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Smart implements by leveraging ISOBUS: Development and evaluation of field applications

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ABSTRACT

Increased labor scarcity and input costs, as well as the demand for ecologically more sound control of growing conditions while maintaining yield and quality in both viticulture as well as horticulture have proliferated the requirements for the current technologies such as implements and autonomous vehicles used in these domains. The increasing employment of such technology, however, brings up the issue of compatibility, in terms of data exchange, connectivity, and communication between the implements and autonomous vehicles used. Besides that, conducting the connection and communication in a standardized means adds more complexity to the issue. To properly address the above-mentioned issue, this work focused on developing a middleware that introduced the ISO 11783 standard-based communication to the setup for both, a weeder robot and a combination of a sprayer and a retrofitted tractor. The developed middleware also considered the information exchange with external systems such as real-time decision-making sensor systems and a farming controller to accurately carry out the field applications of weeding and spraying. The correctness of the weeding quality computation and the spraying coverage indicating the performance of the developed setups were verified before conducting in-field applications. The subsequent in-field weeding application indicated an adequate evaluation of the weeding quality with a variation from 94 to 100 % and zeros in the regions of the weeding path where the weeding was not necessary. The assessment of the spraying applications based on the comparison between the prescribed and the as-applied information showed a mean value of 1.08×10^4 mm^3 m^{-2} for the absolute deviation from the maximum prescribed rate. Further analyses indicated that the as-applied rate varied with a deviation of 10 % during the field application, which was below the defined threshold.

1. Introduction

Precision agriculture in recent years, especially site-specific applications in arable farming, has benefited significantly from an increased number of ISOBUS-compliant technologies [9,20]. This is due to the standardized communication between tractor and implement, which provides users and farmers a straightforward way to accurately deliver inputs to the field and manage task data. However, the ISO 11783 standard is a new arrival for the implements in other domains of agriculture such as weeding machines in specialty crop fields and sprayers

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for vineyards or apple orchards. In addition to that, employing small autonomous tractors and agricultural robots in specialty crops has become common because of more precision in carrying out the application, cost savings, and filling the gap in the scarcity of labor [15]. The aforementioned points raise concerns about the information exchange between autonomous tractors or mobile robots and the implements. That is why defining alternative solutions for communication and compatibility issues between mobile robots and implements using the developed standards such as the J1939 and ISO 11783 would be imperative.

Robotic platforms such as mobile robots and autonomous vehicles have already found their broad range of applications in many domains of industrial production [24]. Furthermore, the perception abilities of mobile robots, in terms of recognizing e.g. obstacles and positions of interest in their surroundings, have also reached an acceptable level [1]. Nonetheless, the capability of interpreting complex field tasks and properly reacting to agronomic aspects (e.g. soil compaction and crop status) still needs to be addressed [1,16]. The incompatibility and interoperability issues between the robotic platforms and agricultural implements add more to the aspects that prevent the full acceptance of mobile robots and autonomous vehicles in agriculture [4,6]. Therefore, standardized communication and compatibility between the robotic platforms, the latest agricultural implements, and decision-making systems continue to be a further task.

By looking at the entire integration path of the ISO 11783 standard into the tractor – implement communication [17,18], many advances in functionality and an increase in the number of agricultural machinery manufacturers implementing ISOBUS, could be seen. In addition to that, the review studies by Smart and Brill, [23] and Brodie et al. [2] have highlighted the next generation of High-Speed ISOBUS (HSI). The HSI is expected to enable a higher level of automation, implement high-resolution cameras to control the process with more accuracy, and provide in-field communication and connectivity among multiple implements. As the advances and improvements in ISOBUS technology continue to grow rapidly, several research studies have been conducted to explore the insights of ISOBUS. The concern of compliance between the ISOBUS technology and external decision-making (sensors) systems has been thoroughly investigated and reviewed by Paraforos et al. [20]. Their study also identified the potential gaps for further upgrades to overcome the technical challenges of using ISOBUS together with the systems for autonomous navigation, plant protection sensors, etc. Moreover, Sharipov et al. [22] and Heiß et al. [8] evaluated the performance of ISOBUS-compliant implements and the efficiency of their agricultural operations. The above analysis of the studies shows that the functionalities of ISOBUS for carrying out agricultural applications have been regularly enhanced, while the requirements for the capacity of the ISO 11783 network have been noticeably strengthened. With regard to the network performance of ISOBUS, Iglesias et al. [10] have trained different modes of network initialization, resulting in an optimal means of compressing and decompressing implement object pool (IOP) files for bus utilization. The ISO 11783 standard is de facto the most integrated protocol for the communication between the tractor and implement in arable farming [7,19]. However, the ISOBUS technologies have not yet been fully incorporated into implements such as weeding machines and sprayers that are employed in the domain of horticulture [21]. Therefore, there have been very limited research studies investigating the in-field operation of the horticultural implements, especially, when it comes to connecting them to the mobile robots or autonomous tractors and using ISO 11783 and J1939 protocols for the communication.

The project was set with the aim to exploit ISOBUS advances in communication between horticultural implements, robotic platforms (mobile robots and autonomous tractors), and decision-making sensor systems. This was supposed to achieve weeding and spraying applications in vineyards and apple orchards with more quality and accuracy. For this, a middleware was developed to integrate the ISO 11783 and J1939 protocols for the communication between the mobile robot and the mechanical weeder at the software level, and for the one between the retrofitted tractor and the sprayer at the hardware level. The developed middleware was also in charge of utilizing the real-time decision from the sensor systems (weeding quality analytics system for the weeder and crop perception unit (PU) for the sprayer) for the application. Besides that, dispatching the task data to the farming controller (FC), which assists in making guidance for navigating the robot or tractor, was established through the middleware. Eventually, the evaluation of the in-field performance of the developed weeder and the sprayer, in terms of the weeding quality and as-applied accuracy information, was carried out. The novelty of the present work remains in (1) the approach to developing a realistic middleware that incorporates industry standards (ISO 11783 and J1939) into (2) the communication between the horticultural implements (weeders and sprayers) with real-time decision-making systems and advanced mobile robots as well as retrofitted tractors with cognitive capabilities.

2. Materials and methods

2.1. Approaches and actors of communication

2.1.1. Connecting weeding implement to CEOL robot

The development of the architecture for the communication between the robot and the weeding implement using the ISO 11783 standard (commonly referred to as ISOBUS) was the first stage. Fig. 1 shows the communication details in depth. The main objective of the architecture was to define the necessary components and connectors that would allow communication between the robot and the weeder in accordance with ISOBUS. For the robot, the AGC-Box translated the CANopen messages of the robot into proprietary ISOBUS messages that were required to carry out the weeding application. Besides that, the communication between the robot and the FC to exchange navigation guidance was also via the AGC-Box. This, however, was intricate on the implement side since the weeder does not contain a real control unit (ECU) to integrate the ISO 11783 protocol ([11,12]). Therefore, the architecture defined the need for the middleware to establish three communication networks: (1) the J1939 network, which introduced the robot CAN bus, in terms of the required messages from the AGC-Box to the implement bus; (2) the ISO 11783 network for the implement bus, which specified a virtual ECU of the weeder as well as a physical connection with the ISOBUS virtual terminal (VT); (3) the virtual CAN network, which established communication with external components such as the FC and the Analytics software.

2.1.2. Decision-making system for weeding

The decision-making system used in the weeding application was the so-called “Analytics”, as mentioned in Section 2.1.1. The Analytics software was synchronized with the virtual network of the middleware and operated on the same rugged PC (Karbon 700-X2, OnLogic, USA) as the middleware. The final decisions such as the quantified weeding quality and capacity were transferred to the ISOBUS VT through the simulated weeder ECU on the ISO 11783 network of the middleware. As it can be seen from Table 1, the algorithm performs data acquisition and processing from the sensors and implements with various functionalities. It starts by importing the necessary libraries and setting up the file path based on the operating system. Then, it loads a CAN database file and establishes communication with a serial port and CAN bus. It also initializes a connection to a Robot Operating System (ROS) framework. Within the main loop, the code reads sensor data, processes it, and sends the processed data to relevant ROS topics. The software calculates the frequency of sensor value changes, updates the quality metric based on the changes, and publishes the frequency and quality values. Further, it also checks a buffer condition and takes appropriate action. Overall, the code provides real-time monitoring of sensor data, communication via CAN bus, and integration with the ROS framework for data publication and control.

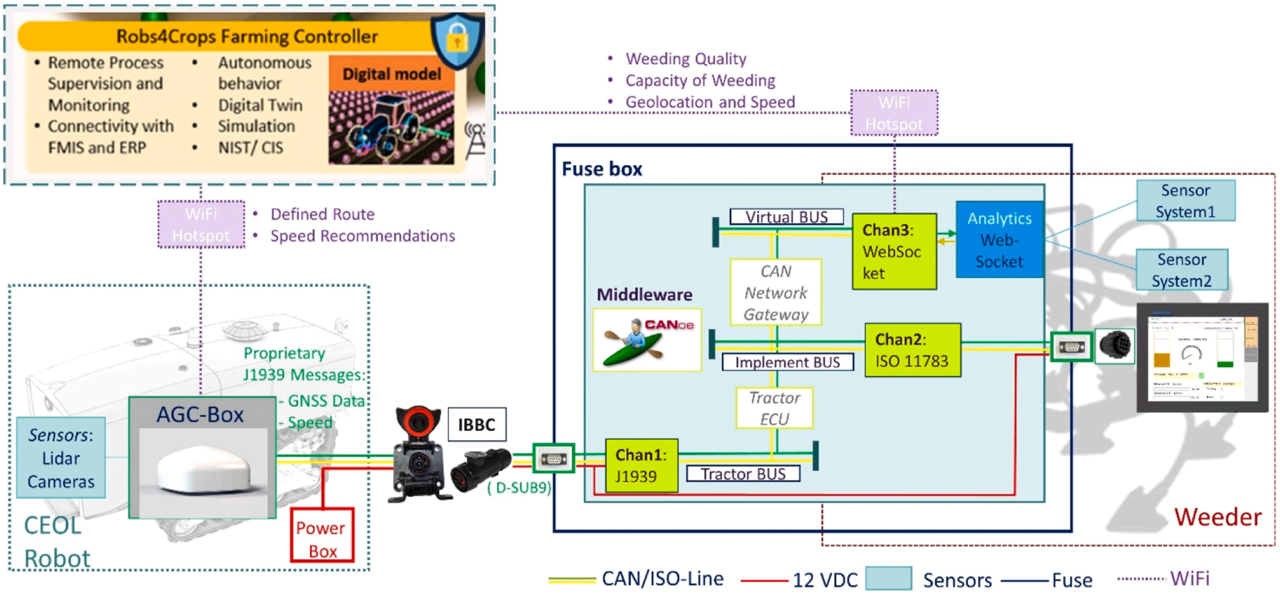

Fig. 1. The architecture of the CEOL robot and weeder communication.

Table 1
Pseudo-code representation of the weeding quality algorithm.

```
Load CAN database file
Establish serial communication and CAN bus connection
Initialize ROS connection
Loop indefinitely
    Read sensor data
    Process sensor data and calculate frequency of change
    Update quality based on sensor changes
    Send updated sensor frequency and quality values
```

The algorithm also includes the collection of raw data from the sensors and encoders that capture the full information on the spins and rotations of each weed-removing metallic disk. This information specified the irregularity of the disk spins, in terms of the heartbeats of the sensors. The "heartbeat" is a value or impulse that was calculated based on the sensor type and the probability of the sensor having irregularities (a factor extracted from the sensor website) and priority (in case many sensors are connected). If the examination of the sensors reveals inconsistencies, the algorithm organizes an analysis of how much the "heartbeat" hasn't been heard by setting a secondary timer. Then, the algorithm also computationally reflects the effect of the portion of the unheard heartbeats on the "weeding quality" parameter. The Analytics software also specifies the frequencies of the spinning disk to define the blockage in the frequency domain. If the "heartbeat" of the specific sensor is totally inaudible for a specific time, the algorithm immediately logs in GPS-based distance and the time of the sensor being inactive to determine the area of missed weeding. The quality of the weeding in percentage was then defined by comparing the area of the missed weeding with the total area operated. In this scenario, the algorithm has acceptably high accuracy in evaluating the weeding quality. Besides that, the algorithm decides about stopping the robot or the complete setup based on factors such as low-weeding quality, blockage on the rotating discs, and default sensor status. The decision is transmitted to the robot through the ISO 11783 network of the middleware using proprietary ISOBUS TIM (tractor-implement-management) messages. The decision, in the form of a camera feed, is also sent to the FC so that the farmer could examine the reason for the stop.

2.1.3. *Connecting sprayer to retrofitted tractor*

The communication architecture for the setup of the retrofitted tractor and sprayer was considerably different from that for the weeding case because of a real physical implement bus and the decision-making system (Fig. 2). However, the same type of AGC-Box was employed to feed the sprayer ECU with the geolocations and speed information. In this case, the AGC-Box plays a major role in making the retrofitted tractor autonomous since it is also responsible for communicating with the "Navigation Stack" (NS) and translating the navigation commands to the tractor. The NS is connected to the AGC-Box on the tractor CAN bus through the D-Sub9 connector and is in charge of providing navigation guidance to the robot based on the information coming from the sensors and the FC.

On the implement side, the sprayer is designed with a real implement bus and an ECU to integrate the ISO 11783 standard. Besides that, the PU (see Section 2.1.4) is directly connected to the implement bus. Although the sprayer is fully ISOBUS compliant, the developed middleware was essential for communication with the tractor. This is because the retrofitted tractor does not designate the tractor CAN bus (J1939 protocol), in terms of the ISOBUS stack. The virtual network of the middleware was also used to exchange data with the FC.

2.1.4. *Working principle of decision-making system for spraying*

The vision-based system used depth and color information to estimate the canopy density and generate real-time spraying recommendations. A hue-saturation-value (HSV) filter was applied to keep only the green pixels in the depth image. Two main features were considered for the processing of depth information: (1) the total pixel count of the depth image, which was similar to the canopy information that was present in the camera's field of view (FOV); and (2) the relative proximity index of neighboring pixels that corresponded to different leaf layers at different depths. A machine learning model (Multi-Layer Perceptron) was trained to predict the density profile in the image, using three categorical classes based on the canopy presence: i) no canopy, ii) sparse canopy, and iii) full canopy. Annotation of the depth data was performed by field experts that categorized each image into the corresponding class, using the Point Quadrant measurement technique and domain knowledge where necessary. As a result, the PU could modulate the default/maximum tree row spraying volume based on color and depth information. If no canopy was detected, the spraying rate was set to 0. If a sparse canopy was identified, then the spraying rate was set to 50 % of the maximum rate. Finally, if a dense canopy was detected, a maximum spraying rate of 100 % was recommended. Since the device

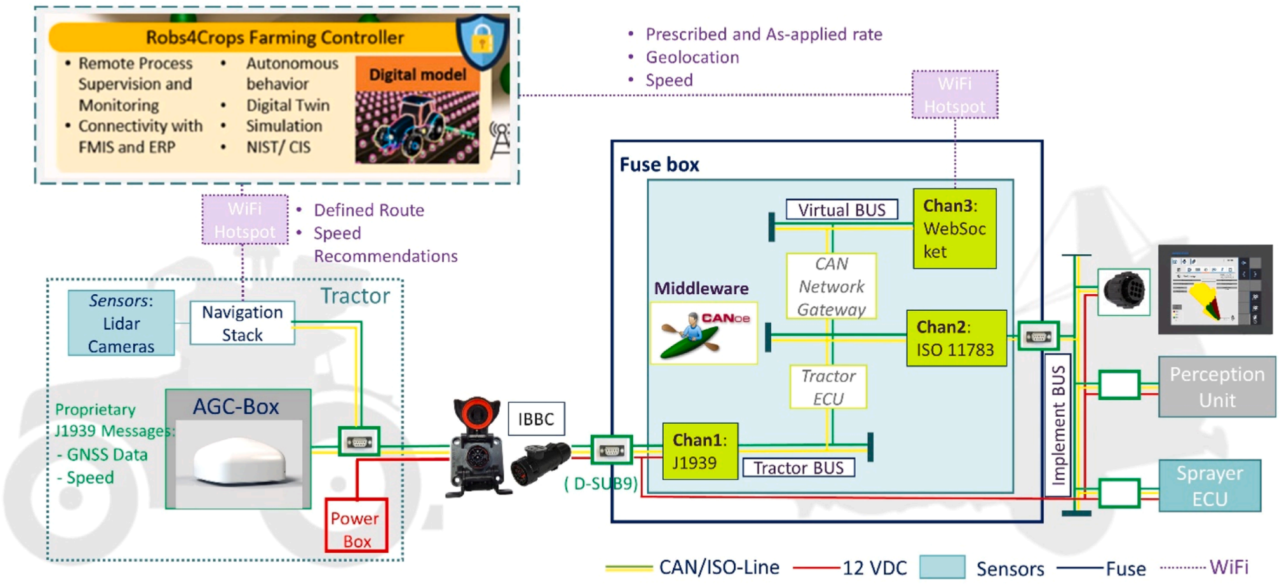

Fig. 2. The architecture of the retrofitted tractor and sprayer communication.

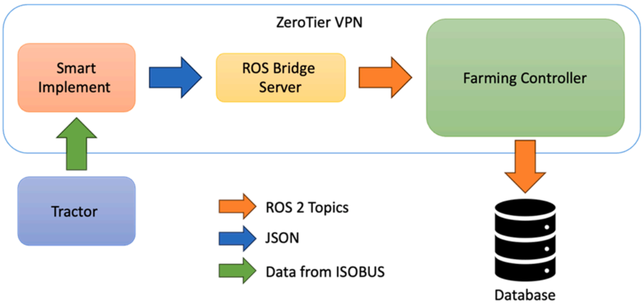

Fig. 4. Representative scheme of the FC approach for communicating with the implements and representing the process data such as weeding quality and as-applied amount.

was mounted in the front of the tractor/robot, an offset distance and the operation speed were taken into account to compensate for the delay in generating each iterative spraying recommendation and sending it to the implement bus at the correct time. All the communication, in terms of message exchange with the implement bus, used the messages defined in the ISO 11783/J1939 protocol. The software implementation used Python-Can 16 to send and receive messages on a CAN bus line. The information flow about the sequences implemented into the PU can be seen in Fig. 3.

2.1.5. *Farming controller*

The FC platform was designed to help farmers plan and manage their farming activities. More specifically, the FC offered farmers the ability to configure, execute, and monitor agricultural tasks by selecting the field of operation. This would be possible for the FC by establishing a seamless communication of all resources and sensors with a digital visualization of the field under a common framework.

The preliminary approach to data interpretation within the FC is illustrated in Fig. 4. The Smart Implement retrieved data from the tractor and certain sensors that tracked farming activities, such as weed quality or spraying rate. A script then serialized this information into a JSON file and sent it to the FC via a web socket opened by the ROS bridge server. The FC then deserialized the JSON file back into the pre-defined variables and processed them according to the required activity. It is worth noting that web communication is protected using the ZeroTier VPN.

2.1.6. *Middleware and data collection*

It can be noticed in Sections 2.1.1 and 2.1.3 that the middleware was supposed to be developed for two different cases of vehicle-implement combination: (1) the CEOL robot and weeder; and (2) the retrofitted tractor and sprayer.

The CEOL robot and weeder: the main assignment of the middleware lies on the ISO 11783 network [26], as shown in Fig. 5. The ECU of the implement [11] is virtually configured on the ISO 11783 network by setting the application layer of implement messages [12]. The application layer of the implement messages is then identified by an interaction node layer of the CANoe v15 (Vector Informatik GmbH, Stuttgart, Germany). Activating the interaction layer in the CANoe allows the use of ISOBUS-dedicated Communication Access Programming Language (CAPL) functions. The dedicated CAPL functions are straightforward to control nodes, access the messages and signals, and implement the object pool APIs [25]. Setting up all the aforementioned layers and functions, the middleware is designed with a node for the virtual ECU of the weeder, which acts as a real ECU in the network and communicates with any other virtual and physical nodes of the network, such as the ISOBUS VT and the decision-making system. The developed “Implement Object Pool” (Jetter AG automation, Ludwigsburg, Germany) for a real-time representation of the process information such as weeding quality and capacity is also assigned in the CAPL. Furthermore, a node of the tractor ECU, which characterizes the ISOBUS TECU functionality, is also designed in the ISO 11783 network to translate the GNNS and

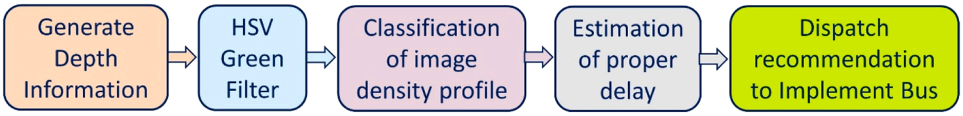

Fig. 3. The information flow from the detection of the canopy to the recommendation of the spraying rate.

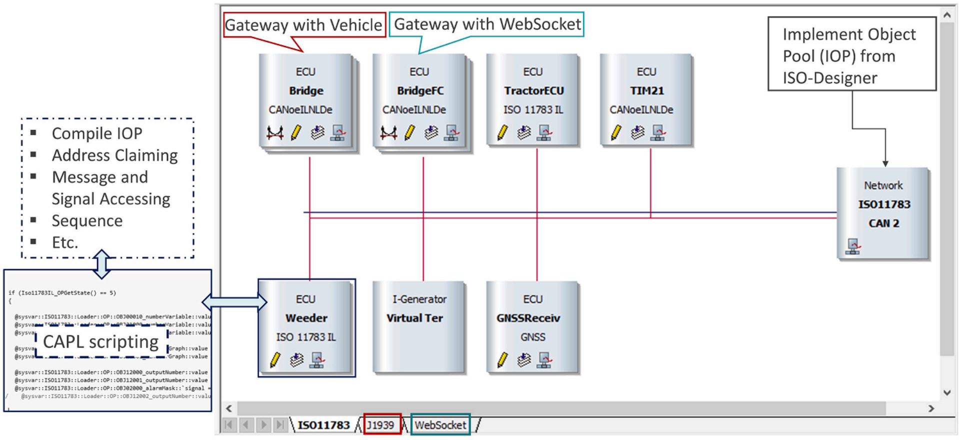

Fig. 5. The configuration of gateways and ISO 11783 networks of the middleware in CANoe.

wheel-based speed information from the gateway of the robot (Chan 1) to the weeder ECU.

The retrofitted tractor and sprayer: the setup in CANoe for the middleware was the same as in the weeding case, in terms of three fixed networks for the tractor, the implement, and the WebSocket. However, the implement-bus was coordinated by a real ISOBUS ECU (EPEC 3724, Seinäjoki, Finland) that was fully compliant with the ISO 11783 standard [12]. Aside from the ISOBUS ECU, there was another physical component, which is the real-time (decision-making) sensor system connected to the implement bus. Therefore, it was necessary to develop a “TractorECU” node with full ISOBUS TECU functionality and an additional node for “GNSS Receiver” on the Chan 2 of the middleware to accord with the ISO 11783 protocol while feeding the sprayer ECU and PU with the GNSS and speed information. The configuration for the WebSocket was identical to the weeding case but different information such as the prescribed rate from the PU (DDI1) and the actual rate from the sprayer (DDI2) was exchanged with the FC.

In both cases, the FC was in charge of collecting, storing, and representing the data. However, the exchange of information between the implements and the FC was limited to the prescribed and applied data, including geolocation and speed information, due to their priority in guiding the vehicle and the interest of the farmers. Therefore, in addition to the FC, the data logging and storage in the middleware were configured to capture the full CAN/ISOBUS data of the vehicle-implement setup. For the weeding application, the data acquisition was performed at the field of a vineyard (47°23′04.1″N 0°29′02.5″W) in TERRENA, Ancenis-Saint-Géréon, France. For the spraying application, it was carried out in apple orchards of SERRATER (42°09′41.8″N 3°05′37.6″E), Girona, Spain.

2.2. Instrumentation

2.2.1. Setup for robot-weeder combination

Fig. 6 shows the final setup of the mechanical weeder (TERRENA, Angers, France) connected to the CEOL robot (AgreenCulture, Toulouse, France) to carry out a weeding operation in the fields of TERRENA, France. The main frame of the weeder was equipped with side rollers and ground contact discs for weeding. The CEOL robot carried a category 1 linkage system that gave the flexibility to attach to various farming implements. Because of the possible disturbances such as metal frames and nets in the field that might cause inaccuracies in receiving GNNS data, a special frame was developed and fastened to the robot to hold the AGC-Box with a fixed height above the canopy. The AGC-Box provided the robot with the position data and was responsible for guiding the robot. It also acted as a real interface between the robot and the attached implement since it complied with the CANopen protocol of

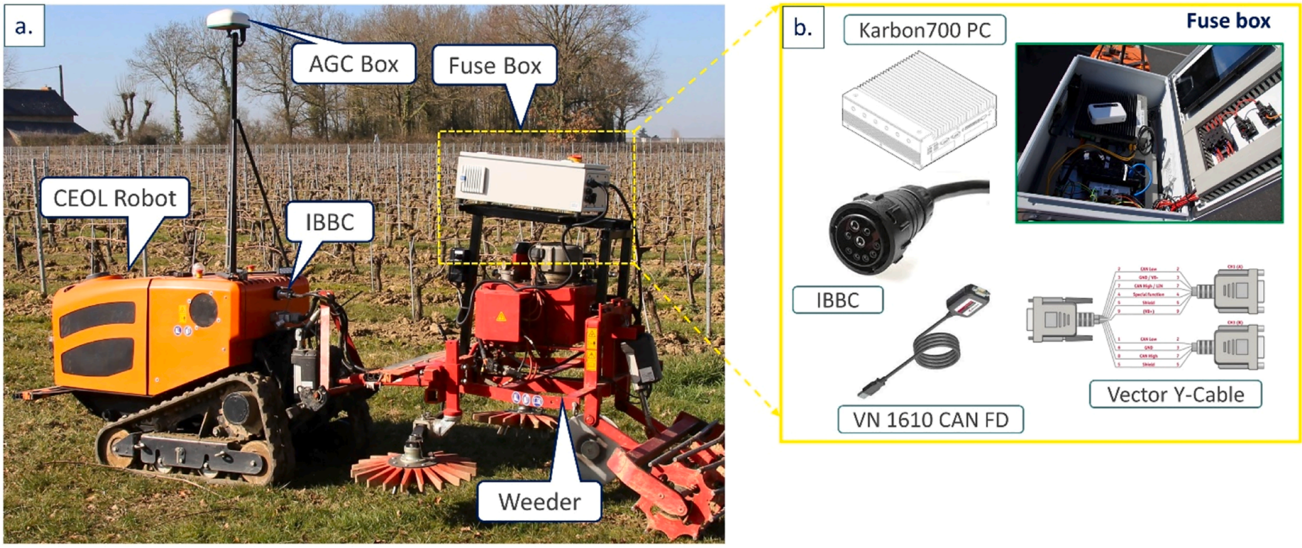

Fig. 6. (a) The setup of the weeding implement connected to the CEOL robot and (b) the developed Fuse-box that fuses the middleware with all the needed software and hardware for the robot-implement communication.

the Controller Area Network (CAN). The output of the AGC-Box could also be monitored and regulated from a distance using smartphones/tablets.

There was another frame developed for the weeder to carry the Fuse-box (Fig. 6b). The Fuse-box consisted of the rugged PC running the middleware and the Analytics software, and all the necessary cables for the robot-implement communication as well as power supply. The Fuse-box was connected to the AGC-Box via ISOBUS Break-Away Connector/Cable (IBBC, Erich Jaeger GmbH, Friedberg, Germany). On the implement side, the IBBC was connected to one of the two channels of the VN1610 CAN interface (2 x CAN high-speed transceiver, Vector Informatik GmbH, Stuttgart, Germany) using a Y-Cable (Vector Informatik GmbH, Stuttgart, Germany).

The use of the robot battery to power the rugged PC was controlled by a microcontroller built into the Fuse-box. This has been done to allow the robot to be switched on and off at will and to avoid the rugged PC's power supply being cut off abruptly. The analytics software checked the depth and color information based on data from two stereo cameras (OAK-D-PoE) connected to the rugged PC via PoE, while other sensors such as a ZF Terental sensor (GS100701) and an encoder (Joy-it COM-KY04ORE) detected the presence of the magnetic field and rotation respectively to check for blockages on the discs.

2.2.2. *Setup for tractor-sprayer combination*

A trailed air-assisted sprayer (EOLO-VM, TEYME Tecnología Agrícola, S.L.U., Lleida, Spain) was mounted on a NEW HOLLAND T4.110F tractor (New Holland, Pennsylvania, USA) to carry out a spraying application in apple orchards (Fig. 7). The developed Fuse-box was integrated into the sprayer. The AGC-Box was attached to the roof of the tractor and was in charge of dispatching the proprietary ISOBUS messages for the GNSS and speed information to the middleware. The PU was mounted in front of the tractor to supply the sprayer with the prescribed rate in real-time. The PU was equipped with two sets of RGB-D cameras on the left and right sides to collect sufficient information on the canopy from both sides of the implement. Furthermore, the ISOBUS VT (ANEDO T50i, ANEDO GmbH, Eydelstedt, Germany) fastened in the tractor cab was employed to set some application parameters such as working width, number of sections, etc. prior to starting the application as well as to observe the real-time performance of the sprayer.

2.3. *Verification of the implement performances*

2.3.1. *The correctness of weed detection*

The data collected from the external sensors on the weeding machine were reflected in the frequency domain to define the critical frequency of the spinning disk for the blockage and the weeding quality (see Section 2.1.2). Therefore, the pattern agreement between the frequencies of the sensors' impulse and the computed weeding quality verified the correctness of the weed detection. The frequency falling below a certain threshold (in this case, 5 Hz) indicated the blockage on the disk. The algorithm re-evaluated the raw data, and if there were no changes detected, it initiated a reduction in the quality parameter. The rate at which the quality parameter decreases was determined by a customizable or hyper-parameter. In our case, a reduction of three percent per meter was chosen based on an assessment derived from empirical observations. In the forthcoming iterations, this parameter should be configurable by the farmer via the Virtual Terminal or the Farming Controller interface. The value chosen for the reduction would delineate the extent to which the user or farmer desires the automated system to operate continuously without interruption. As the effectiveness of the rotary disk depends on factors such as soil conditions and the type of weeds encountered, the determination of the reduction remains a highly subjective one for the farmer.

2.3.2. *Verification of spraying pattern*

Prior considerations such as the selection of the correct row for the operation and the representative canopy for the attachment of the hydrosensitive papers (HSP) can be seen in Fig. 8a. In the representative canopy, there were four vigor regions selected to adhere the HSPs along the height of the canopy, as shown in Fig. 8b. The volume sprayer tank before and after the test has been traced to compute the average applied rate. After the test was finished, the HSPs were placed in the sample templates to digitalize them for further analysis. The collected templates, in terms of HSPs, were digitized using a camera (RAMMAIN Quad 48 MP, 0.8 μm, PDAF). This was proceeded by processing the digitized information of the images in the so-called "CUTHILL Hydroreader" (Cuthill, Punto Tandil, Argentina) to assess the spraying quantity and quality.

In order to verify the spraying distribution, a prevalent method that considered the analyses of the collected HSPs for quantifying the distribution quality [3,5] was utilized. Besides that, the assessment of the quality of the sprayed amount was followed by a commonly accepted method [13,14] that examines the distributions from the droplets

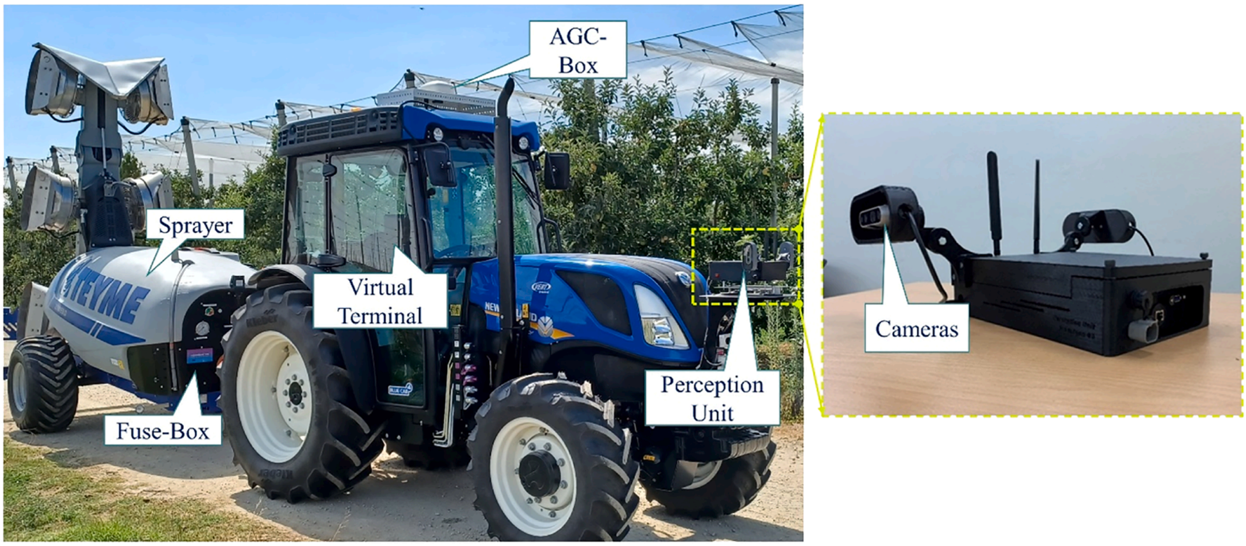

Fig. 7. The sprayer mounted on the tractor and the real-time decision-making system (PU) to perform the spraying application.

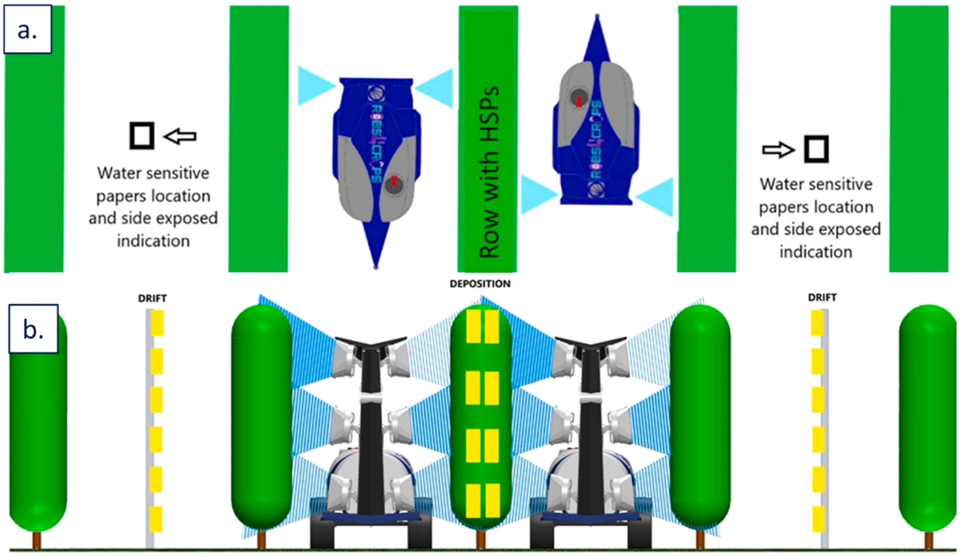

Fig. 8. (a) A schematic view of the rows to attach the HSPs, the in-field movements of the setup for spraying, and (b) the elevation view of the HSPs location.

detected on the HSPs. Two main parameters were considered to evaluate the spraying quality, in terms of the distribution of the amount landed on the HSPs: (1) the average of the deposit density for the droplets (NMD), which estimates the discrete stains and the numbers of the droplets median diameter per cm^2 area; and (2) the volume median diameter (VMD) at different thresholds of the sizes for the coarse. The combination of the NMD and VMD offered to properly depict the coverage and degree of the spraying patterns on the HSPs.

3. Results and discussion

3.1. Analysis of verifications

3.1.1. Evaluation of the correctness of weed detection

The impulse information obtained from the sensors used, differentiated for low- and high-quality weeding, is shown in Fig. 9a and b respectively. The conversion of the presented data (Fig. 9a and b) for the low- and high-quality into the frequency domain (Fig. 9c) was regarded

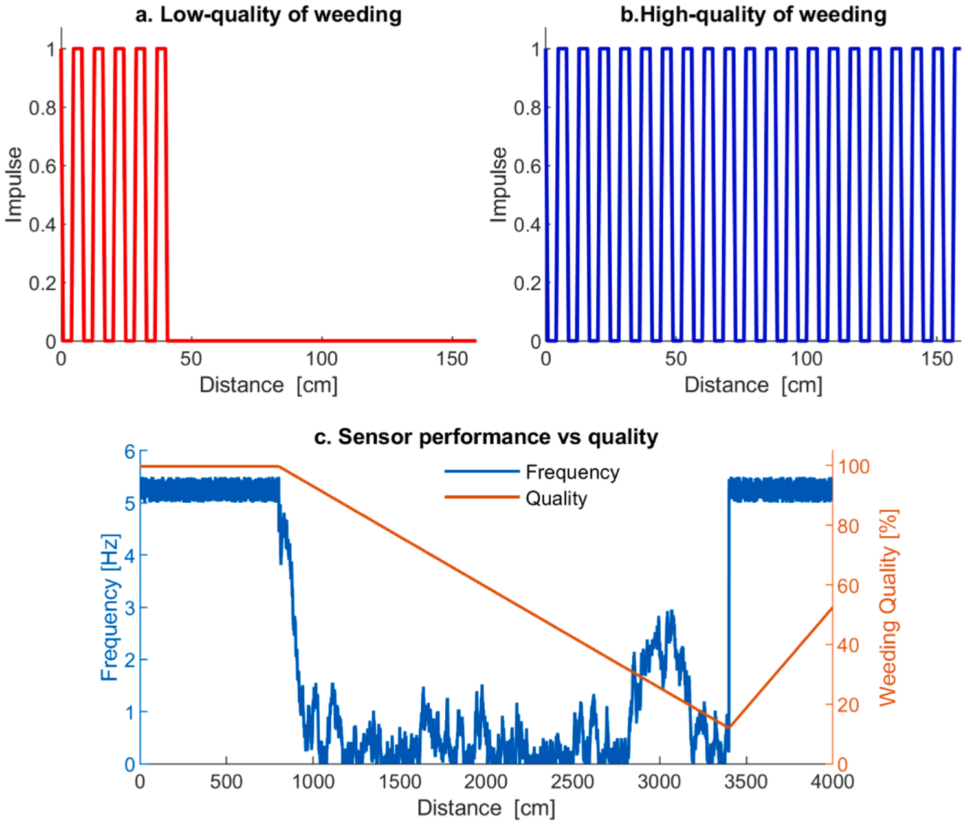

Fig. 9. The impulses of the sensors for (a) low- and (b) high- quality of weeding together with (c) the overlap between the frequency domain and the weeding quality to verify the correctness.

as the weeder performance in the frequency domain since the sensors directly recorded the behavior of the spinning disk (e.g. disk rotations). In both instances, a frequency in Hertz (Hz) was derived from the recorded data. This frequency serves as the basis for calculating the quality metric depicted in Fig. 9c. In this representation, the X-axis spans a length of 4000 cm, while the left Y-axis represents quality and the right Y-axis signifies the frequency of the pulses. Based on the qualitative observation, the pattern between the weeding quality and frequency showed a strong agreement. Furthermore, this analysis resulted in a decision to set an emergency stop when the weeding quality is lower than 50 % which was set as a threshold through empirical expertise. This alert serves as a real-time recommendation, urging the robot to cease the in-field weeding operation as soon as feasible under the prevailing conditions. Note that setting lower thresholds (eg., 30 % resulting in a more substantial quality reduction rate of 4 % per meter) for stopping the robot could be possible by the farmer in conjunction with the farming controller.

3.1.2. *Evaluation of spraying quality*

For both two sides of the leaves, the deposition of the coverage on the HSPs adhered at four selected heights of the canopy can be seen in Fig. 10 below.

Each pattern (e.g., each side of the leaf) resulted in a single distribution chart that was assessed by the parameters, given in Section 2.3.2. To summarize the pattern, the average of the values for the NMD and VMD from two sides of the leave was taken into consideration. This was done for both parameters at each of the vigor heights and the defined thresholds, as given in Table 2. The considerations for the acceptable range of the values and the pattern of the final figures for the NMD and VMD indicated that the PWM frequency of nozzles was high enough to cover all parts homogeneously. In the same way, this indicated that the camera system properly followed the sequence of on/off nozzles when vegetation was present. Besides that, the pattern of the spraying coverage properly confirmed the discussion of the qualitative analysis.

Table 2
The distribution analyses of the HSPs.

Height of the measurement [m]	Average of Deposit Density (NMD) [deposits / cm^2]	Average of VMD from the back/ front side of the leaf at different thresholds [μm]		
		0.1	0.5	0.9
0.5	269	236	273	547
1.5	213	237	275	550
2.5	208	247	330	613
3.5	114	221	257	288

3.2. *Assessment of the field applications*

In the case of weeding: The analysis of the correctness of weed detection (see 2.3.1) was extended to a further in-field trial for weeding in the vineyard. Fig. 11 shows the variance of the weeding quality together with the geolocations in the Universal Transverse Mercator (UTM) coordinate system from the field trial. There was no difference detected from a quantitative comparison between the real-time observation and the post-processed one. The assessment of the processed weeding quality (Fig. 11) represented that the quality varied from 94 to 100 % across the operated area of the field. There were empty spots that can be observed in between the rows. This means that the Analytics sensor system decided not to perform weeding in these empty zones based on the performance of the sensors detecting the heartbeats.

In the case of spraying: The sample points of the prescribed rates generated by the PU for the application and the corresponding points of the applied amount recorded by the FC during the operation of spraying are represented in Fig. 12a and b, respectively. The correspondence between the prescribed and applied amount facilitated examining accurately the quantity of the absolute deviation from the prescribed rates that occurred while performing the application. The normalized values of the quantified deviation resulting from the comparison between the prescribed and as-applied rates together with the probability distribution function of its occurrences are illustrated in Fig. 12c.

The analysis of the statistics for the deviation indicated a mean value of 1.08×10^4 mm^3 m^{-2} and a standard deviation of 1.21×10^4 mm^3 m^{-2}. The 75th percentile of the deviation with a value of 0.94×10^4 mm^3

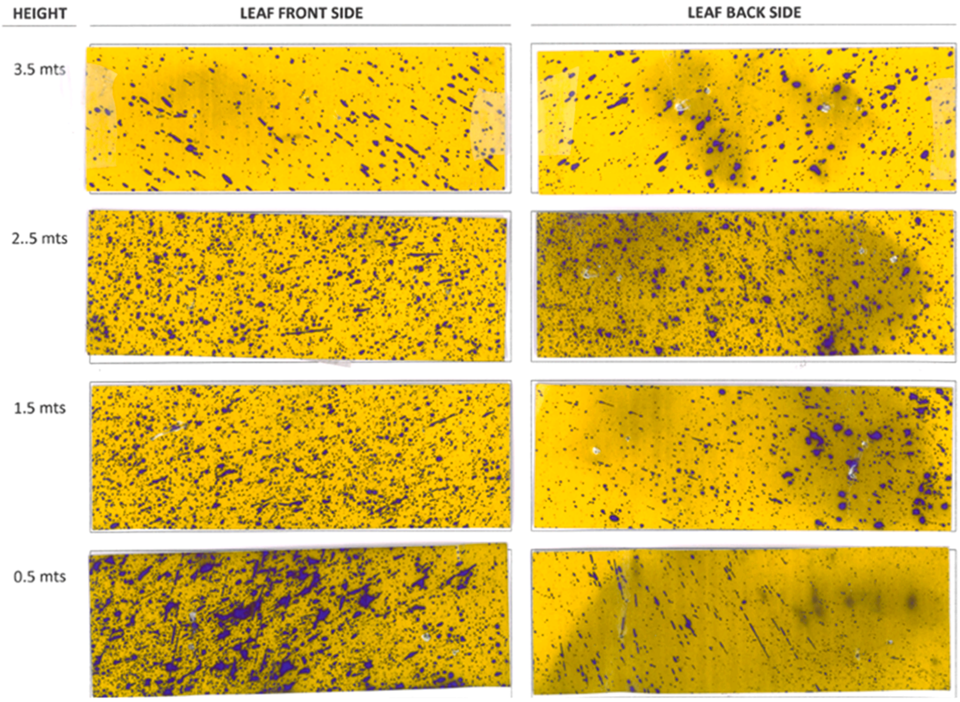

Fig. 10. Spraying coverage on HDPs at four different heights of the selected canopy.

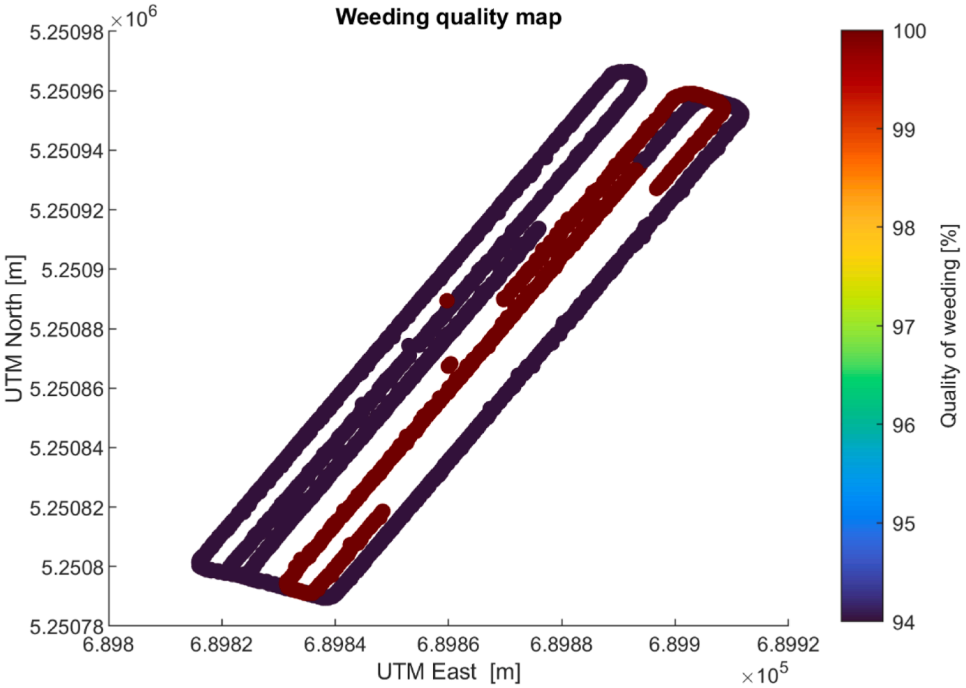

Fig. 11. The in-field evaluation of the weeding quality in percentage.

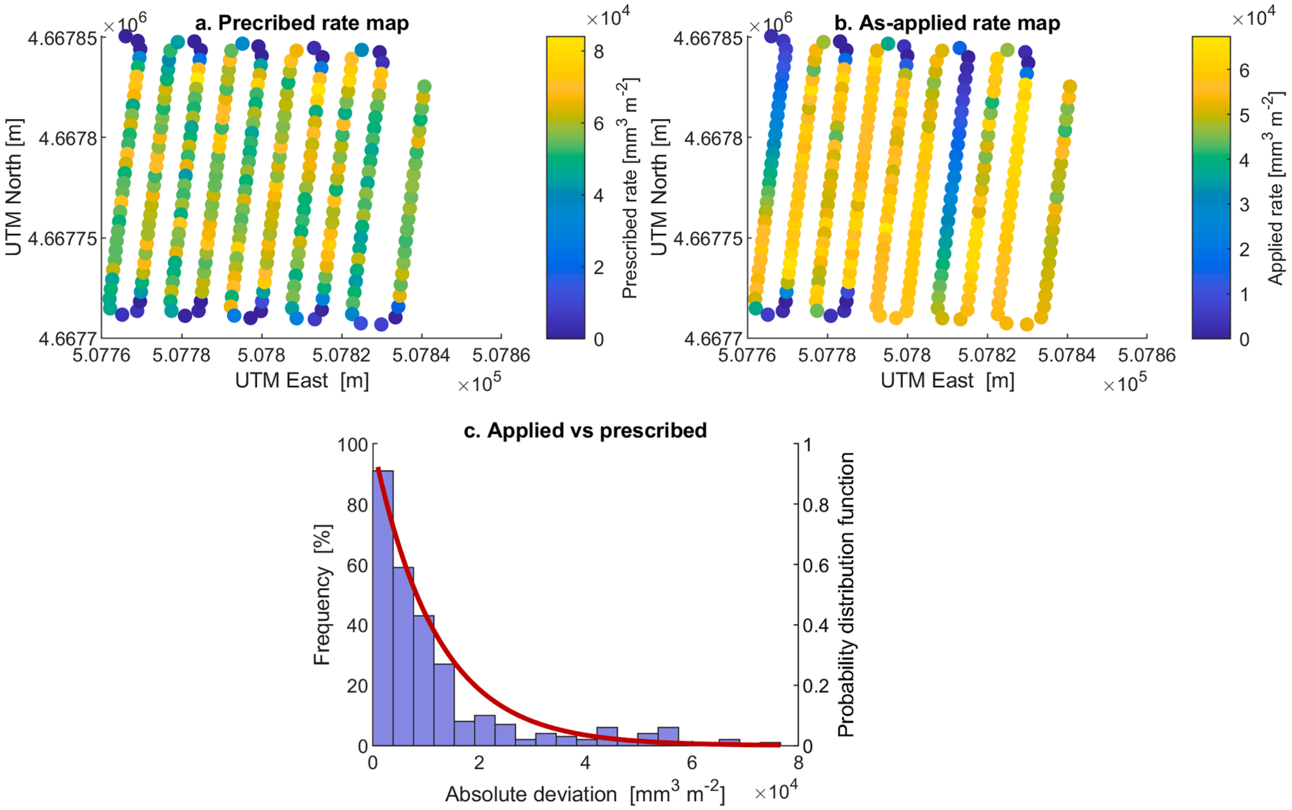

Fig. 12. (a) The corresponding sample points of the prescription point map to (b) the as-applied map of the application and (c) the histogram of the normalized values for the absolute deviation from the prescribed amount together with its cumulative distribution.

m^{-2} proved that most of the absolute deviations from the prescribed rate varied below 10 % of the maximum prescribed amount. This can be regarded as an acceptable range of the threshold for the deviations. The statistical analysis of the deviations was furthered by considering the best-fit distribution of probability. This was identified with a mean parameter that was equal to approximately 1.14×10^4 mm^3 m^{-2}. The occurrence of absolute deviations from the prescribed amount could be justified by a delayed response of the sprayer to the rapid changes in the prescribed rate, a transition offset set on the PU and sprayer actuators, etc. Based on the given analyses above, it could be stated that the accuracy of the spraying application was adequately evaluated.

4. Conclusion

The organized architectures for defining the communication between the CEOL robot – weeder combination as well as the retrofitted tractor–sprayer combination yielded an accurate integration of all the necessary components (e.g., the PU, Analytics, and all other physical layers) with the selected implements. In both cases, the developed middleware assisted in successfully integrating the necessary parts of the ISO 11783 standard into the communication between the implement-vehicle-FC-sensor systems.

The performance verification of the final setups for the weeder and the sprayer indicated an acceptable span of weeding and spraying quality, respectively. In the case of weeding, the well-matched correlation between the frequency domain of the sensor performance and the determined weeding quality confirmed the correctness of the implemented algorithm. For the sprayer, the analysis of the sprayed amount on the HSPs, in terms of the droplet distribution, manifested a proper spraying coverage based on the density and volume of the landed amount. Subsequently, this resulted in a precise acquisition of field application data (e.g., geo-located weeding quality and as-applied amount of spraying). The evaluation of the application accuracy expounded that the deviations of the applied rate from the prescribed amount occurred below 10 % of the maximum prescribed rate, which was considered a justifiable threshold in this work. All of the given analyses and investigations explicated that the integration of the ISOBUS protocol into the communication between the autonomous platforms, selected implements, and real-time decision-making sensor systems results in a better assessment of their in-field performances. In addition to that, the defined setup, integrations, and evaluations could be imperative in further steps of the work that concerns the model-based evaluation of the implements' in-field operations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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