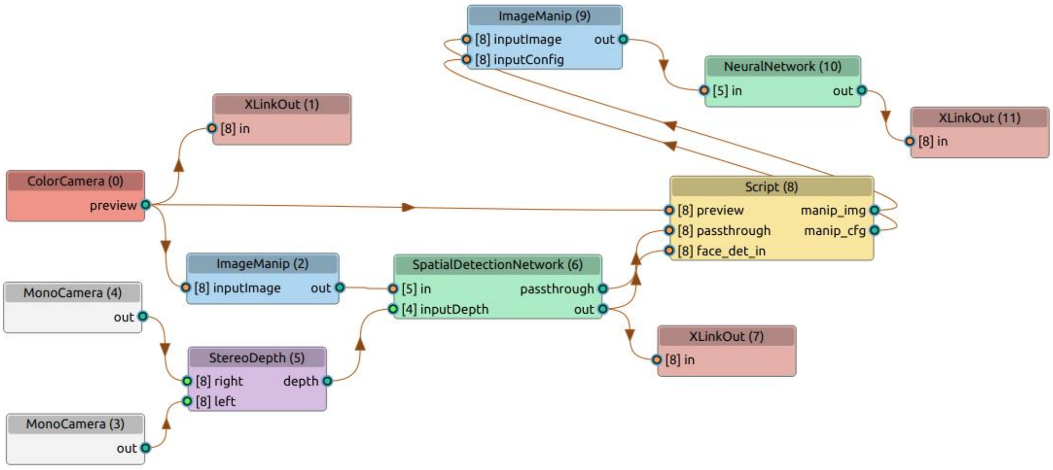

Figure 9. OAK-D camera-Network running in the camera.

Two PoE cameras are connected to the analytics PC via Ethernet Cat6 cables, which provide both power and communication. One camera is placed in front of the Robboti robot at a 45-degree angle facing downward, while the other is placed behind the robot at the same angle. The camera located at the back has a partial view of the implement, allowing for the detection of blockages and irregularities within the implement.

3.3.2.3 Algorithm

The most challenging aspect of this system is developing an algorithm to determine weeding quality, as it is difficult to define what constitutes "good" quality. For the time being, we have implemented basic image processing techniques to ensure the functionality of the components. This includes:

- Correlating the front and back cameras based on the speed of the robot
- Mapping each line/row/ridge (and tentatively each plant) of one camera to the corresponding plant in the other camera, referred to as a measurement point
- Assigning RTK-GPS coordinates to each measurement point
- Analysing images of the measurement units before and after weeding
- Determining whether a plant is present after the analysis and adjusting the quality parameter accordingly.

During the 2022 growing season, we collected a large amount of data, totalling over 500 GB, from the beginning of the season. The data was automatically collected every time the robot was in the field, although the amount of data captured also included periods when the robot was in the garage or being transported to the field. In the future, with the implementation of TIM functionality, we will be able to detect when the robot is in the field and collect data only during active work periods. Despite this, by filtering the data based on the location of the images, we were able to remove all data collected when the robot was not working.

During data collection, we intentionally made the robot destroy plants or drive irregularly in order to capture data on potential issues. Figure 10 shows a typical pattern of the crop, with the front and back cameras displaying the same pattern. There should be six rows present, but in this case, there are only five, as the middle row is missing. This will not trigger a warning, as the front camera is also missing the same row. This was done deliberately to test the system's ability to detect and respond to potential problems.

Figure 10. Good working conditions: a) Front camera, b) Back camera

Figure 11. Intentional damage of crops: a) Front camera, b) Back camera

Intentional wrong steering (see Figure 11) result in instances of empty of rows of instead of crops. The implemented algorithm is able to detect this issue and adjust the quality parameter accordingly. In the event that this issue persists for an extended period of time, the error signal is triggered, causing the robot to halt all operations. This also initiates a flag, enabling the Farming Controller to access the camera feed and present it to the farmer for evaluation. The farmer is then able to determine if the issue is a false positive or a true positive.

As previously mentioned, the algorithm utilizes computer vision techniques to detect irregularities in the crops. The current implementation is relatively basic, with the aim of establishing an infrastructure for future systems. Nonetheless, the model is functional as an alpha version. In the first half of 2023, we will implement a more advanced AI-based algorithm to replace the current one. The steps of the current implementation are as follows (applied to both cameras):

- The image is divided horizontally, with the upper half ignored (as objects beyond a meter from the robot are not relevant to the task).
- Six regions are cropped from the lower half of the image, corresponding to the rows of crops.
- The colour of each region is filtered, with greenish hues indicating the presence of crops and brownish hues indicating the ground.
- The filtered images from the two cameras are compared using a pipeline to correlate them. If the camera in the back shows significantly more brown hues, it can be inferred that damage has occurred.
- The locations of these instances of damage are marked with RTK-GPS measurements and saved to a shape file for future reference

3.3.3 Analytics – Middleware communication

From this point on, in both the LSP France and the Netherlands, the quality parameter of the weeding is reported to the middleware system for: visualization in VT, logging for debug purposes and sending actions i.e., stop signal, hitch up-down…

The middleware itself consists of three networks:

- The first network utilizes the J1939 protocol to receive and investigate messages for compliance and transfer them to the simulated TECU node of the second network.
- The second network utilizes the ISO11783 standard and includes the simulated ECU of the weeding machine, the simulated TECU functionality, and a special network node for transferring emergency stop signals from the analytics software. The simulated ECU of the implement interacts with the "Object Pool" elements of the developed VT interface based on incoming signals from the analytics software and communicates with the simulated TECU. Since the AGC-Box of the CEOL robot does not have TECU functionality, the ISO11783 network's simulated TECU node specifies the robot ECU as a class 2 device to provide the implement ECU with necessary data.
- The third network of the middleware, on channel 3, connects the WebSocket and the analytics software to the ISO11783 network. The main functions of the third network are to exchange as-applied information with the Farming Controller via the WebSocket and to communicate with the analytics software.

AGCbox communicates with the middleware and the fusebox through can bus. The DBC file (that specifies signals and messages) contains both ISOBUS11783 and CANOpen messages:

The ISOBUS11783 messages are the following:

- **(0x9F8011C) GNSS_WGS84 (node GPS)**, which contains the Longitude and Latitude signals.
- **(0xCFE49F0) GBSD_TECU (node TECU)** which contains the signals **GroundBasedImplementedSpeed**, **GroundBasedDistance** and **GroundBasedDirection**. These signals are radar measurements according to the norm ISO11783. However, there is no radar on the robot. Therefore, the signals **GroundBasedImplementedSpeed** and **GroundBasedDirection** can be replaced with GNSS values of speed and direction (Velocity in ENU local frame and signal indicating either forward or reverse as the direction of travel).

The CANOpen messages are:

- 10 messages in CANOpen (node AGC_SPE), containing the GNSS positions and velocities, in the ENU frame, and the IMU measurements (Euler angles, speed rotation, acceleration).

The weeder implements in the LSP – France uses the robot, CEOL, and an AGCbox with the complete robotic system of CEOL (path planning, application, monitoring, navigation, positioning). The CEOL is ISO Bus compatible through an IDDC connector connecting the robot to the smart implement (fuse box). Following the ISO 11783, the AGCbox sends the velocity and speed messages through ISOBUS, and the other messages are sent through the CAN Bus in DBC form (ex: GNSS- RTK, the height of the tool, etc.). The AGCbox communicates with the ECU of the robot and the ECU for the safety of the robot.
AGCbox sends messages to the fuse box and reads the messages below for instant stop.

Developing ISOBUS messages for the smart weeder **(0x18FECAFE) DM1**, which allows the AGCbox to receive the stop command. The size of this message is of 22 bytes, which I reduced to 2 bytes, as we only need the signal **RedStopLampState**

3.3.4 Middleware – FC communication

A Farming Controller (FC) computer has been installed at the LMS premises, enabling remote communication and information exchange between implements, robots, and tractors from all LSPs. The FC computer has the following specifications: an Intel(R) Core (TM) i7-9700 processor, 16GB RAM, a GeForce GTX 1650 graphics card, and runs the FC algorithm using the ROS2 framework on an Ubuntu 20.04 operating system. In the case of weeding, the following topics are exposed by the FC:

- **latitude/longitude**: Receive GNSS location of the robot/tractor
- **speed**: Receive the speed of the robot/tractor
- **quality**: Receive weeding quality value from the implement
- **trigger_flag**: A message to enable FC logging process
- **capacity**: Receive the capacity of the weeding
- **camera_on_flag**: Receive a flag that indicates that the camera is on
- **emergency_stop_flag**: Receive a flag that indicates that emergency stop is triggered

The communication between the FC computer and the middleware's PC is achieved using TCP/IP sockets through a static public IP. On the FC side, the ROSBridge library is utilized to convert ROS messages into JSON-formatted text, which is then sent through the socket to the middleware's PC.

4 Spraying Implement

4.1 Technical Overview

In the sprayer case as presented in ROBS4CROPS **Deliverable 2.1**, two different spraying units will be used from the Greek and Spanish pilot. The EOLO for Spanish pilot and ASM model for the Greek pilot that was developed by TEYME but both spraying units share the same working concepts with minor changes of the sensor and actuators to provide the proper functionality regarding the pilot case. In the following schematic the technical overview of both Sprayers is presented as described in **Deliverable 2.1**.

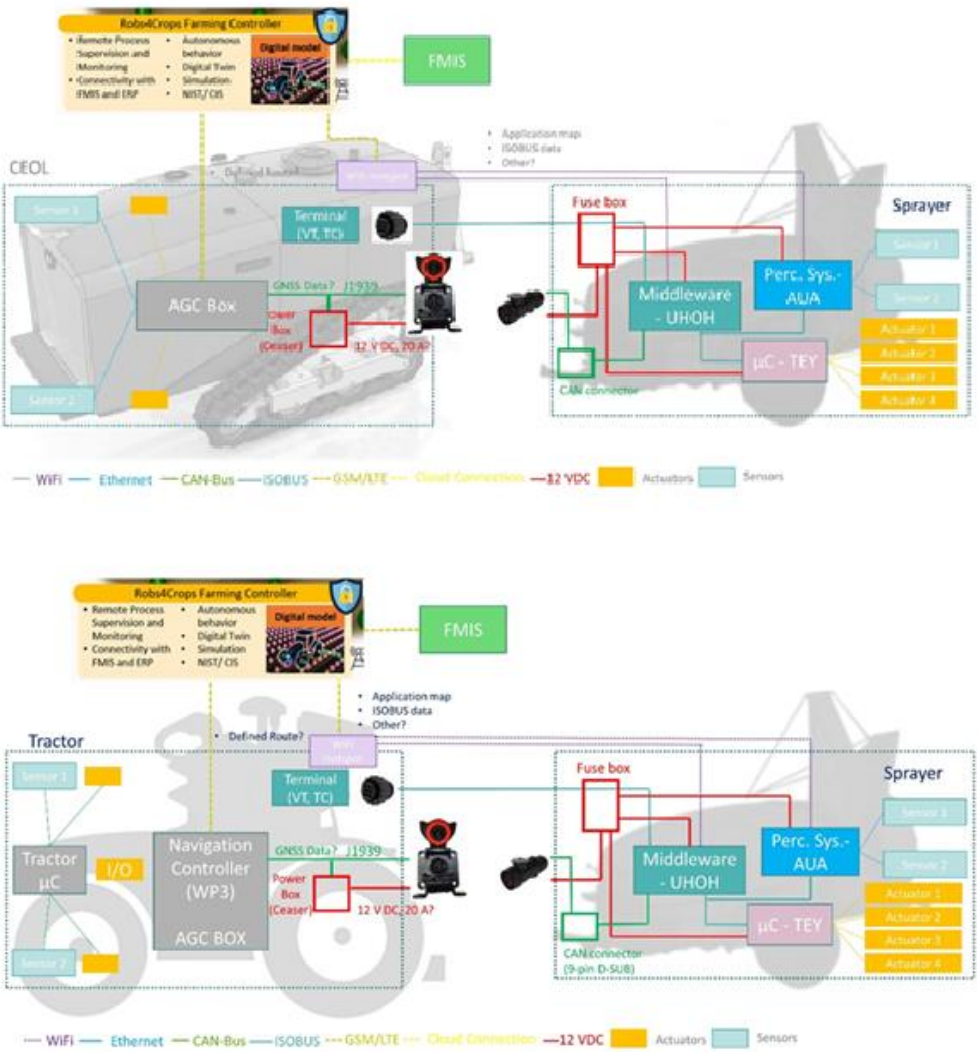

Figure 12. Overall Architecture Scheme for the Sprayer using Ceol Robot in Greek Pilot (Up) and using the Retrofitted tractor Greek and Spanish Pilot (Down).

In the Robs4Crops project, the main communication node will be established from a dedicated computer developed from UHOH, named Middleware. This computer will be installed on the implement side and will be responsible to secure all communications between the vehicle and the implement, including combining the recommendation taken from the Perception System with a predefined process parameter (prescribed rate). At the top level of the communication hierarchy is the Farming Controller (FC). Lastly, the AGCbox used on the robot and the retrofitted tractor for the spraying use case is responsible for the positioning and the guidance of the machines. In the next paragraph, it will present with more technical details each module developed from each partner for the spraying in the Robs4Crops EU project. The modules that will be discussed are the Middleware, the Farming Controller, the Perception Unit, the AGCBOX and the Spraying Units.

4.2 Functionalities and Capabilities

It is noteworthy that for the sprayer implements in both apples and table grapes there is no difference in the functionality block. In both systems, there is a common system architecture, communication and sensor layout.

4.2.1 ISOBUS functionality

For the spraying case, the Middleware is the main component as described in Deliverable 2.1. In the spraying case, both in Greek and Spanish pilot, the configuration of the middleware is the same as the weeding case, in terms of having three network configurations (Channels) as shown in **Figure 2**. However, the network of the ISO11783 has communication with a real ISOBUS-compliant ECU of the Sprayer. Therefore, the task operation includes the TC, UT functionalities of ISOBUS. However, the first network, J1939, is still in charge of receiving the J1939 protocol-compliant messages, investigating the message compliance, and transferring them to the simulated TECU node of the second network. The TECU functionality of ISO11783 network still remains simulated, since the AGC-Box of the CEOL robot does not designate with the TECU functionality. The node of the ISO11783 network for the simulated TECU specifies the Robot/Tractor ECU (class 2) based on the ISO interaction layer to feed the implemented ECU with the needed data (GNSS and speed). Finally, the third network of the middleware on channel 3 virtually introduces the WebSocket to the ISO11783 network. The main functions of the third network are to exchange as-applied information with the Farming Controller using WebSockets.

Similar to the weeding case, the exact same system and communication architecture is used, to enable the data exchange between the FC and the implements, robots and tractors from all LSPs. The topics exposed in the spraying case are the following:

- **latitude/longitude**: Receive GNSS location of the robot/tractor
- **speed**: Receive the speed of the robot/tractor
- **quantity**: Receive spray quantity value from the implement
- **trigger_flag**: A message to enable FC logging process
- **capacity**: Receive the capacity of the weeding
- **vol_per_area_act**: Receive Application per area value from the implement
- **vol_per_time_act**: Receive Application per time value from the implement
- **vol_per_time_set**: Receive Application per time (set) value from the implement
- **camera_on_flag**: Receive a flag that indicates that the camera is on
- **emergency_stop_flag**: Receive a flag that indicates that emergency stop is triggered

Regarding the GNSS coordinates, all coordinate messages, like the weeder case, are generated by the AGCbox using two distinct files that contain the ISOBUS11783 and CANOpen messages. For the ISOBUS the following messages are generated:

- **(0x9F8011C) GNSS_WGS84 (node GPS)**, which contains the Longitude and Latitude signals.
- **(0xCFE49F0) GBSD_TECU (node TECU)** which contains the signals **GroundBasedImplementedSpeed**, **GroundBasedDistance** and **GroundBasedDirection**. These signals are radar measurements according to the norm ISO11783. However, there is no radar on the robot. Therefore, the signals **GroundBasedImplementedSpeed** and **GroundBasedDirection** can be replaced with GNSS values of speed and direction (Velocity in ENU local frame and signal indicating either forward or reverse as the direction of travel).

For the CANOpen messages the following are generated:

- 10 messages in CANOpen (node AGC_SPE), containing the GNSS positions and velocities, in the ENU frame, and the IMU measurements (Euler angles, speed rotation, acceleration).

As already mentioned, the Perception Unit is the main module that is responsible to detect canopy presence and foliage density in order to generate spraying recommendations in real-time field trial operations. The functionalities that have been developed so far in Robs4Crops project for the Perception Unit are listed below:

- Detection of Canopy Presence and Canopy Density using Computer Vision and Machine Learning algorithms and generate spraying recommendation using those information fused with current velocity and agronomic information.
- Generate DDI36 ISOBUS and proprietary J1939 messages for Spraying Recommendation.
- Receive GPS and Velocity ISOBUS messages that are generated from AGC box and middleware.
- Generate J1939 Alive Signal notification when the Perception Unit is operational.
- Generate ISOBUS address claim message procedure to proper communicate with spraying units.
- Logging Functionality that stores all generated spraying recommendations for further offline validation.
- Automatic start-up for all previous functionalities when the device is activated.

4.2.2 Perception unit

The Perception Unit adopts a modular camera design and mounting solution, in order to accommodate different canopy geometries and heights (**Figure 13**). This vision-based system relies on depth image information in order to estimate the canopy density. There are two main features considered when processing depth information: i) the total pixel count on the depth image, which resembles to the canopy information that is present in the camera Field of View (FOV) and ii) the relative proximity index of neighbouring pixels, which corresponds to different leaf layers at different depths.

Figure 13. Perception Unit system mounted in the front part of the tractor during field trials.

To this end, a machine learning model (Multi Layer Perceptron) has been trained to predict the density profile in the image, using three categorical classes: i) no canopy, ii) sparse canopy, and iii) full canopy. Annotation of depth data is performed by field experts categorizing each image in the corresponding class, using the Point Quadrant measuring technique and domain knowledge where necessary.

As a result, based on incoming depth information, the Perception Unit can modulate the default/maximum spraying volume, considering the canopy density information, thus outputting new spraying volume values in the ISOBUS line, following the conditions below:

- if canopy is class 0 → No canopy detected → spraying volume is set to 0% of the default/maximum
- if canopy is class 1 → Sparse canopy detected → spraying volume is set to 50% of the default/maximum
- if canopy is class 2 → Dense canopy detected → spraying volume is set to 100% of the the default/maximum

Next, sprayer application performance was measured by placing Water Sensitive Papers (WSP) in diversified canopy density scenarios, across different canopy heights and depths. The objective was to assess the spraying deposition in real field scenarios, especially in i) no canopy, ii) sparse caniopy and iii) dense canopy scenarios, as shown in the **Figure 14**, below. Same spray assessment protocols are followed for both table grapes (LSP3) and apples (LSP2).

Figure 14. Ground truth locations for measuring spray performance in no canopy (left), sparse canopy (middle) and dense canopy (right).

WSP tracers were used as spray liquid tracers and the amount of droplets was evaluated, for understanding the total number of droplet impacts in each scenario. WSP tracer data were assessed following standard methodologies using an image processing software, and an example is shown (Figure XX). Actual liquid deposition in each canopy scenario was verified by extracting the percentile (%) area of the WSP covered by spraying liquid. Locations with in-row gaps were not sprayed and the amount of liquid applied when vegetation was present have been thoroughly examined. Nonetheless, the description of sprayer assessment methodologies and interpretation of results goes beyond the scope of this deliverable.

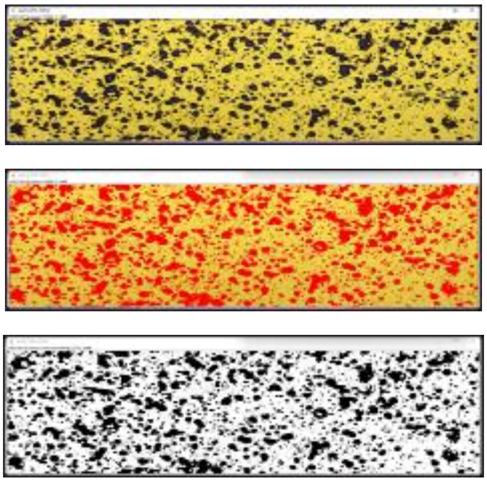

Figure 15. Image processing steps for the analysis of Water Sensitive Papers.

A post-application analysis was conducted by assessing the data recorded from the pilot sessions, including depth images, machine learning predictions, velocity measurements, default and recommended spraying values. Overall, it was possible to evaluate the sprayer and perception unit performance by assessing the as-applied maps generated after the session was completed. Data logging allowed for a per-tree evaluation, in order to measure the canopy estimation accuracy of the system and the actual spraying liquid applied in each case.

4.3 Sprayer implement for LSP3 (Greece)

Regarding the sprayer configuration, the ECU is in charge of the sprayer functions control. The ECU has two distinct modes: "Spraying Auto" where the sprayer is controlled from the spraying recommendations from the Perception Unit and "Spraying Manual" where manual spraying from the user is performed. Additionally, there are two main systems: the water hydraulic circuit for nozzle spraying, tank filling and cleaning, but also the hydraulic oil circuit system for air flow generation. For actuation part, several sensors are displayed, as shown in the next diagram.

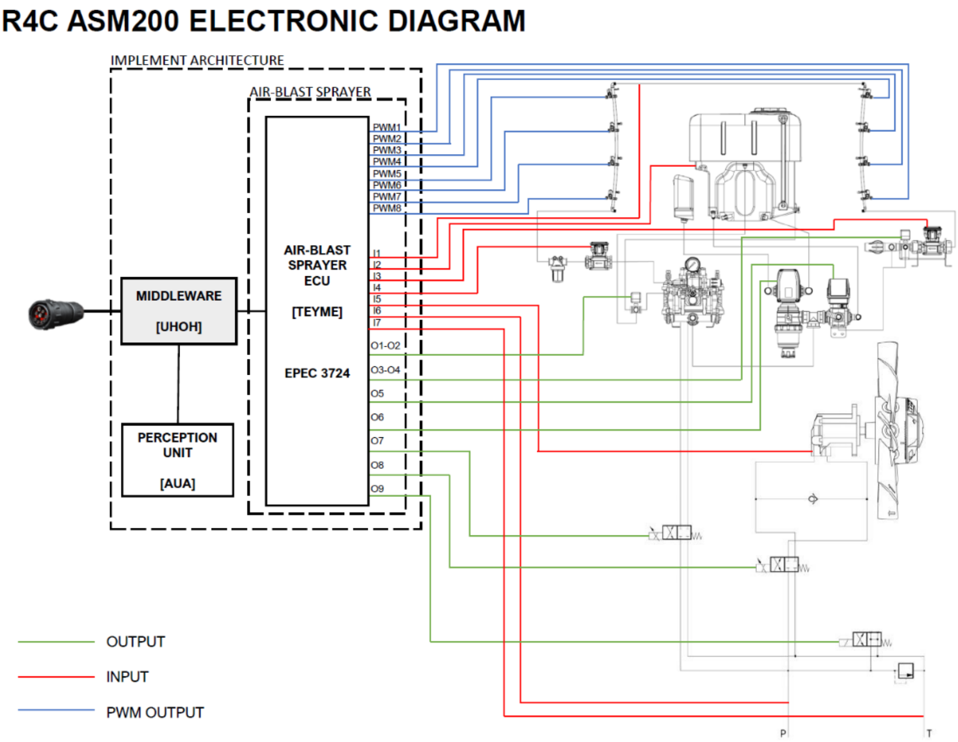

Figure 16. Electronic Diagram for Robs4Crops ASM200 Spraying Unit.

For the table grapes in the Greek Pilot case, the main characteristics of the Sprayer are:

- Sprayer type: Lift-mounted and air assisted.
- Tank capacity: 200 L
- Pump Hydraulic Driven
    - $62 \frac{lts}{min} @540\ RPM$
- 1 axial fan hydraulic driven
    - Max air flow Rate per fan: $33.000 \frac{m^3}{h}\ @2500\ rpm$
    - Fan hydraulic consumption $@2500\ rpm$: $25 \frac{lts}{min}\ 180\ bar$
    - Fan power consumption $@\ 2500\ rpm$: $5\ KW$
- Electronics controls, sensors and actuators
- Pulse Width Modulation (PWM) nozzle control system allowing individual/section/total nozzle control.

As already discussed, the following operation modes are currently installed in both Sprayer ECU:

- Stopped
- Spraying Auto
- Spraying Manual
- Tank Cleaning
- Tank Filling

For every operation mode, the Sprayer ECU will give feedback to the middleware for real values measured by its own sensors that is going to be used to compare prescribed rate from the middleware against real values of the job done. According to spraying operations ASM sprayer has 2 horizontal sections (right and left) divided in four vertical layers resulting in a total of eight spraying independent sections. Flow air rate generation can be variable and is defined by the perception system.

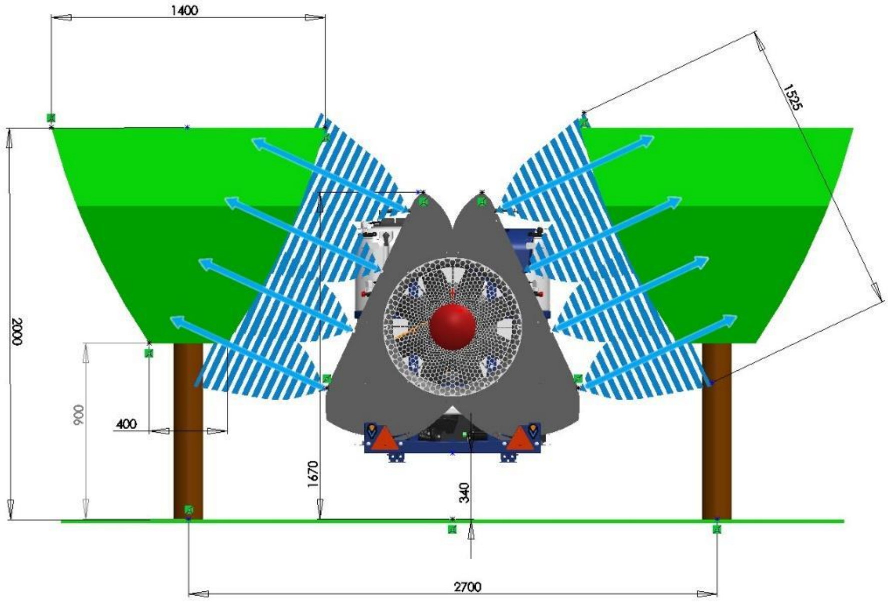

Figure 17. Figure with Back Side of ASM200 Unit during operation in vineyard case.

4.4 Sprayer implement for LSP2 (Spain)

For the apple orchard in the Spanish Pilot case the main characteristics of the Sprayer are:

- Sprayer type: Trailed and air assisted.
- Tank capacity: 2000 L
- Pump PTO Driven
  - $140 \frac{lts}{min}$ @ $540\ RPM$
  - Max PTO power consumption required @540 rpm: 4 KW
- Axial fans independently hydraulic driven
  - Max air flow Rate per fan: $15.000 \frac{m^3}{h}$ $@2500\ rpm$
  - Fan hydraulic consumption $@2500\ rpm$: $75 \frac{lts}{min} 180\ bar$
  - Fan power consumption @ 2500 rpm: 10 KW
- Pulse Width Modulation (PWM) nozzle control system allowing individual/section/total nozzle control.

- Electronics controls, sensors and actuators
  - Power supply required: 12V CC and 25A max.

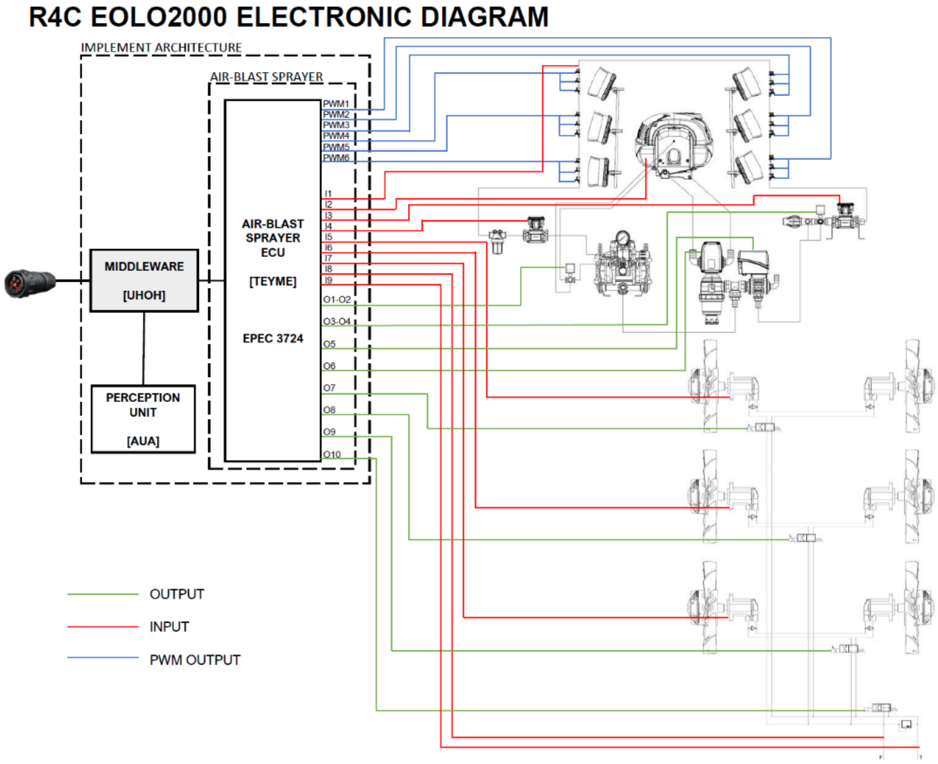

Figure 18. Electronic Diagram for Robs4Crops EOLO2000 Spraying Unit.

The hardware of both sprayers (lift-mounted **ASM** and trailed **EOLO**) is independent of the tractor or robotic platform on which they are attached. The lift-mounted **ASM model** is the only sprayer used with different vehicles, however, the electronic system will be exactly the same. In case of the **EOLO model**, the working concept is the same compared to the **ASM**, using the same ECU unit, and with only few changes in the sensor or actuators installed due to different components used in the sprayer. As with both sprayers, with the purpose of establishing dose rates assigned by the Perception Unit, the Sprayer ECU will be in charge of the regulation of all devices in the implement. In the following diagram, all is shown the electronic system of the **EOLO Sprayer**. Unlike the ASM model, EOLO sprayer has 2 horizontal sections (right and left) divided in 3 vertical layers resulting in a total of 6 spraying independent sections. Flow air rate generation can be variable and independently controlled in the 3 vertical layers and is defined by the perception system.

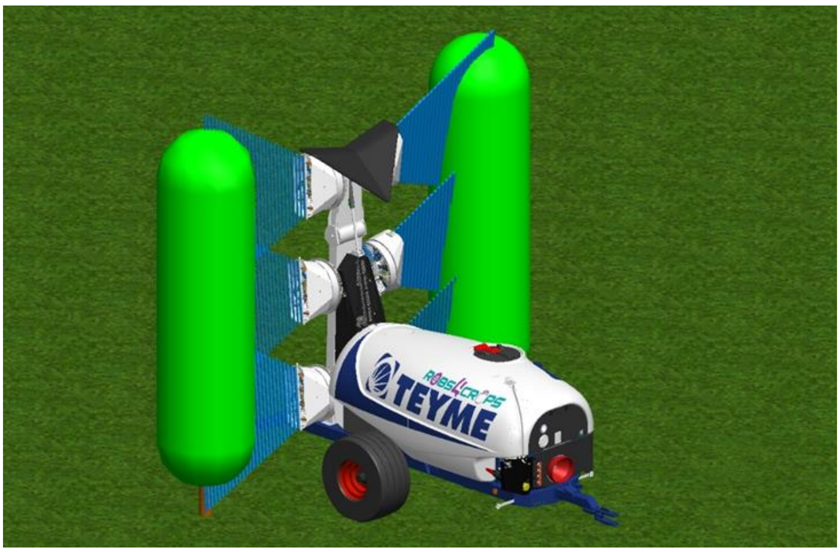

Figure 19. Figure with 3D Side of EOLO200 Unit during operation in orchard case.

5 Discussion

In this last section of this Technical document, it will be described for both the weeding and sprayer implements what should be further developed and what deviations from the initial development plan was done.

5.1. Weeder Case

Starting with the analytics module that has been developed, position (GNSS) and speed was received. Data such as Quality and Quantity have not been sent, but for communication validation purposes, the information was tested with dummy generated values. The purpose of the current season was to record all data in order to develop a detection algorithm for accurate pinpoint (per individual plant) the damage on weeding and report it as "quality". A goal of next season will be to test the current development during the next operational season. In addition, the camera feed was not sent to the FC due to the protocol we are using for communication. Currently, together with the FC, we are planning to switch to DDS (Data Distribution Service) which is the underlying technology of ROS2 (Robotic Operating System) to send the data from Analytics directly to the FC.

With respect to the middleware communication, it is worth mentioning that the setup of the weeder in the combination with the Robotti, the CANBUS of the Robotti will be modified for receiving ISOBUS messages from the middleware. The current status of the configuration stands for one-way communication. When it is able to hear the CANBUS signals (compliant with ISO11783 protocol), then further improvements, in terms of emergency STOP, work-states for the hitch positions shall be implemented. In the combination of the weeder with the CEOL robot, the middleware configuration is final and fully set. Also, the emergency stop signal has been included in the communication between the CEOL robot – middleware – Analytics. The further improvements will be the control of the hitch position based on the weeding quality resulting from the Analytics software. For that, the middleware will choose a proper signal from ISO11783 protocol and put the decision/values of the quality/as-applied info from the Analytics into the selected signal/message. The selected ISOBUS message for the work-states of the hitch position should be integrated with AGC-Box of the CEOL robot as well to enable the robot to receive the signal.

Regarding the communication between the implement and the FC, no major deviations have been identified. At the moment, the variables received by the weeder are demo values for testing purposes and no real values from the weeding operation have been received so far. As a next step, we consider the data capturing from the fields, running the implement in all LSPs. In the future, development will include further expansion of the variables exchanged between the FC and the implement, based on the lessons learnt and the requirements that would emerge from the MVP2 and the second round of LSPs.

Lastly, for the hardware of the weeder case, hardware integration of the ISOBUS connector has been integrated to the CEOL robot. The CEOL is ISOBUS compliant (hardware and software) the ISOBUS messages of velocity, speed and GNSS. The hitch position messages need to be developed in ISOBUS. The hardware needs to be tested for vibrations and robustness in the field.

5.2. Sprayer Case

For the sprayer case, the communication between the middleware and all other components is fully set and functional. The Middleware records the as-applied information together with its geo-location as well as other CANBUS data. The prescribed and as-applied rates including the geo-locations are simultaneously transferred to the FC using the WebSocket designed on the middleware. The Perception Unit communicates with the middleware through the ISO11783 network and with the ECU through a separate channel using proprietary messages. The prescribed rates based on the integrated agronomic algorithm are dispatched to the ECU of the Sprayer and the middleware. The communication between the WebSocket of the middleware and the FC is fully set and functional and as-applied rates including the geo-location are exchanged.

Regarding the communication between the implement and the FC, no major deviations have been identified. One minor deviation that could be mentioned, is that the application map is not received by the implement through the FC from the FMIS, but the file is manually inserted directly to the implement, for simplicity reasons, without compromising the overall functionality. At the moment, the variables received by the implement are demo values for testing purposes and no real values from a spraying operation have been received so far. As a next step, we consider the data capturing from the fields, running the implement in all LSPs and the data visualization to the user interface in the form of a heatmap. As a future goal for the communication between the implement and the FC, further expansion of the variables exchanged between the FC and the implement, based on the lessons learnt and the requirements that would emerge from the MVP2 and the second round of LSPs.

For the Perception Unit, the device is operational and spraying recommendations are sent in sprayer. Field trials in the Greek and Spanish pilots are performed in order to check all corner cases and thus getting the best parameterization based on these pilot tests for the image processing and AI pipeline that were developed in the previous season. Further tests are performed for the proper delay needed for precise spraying based on the distance between the Perception Unit and the sprayer. Additional data collection and further improvements on the vision software stack, will allow the system to react faster in smaller canopy gaps, as well as estimate with higher accuracy intermediate canopy density values.

Regarding the spraying unit, further developments for outputting proper warning, alarm messages for TIM functionality and outputting significant messages for the FMI data analytics related to sprayer. Additionally, some TC to controller issues should be solved but also assure the mechanical hardware proper functioning and the maintenance of the sprayers in both sprayer pilots.

The final setup, which is in the architecture above, has been tested in the pilot case in Spain as well as Greece. The setup for the pilot case in Greece has not yet been finalized, where it is expected to get finalized in November 2022. This needs to be followed to prepare the setup for the connection with the CEOL robot for the season in 2023. Lastly, for the robot side, the setup of the CEOL robot with the sprayer has to be finalized and the improvements to be further applied are the speed reduction or emergency stop according to the spraying status.