Development of a VR Simulator for Speed Sprayer Operation Training

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Abstract— **Speed (boom) sprayers, the agricultural chemical spraying vehicles, are generally used in orchards of grapes and apples to efficiently control pests. Speed sprayers require skill to operate, and improper operation can result in pesticides drifting off the field. It also requires significant time to train the operator, as adjustments to travel speed, pressure, and nozzle selection need to be considered. Meanwhile, to make the operation of the speed sprayer easier and safer, improvements to the control panel in the cockpit have become necessary. In this study, we developed a simulator of a speed sprayer based on Virtual Reality (VR) and conducted analysis of the driving and operation of the speed sprayer. Experiments using the developed simulator with ten subjects showed that the trend of the subjects' steering wheel rotation angles was the same as that of an actual speed sprayer driver. Furthermore, the head posture when operating the spray button were also the same as that of the driver operating the actual speed sprayers. While there is room for improvement in terms of the real motion cueing and field of view provided to the user, this simulator allowed us to practice the basic operations necessary for pesticide spraying.**

Keywords-vr-simulator; speed sprayer; virtual reality; training simulator; deep feedforward neural network.

I. INTRODUCTION

Orchards have become an important core sector of agriculture in terms of production value, land use, and development of local agriculture in Japan. Many orchards are sprayed with pesticides. Speed sprayers (boom sprayers) have been introduced to improve the efficiency and labor saving of pesticide spraying in orchards. However, many orchardists are aging and depopulating, making succession training and securing labor a major social problem. This study extends our previous work on the analysis of the development of a Virtual Reality (VR) simulator for speed sprayers [1].

The first domestically produced speed sprayer was made in 1957 in Japan. Early speed sprayers were towed by tractors, but in 1965, they were replaced by self-propelled ones. There are several issues with the use of speed sprayers in terms of occupational safety and environmental protection. Speed sprayers used in orchards increase the amount of pesticides sprayed due to the large spray area. Since the Japanese Ministry of Health, Labor and Welfare introduced a positive list system for pesticide residues in food, feed additives, and veterinary drugs [2], measures to prevent pesticide drift into adjacent fields have become urgent.

Many studies have been conducted to minimize the effects of pesticide drift. These studies include the improvement of spray nozzles, the development of remotely operated sprayers, and the development of unmanned sprayers. The low-drift nozzle could not compensate for the increase in spray drift due to the increase in sprayer speed [3]. The sprayer travel speed had a significant influence on the drift values. However, the coarse spraying did not result in that much higher drift [4]. While various unmanned pest control machines have been developed for more accurate spraying [5][6][7], they have not been widely adopted.

To operate a speed sprayer, the relationship between travel speed, pressure, and nozzle selection must be considered. This operation, therefore, requires a skilled operator. Driving skills are expected in areas where the vehicle must pass through a narrow path between branches. On the other hand, the speed sprayer also needs to be improved as well, since it is difficult to see the surrounding from inside the vehicle and the operation panel is complicated. To solve these problems, there is a need to develop a speed sprayer simulator. This simulator will enable improvement in the work capacity of the spraying sequence and the interface for operating the sprayer. A more efficient interface needs to be developed to simplify tasks that require technical skills.

Research and development of driving simulators are now common because they allow drivers to examine any scenario or situation. During the simulation of each driving task, sensory-based operation information can be analyzed. Attempts were made to develop a tractor driving simulator to prevent accidents during work [8][9]. Fujimoto et al. (2016) simulated the spray distribution of a speed sprayer using the coverage of water-sensitive paper placed in the path of travel [10]. By integrating these studies, the training simulator can be constructed to improve the operation skills of speed sprayers, but such an effort is still developing.

In this study, we build a speed sprayer simulator using VR and analyze the driving and operation of the speed sprayer. To provide the user with the experience of operating a speed sprayer, the control buttons, steering wheel, and other control interfaces are made to resemble those of an actual speed sprayer. Information obtained from the VR simulator, such as button operations, head posture while driving, and steering wheel rotation, is recorded. Cameras were installed in the cockpit of the actual speed sprayer to obtain the same information through automatic image recognition. Finally, we analyze the data from the VR simulator and the actual field operation of the speed sprayer to evaluate the usability of the simulator.

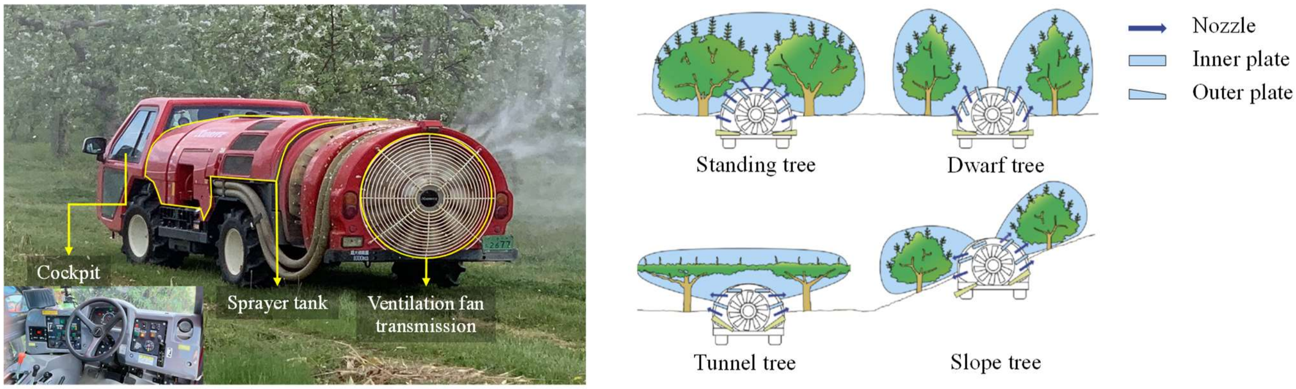


Figure 1. The electric speed sprayer (SSV1091FSC) manufactured by the YAMABIKO Corporation used in this study.

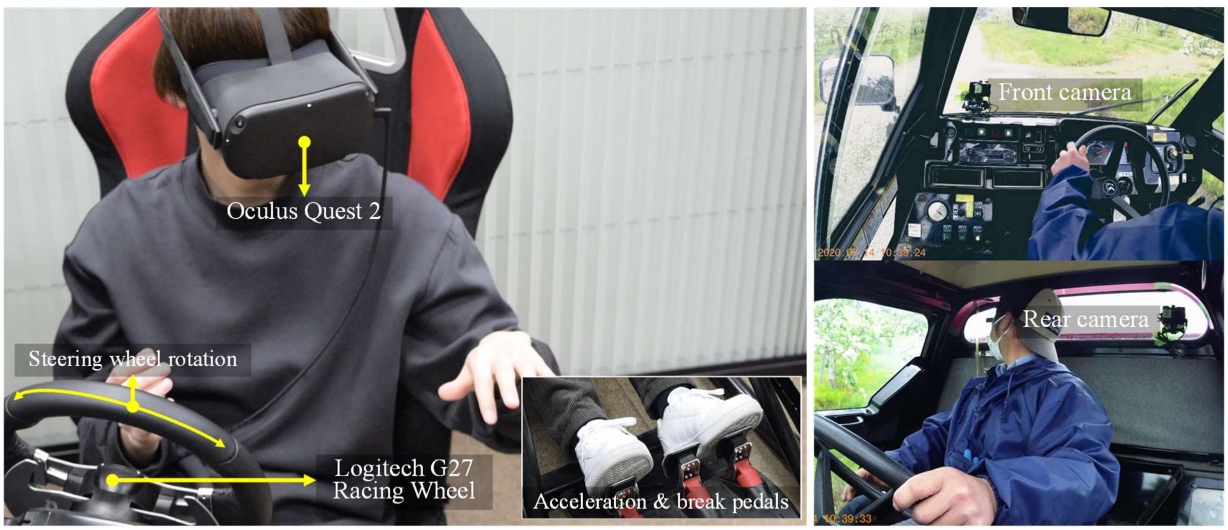


Figure 2. Sensors used in our VR simulator.

The rest of this paper is organized as follows. Section II discusses the speed sprayer in an orchard. Section III describes the proposed speed sprayer simulator. In Section IV, we describe our experiments with the simulator and the results. Finally, Section V summarizes the results of this study and discusses future perspectives.

II. Speed Sprayer in Orchards

Air blast sprayers are used to apply pesticides, plant growth regulators, and foliar nutrients to trees in orchards. Air-blast sprayers can be adapted to different orchard conditions by adjusting the fluid and air delivery systems [11]. A Speed sprayer is an air blast sprayer used for spraying in apple orchards, vineyards, etc. This type of sprayer sprays the pesticide close to the tree, thus reducing the loss of pesticide.

The Speed sprayer is capable of adapting to the spray pattern of the tree. There are four types of tree patterns in orchards: the standing tree, the dwarf tree, the tunnel tree, and the slope types. Figure 1 shows the speed sprayer (SSV1091FSC) manufactured by the YAMABIKO Corporation, which can carry 1000L of pesticide [12]. The speed sprayer can spray pesticides on the entire tree by adjusting the nozzle and the plates that determine the spraying direction as follows.

(1) *Standing trees* : Direct the nozzles and inner plates radially and the outer plate horizontally.
(2) *Dwarf trees* : Direct the nozzles and inner plates to the top but close the top two nozzles.
(3) *Tunnel trees* : Level the topmost plate to block the wind from moving upward and raise the outer plate.
(4) *Slope trees* : Tilt the nozzle and plate in the direction of the slope.

The operation of the speed sprayer is complex. The effective spraying operation depends on the skill of the sprayer operator. Skilled operators continuously check the condition of the trees and adjust the sprayer appropriately.

Several studies have developed simulators to train operators to control agricultural vehicles in orchards [1][13]. Through the simulator, users can experience a variety of training courses, which is expected to improve their driving skills. There have also been attempts to improve the efficiency

TABLE I. SENSORS USED IN THIS STUDY

Sensors	Data	Output
Logitech G27	Steering wheel rotation	-180.0° ~ 180.0°
	Pedal:	
	- Accelerator	0.0 (low) ~ 1.0 (high)
	- Brake	0.0 (low) ~ 1.0 (high)
Oculus Quest 2	Head pose	
	- Position	x, y, z (m)
	- Pitch	-180.0° ~ 180.0°
	- Yaw	-180.0° ~ 180.0°
	- Roll	-180.0° ~ 180.0°
	3D Hand landmark	19 points
GoPro Hero8	Image	3,840x2,160px/60fps (max)

of spraying by introducing machine vision, and its effectiveness has been confirmed in spraying discrete targets [14].

III. SPEED SPRAYER SIMULATOR FOR OPERATION TRAINING

In developing a simulator for speed sprayers, we first consider how to obtain information on operator behavior not only on the simulator, but also in the actual field. Firstly, the sensors must be able to track the driver's head movement and finger movement with Six Degrees of Freedom (6-DoF). Observing the driver's head movement is important because the driver needs to be aware of the trees to be sprayed while operating the nozzle and plates of the speed sprayer. By tracking the finger, we can confirm whether the control buttons for nozzles and plates have been pressed. Secondly, the driver must be able to operate the vehicle using the physical car controls. Finally, the driver must be able to feel the car controls in virtual and physical environments in the same way. The cockpit of the speed spray in the actual field has two camera sensors, one for the front and one for the rear, to detect the driver's behavior while driving and the steering wheel rotations.

A. Sensors

Sensors include wheel and pedal sensors, VR platform sensors, and cameras. All sensors used in this study are as follows.

A.1. Logitech G27 Force Feedback Wheel and Pedal

The Logitech G27 is a gaming racing wheel compatible with PlayStation 2 and 3. These devices were mounted on a cockpit frame manufactured by Rossomodello [15]. Figure 2 shows the steering wheel and pedal of Logitech's G27 attached to the frame and the speed sprayer in the actual field. The steering is equipped with a dual-motor force feedback system that enables the steering to receive inputs from the unevenness of the road surface while driving. The cockpit is equipped with a seat that can be adjusted and reclined. The Logitech G27 operates on Windows and Mac with the Logitech G27 driver.

(a) Exterior

(b) Cockpit

Figure 3. 3D model of the SSV1091FSC in our simulator.

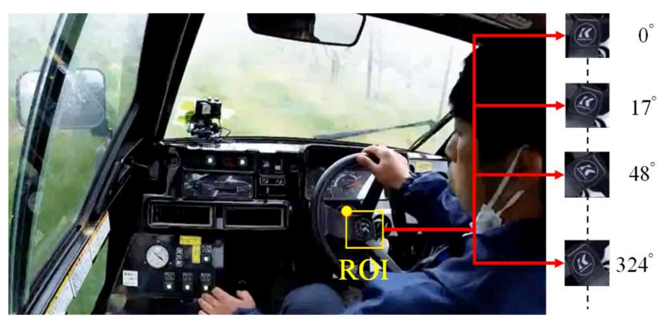


Figure 4. Mark of the steering wheel captured by the rear camera.

A.2. VR Platform: Oculus Quest 2

Oculus Quest 2 is a head-mounted display (HMD)-based VR device developed by Facebook, featuring a 6-DoF angular and linear tracking system that can measure head pose and hand gestures. This system uses Inertial Measurement Units (IMUs) that assess linear acceleration and rotational velocity with low latency and cameras in the HMD that creates a Three-Dimensional (3D) map of the room space and hand landmarks of the user. The initial position of the HMD is pre-calibrated against the position of the car steering wheel since

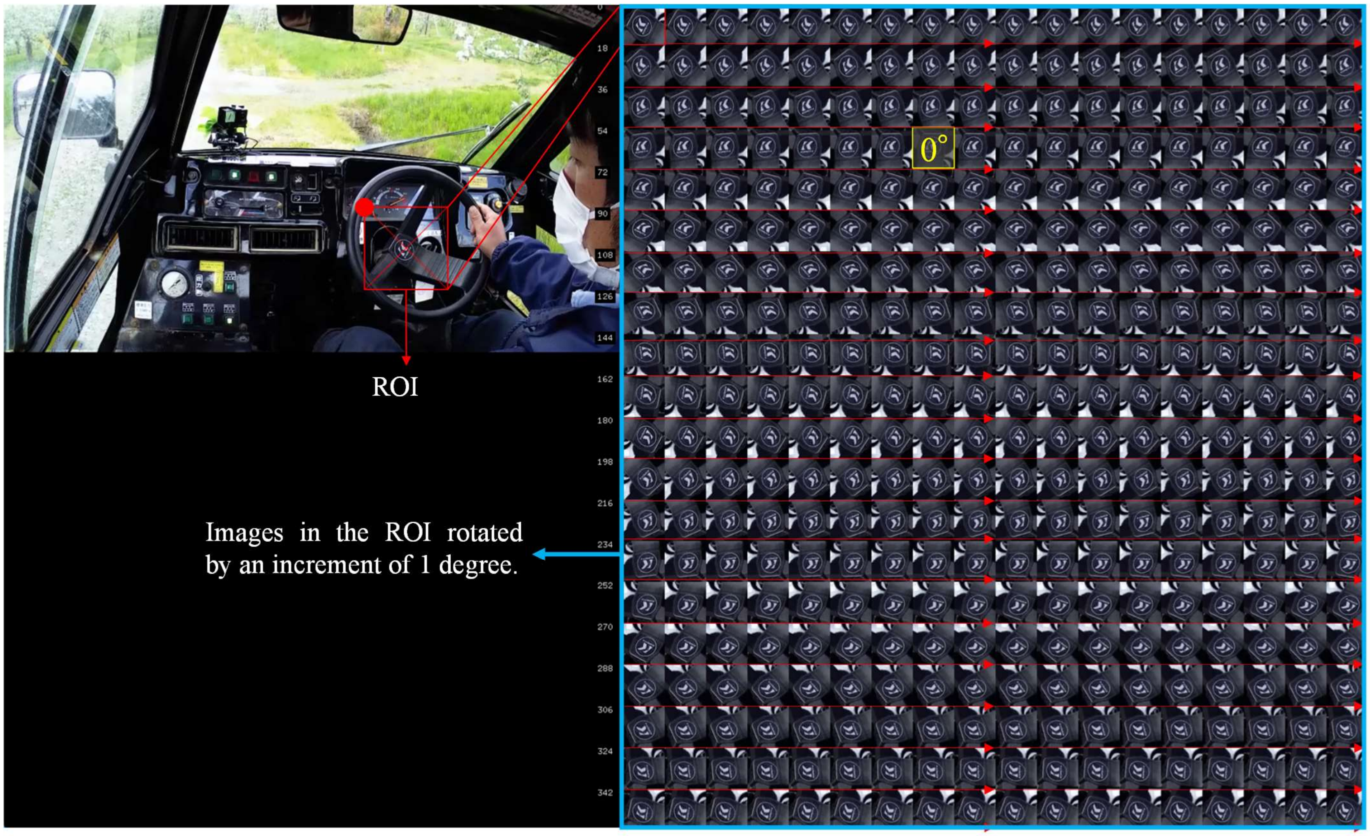


Figure 5. Our tool to semi-automatically specify the angle of the steering wheel marks.

no auxiliary devices, such as base stations, are used to obtain the absolute position of the driver.

A.3. GoPro Hero8 Cameras

Two cameras, as shown in Figure 2, are synchronized to capture videos of the cockpit of the speed sprayer in the actual field from two directions, front and rear. Videos are captured at 60fps with a resolution of 3,840 x 2,160px. The 60fps cameras are considered acceptable because there is no high speed movement in driving or button operation of the speed sprayer. The resulting video from the front camera is analyzed by image processing techniques to obtain the driver's head pose, whereas the video from the rear camera is to obtain the driver's finger movements and steering wheel rotation.

Table I shows data collected from each sensor. The Logitech G27 outputs car driving information such as steering wheel rotation, gas and brake pedals, and sends vibrations from the steering wheel. The amplitude of the vibration can be set in proportion to the speed of the vehicle. The Oculus Quest 2 tracks the driver's head pose and finger movements.

B. Simulator

Our simulator is built for the Unity [16] framework. We chose this framework because of its popularity in game and simulation developments. In addition, we can obtain the 3D data necessary to build the simulation scene from the Unity Asset Store, as well as the Software Development Kit (SDK) for the Logitech G27 used in this study, enabling us to work on the development in a short time.

Figure 3 shows the 3D model of the SSV1091FSC placed in a virtual scene. The scale has been adjusted to give the landscape seen from the model the same appearance as the realistic landscape. Additionally, to simplify the operation of the buttons for spraying the pesticide, these buttons were made larger. The main-button opens or closes all spray nozzles, and the left-, center-, and right-buttons are for spraying the left, center, and right sides of the vehicle's direction of travel, respectively. The operator receives feedback from the sound and the color change of the buttons on pressing them.

The initial position of the Oculus Quest 2 is pre-calibrated against the position of the steering wheel, and no auxiliary device such as a base station can be used to obtain the relative position between these devices. As the simulator is not in mixed-reality, the position of the simulated steering wheel on the VR need to match that of the Logitech G27.

The Oculus Quest 2 runs at a 72fps by default, but to accommodate the reduced frame rate caused by our experimental program, all data was recorded at a sampling rate of 60fps. An Intel Core i7-7700 CPU 3.60GHz, RAM 32GB, NVIDIA GeForce GTX1070 8GB was used as the computing system to control the simulator.

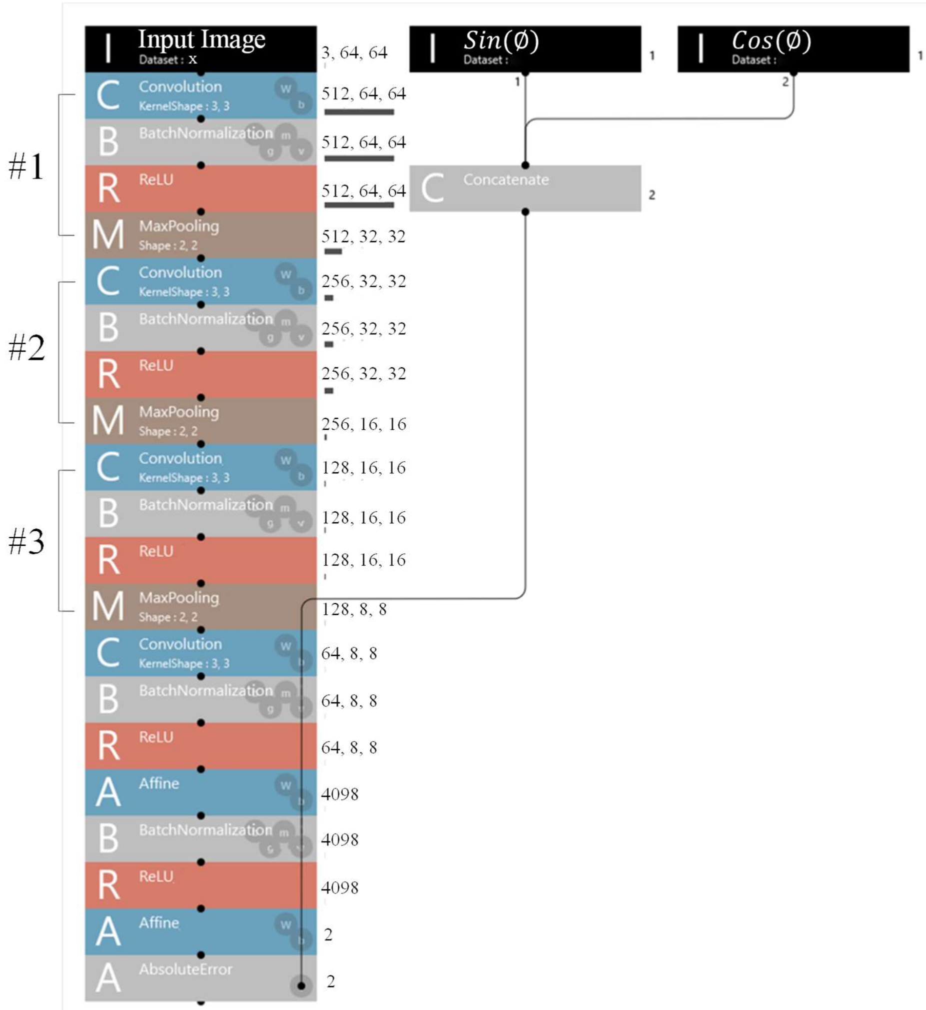


Figure 6. Diagram of the deep feedforward neural network used in this study.

C. Field Measurement

As with the simulator, the operator's behavior and the rotation of the steering wheel during driving a real speed spray are measured using image processing techniques. The methods used to quantify these behaviors are described below.

C.1. Head posture and hand movements

To estimate the head posture from a front-facing camera, facial landmarks need to be extracted from the detected face area. There have been many studies on extracting facial landmarks [17], but we adopted the MediaPipe framework for this study [18]. This framework provides customized machine learning solutions for face detection, facial landmark extraction, and hand tracking.

To extract the facial landmarks, we used the Face Mesh feature of the MediaPipe. From the 468 extracted landmarks, we selected 8 points: the corners of the eyes and mouth, as well as the tips of the nose and chin to determine the head posture. The Perspective-n-Point (PnP) solution was used to estimate the head posture of the 6DoF from these points [19].

The MediaPipe Hands tracks hands and fingers in real time [20]. This feature detects 21 hand landmarks. The tracked fingertip landmarks were used to detect pressed buttons and their frequency.

C.2. Steering wheel rotations

Image recognition was used to estimate the rotation information of the steering wheel from its image. Since most vehicles have a mark on the steering wheel, its rotation can be estimated by measuring the rotation of the mark. For this study, we simply built a Deep Feedforward Neural Network (DFNN) to estimate the rotation of the steering wheel. Figure 4 shows the mark of the steering wheel as it is captured by the rear camera. DFNN extracts the rectangular region of this mark as a Region of Interest (ROI) and estimates the rotation angle of the mark.

To construct a DFNN, pairs of rotation angle data for the image of this ROI are required. Generating these pairs of data one by one manually would be a laborious task. For this study, we developed a tool to generate this data conveniently. This tool works as follows. First, it creates 360 rotated ROIs by

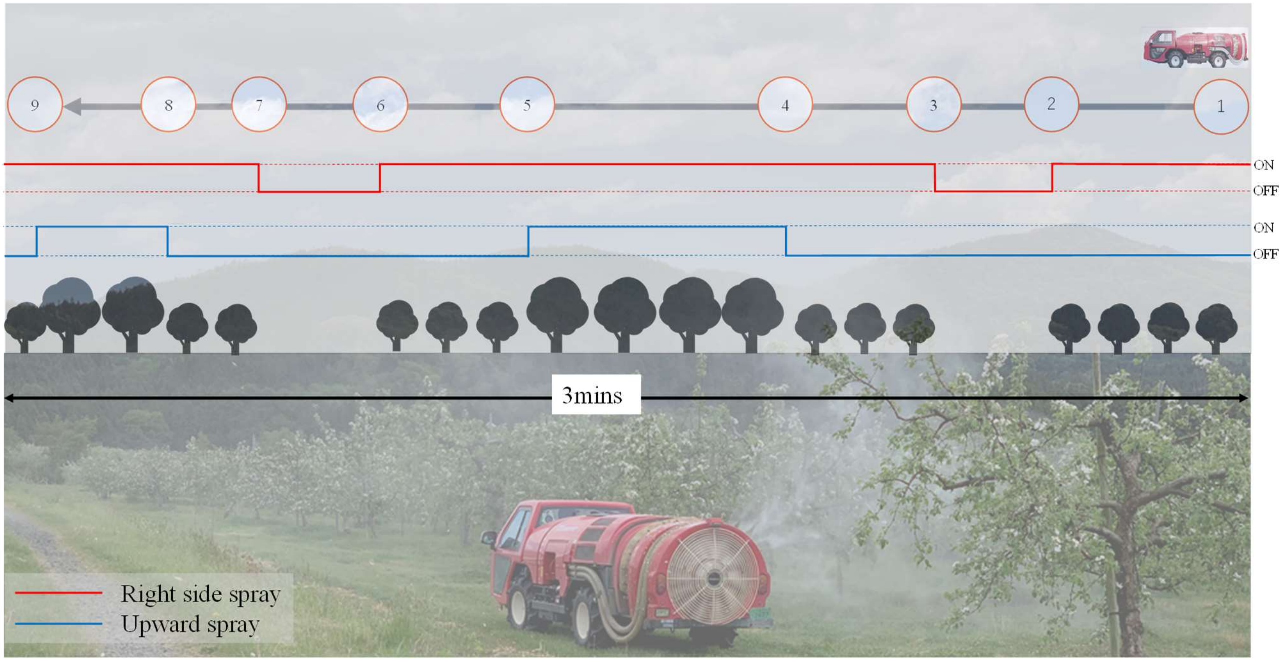


Figure 7. Operator behavior during speed spraying in the experiments of this study.

rotating the ROI image by 1 degree 360 times. By finding a mark with a rotation angle of 0 degree in these images, the rotation angles of the images before and after this mark becomes ±1 degrees. Similarly, the mark with a rotation angle of 1 degree is followed by a mark with a rotation angle of 2 degrees, and the mark with a rotation angle of -1 is preceded by a mark with a rotation angle of -2 degrees. Finally, the rotation angle can be specified for all 360 images in this manner. Figure 5 shows an example of a working interface of our tool. Taking a sufficiently large ROI enables the ROI image to be rotated in its complete shape.

Our DFNN was built using Neural Network Console [21], a deep learning framework developed by Sony Group Corporation designed from the perspective of engineers. Figure 6 shows the diagram of our neural network. The input image is the previously described ROI images in 64x64px. The output is the value of the rotation angle of this image encoded to sine and cosine. This encoding is important when dealing with data with circular topology. We then apply convolution, batch normalization, and Rectified Linear Unit (ReLU) to the input image with the output filter set to 512. The next layer is the maximum pooling layer, defined by a 2x2 pooling window. These procedures are repeated twice, but each time the output filter is reduced by half. Subsequently, the fully connected layer (Affine) is applied after convolution, batch normalization, and ReLU to obtain 4,098 outputs. Again, batch normalization, ReLU, and Affine are applied, and the absolute error between the inferred and true values are evaluated. The network was trained on 44 sets of ROI images corresponding to 1 to 360 degrees for a total of 15,840 images and validated with 18 sets for a total of 6,480 images. This network can infer the rotation angle of the steering wheel with an error of less than 2 degrees, which is comparable to the measurement accuracy of the steering wheel rotation angle of the simulator.

IV. Experiment and Result

This experiment compares the operator's behavior when operating the pesticide spraying in the orchard and when operating it on the simulator to verify whether unique operations are observable in both cases. A three-minute video of the spraying process was selected, and the nine actions taken during the process are summarized below.

- *Action 1*: The operator moves the vehicle to the beginning trees to be sprayed, then presses the main-button to open all spray nozzles, followed by the right-button to start spraying to the right side of the vehicle.
- *Action 2*: The operator presses the right-button again to stop the spraying when the vehicle passes the end point of the group of trees. An action is taken to confirm that the injection has been stopped via the right side mirror.
- *Action 3*: When the next group of trees is reached, the operator presses the right-button again to spray towards the right side of the vehicle. When the next group of trees is reached, the operator presses the right button again to spray towards the right side of the vehicle. At that time, the operator confirms whether the spraying works correctly through looking at the side mirror.
- *Action 4*: The operator presses the center-button to start spraying upward to the tall trees and confirms through the rear window glass.
- *Action 5*: After passing over the tall trees, the operator presses the center-button to stop the upward spraying and confirms through the rear window glass.

(a) Action 1

(b) Action 2

(c) Action 3

(d) Action 4

(e) Action 5

Figure 8. The relationship between the vehicle and the tree for actions 1 through 5.

- *Action 6~9*: The operator performs actions 2~5 to spray a group of trees having similar characteristics.

The actions that occurred during the three-minute spraying task used in this experiment and the direction of the spraying are shown in Figure 7. The vehicle traveled straight at 3.6 km/h and there were few bumps in the path.

To reproduce the above nine actions in the simulator, the operator is given voice guidance. In addition, the buttons in the simulator are virtual. Hence the operator is required to practice pressing the buttons properly while driving the vehicle.

Ten subjects aged between 22 to 26 participated in the spraying experiment on a simulator. These subjects were familiar with operating content in VR or Mixed-Reality (MR) environments. Before starting the experiment, each subject was asked to practice a set of operations twice in about 10

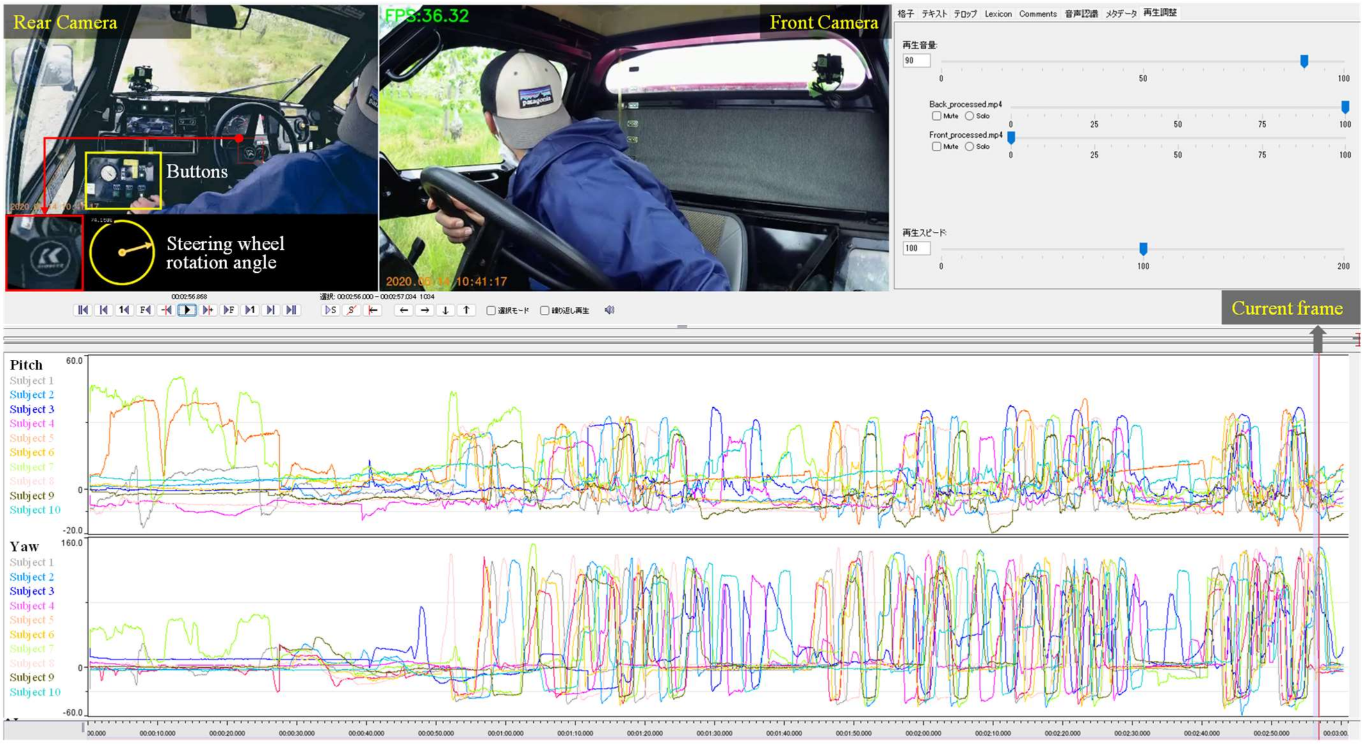


Figure 9. Three-minute of operator behavior data integrated into ELAN.

minutes. However, since this experiment was intended to check how the operator would behave when performing all the operations, we did not require the operator to perform all the operations up to the exact timings. Figure 8 shows images of the relationship between the vehicle and the tree for actions 1 through 5. The first action is to approach a parked speed sprayer to a tree and start spraying. The approach is left up to each subject. The images of actions 2 and 3 show that the trees are lined up about twice as far apart as the length of the vehicle. Finally, the images from actions 4 and 5 show the vehicles before and after passing through a tall tree.

Data as shown in Table I was recorded from the simulator. Since the simulator can be played back using this data, the behavior can be confirmed in detail in the post-experimental analysis. This data was integrated into the EUDICO Linguistic Annotator (ELAN) [22] as time-series data, and the attribute information of the actions were also recorded as annotation labels. Likewise, in the actual speed sprayer, the operator's head posture, hand landmarks, and steering wheel rotation angles were measured from the video taken from the front and rear cameras in the cockpit and integrated into the ELAN. Figure 9 shows the pitch and yaw angles of the heads of ten subjects measured from the simulator during the same three-minute simulation apart from the actual speed sprayer operation. In this way, the operator's behavior data and the videos can be synchronized and displayed.

A. Steering wheel rotation angle

The rotation angle of the steering wheel in action 1 is shown in Figure 10. Overall, the trend of the subject's steering wheel rotation angle is the same as that of the actual speed spray operator, which show large variations in their steering wheel rotation angles. Since the approach steps were not specified in this experiment, some subjects went straight and then turned, while others turned and then went straight. After action 2, there was no significant variation in the steering wheel angles because the vehicle's travel path was linear.

The speed sprayer used in this study is Four Wheel Steering (4WS), while the simulator vehicle used in this study is Two Wheel Steering (2WS), which resulted in differences in driving operation. We intend to analyze the effect of this difference as a simulator for training speed sprayer operation.

B. Characteristics of button operations

As described earlier, there are three operating buttons for spraying pesticides. We attempted to analyze the differences in gestures when operating the buttons by detecting both the operator's hand landmarks in the simulator and in the actual speed spray. However, we found that the operators of the simulator behaved in a fundamentally different way, as they operated the virtual buttons in the air while the actual speed sprayer operators placed their hands on the button platforms.

To observe the differences in button operations, we focus on the head movements. In both the simulator and the actual vehicle, the operator faces in the direction of the button to be operated, hence we analyzed their head movements. Figure 11 shows the operators' head movements in action 9. From this figure, we found that the trend of yaw and pitch angles of the head during button operation are similar even when in different environments.

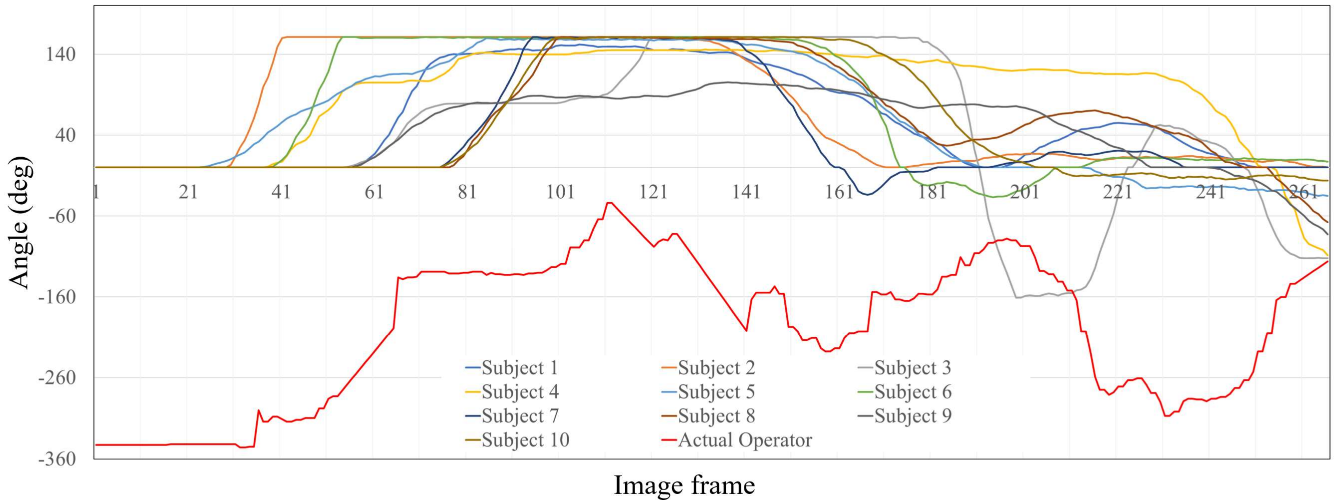
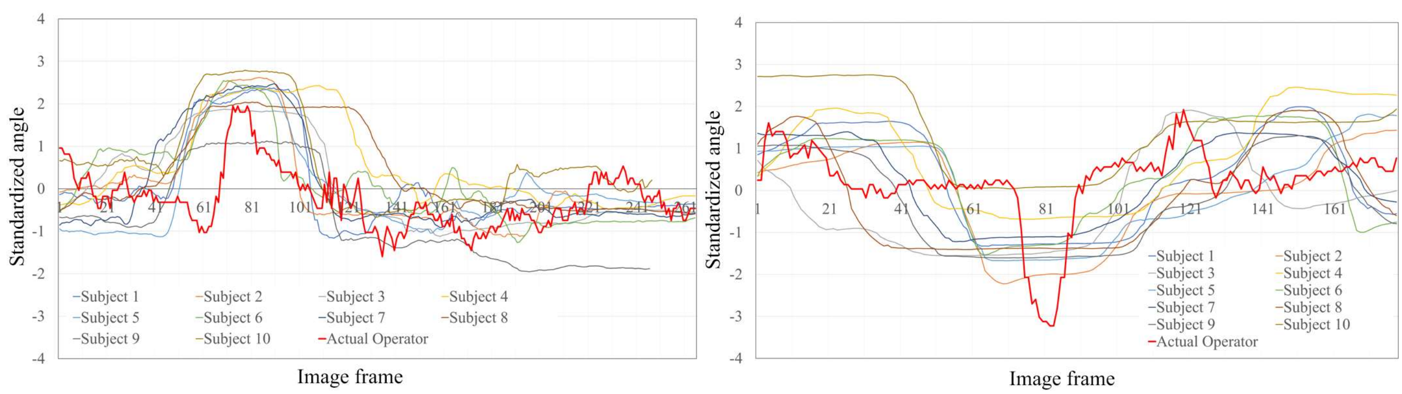


Figure 10. The rotation angle of the steering wheel in action 1.



(a) Pitch angle

(b) Yaw angle

Figure 11. Operators' head movements in action 9.

There was no precise instruction for the button operation timing in this experiment, resulting in a difference in the timing of the button operation among the subjects. For example, the button to stop spraying must be pressed when the vehicle passes the end point of a group of trees, but the subject's judgment of the relative position of the rear-mounted sprayer to the trees causes the button to be pressed at different timings. These situations appear as differences in the variation of the yaw angle of the head, as shown in Figure 12. A positive yaw angle indicates that the subject is checking the relative position of the trees and the sprayer through the window, while a negative yaw angle indicates that the subject is checking the position of the button. The solid and dotted lines indicate subjects who pressed the button early (Group I) and late (Group II), respectively.

V. Conclusion

In this study, we have developed a speed sprayer simulator and analyzed the differences in driving between the actual speed sprayer and the simulator vehicle. From the video footage of the pesticide spraying in the apple orchard, we were able to analyze the operator's speed spray operation characteristics and reproduce each of them on the simulator.

Button operations in the VR simulator were significantly different from those in the actual vehicle. However, we were able to see the characteristics of the button operations from the head movements because the face was always turned in the direction of the button before the button operation in our experiment.

In developing the simulator, we also measured the steering wheel rotation and automatically detected the operator's behavior by image processing. In the future, we plan to improve the simulator by adding a function to measure the amount and percentage of pesticides wasted by the simulator operator and by integrating the control buttons into the steering wheel to reduce head movements.

Acknowledgment

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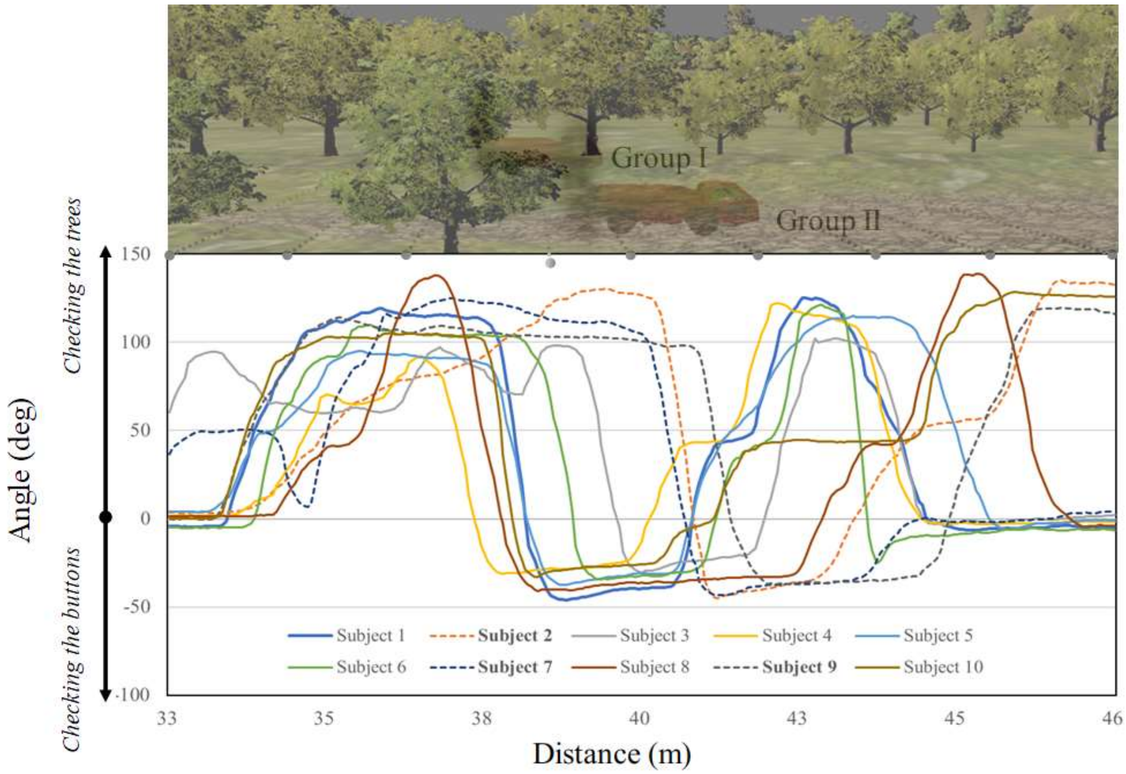

Figure 12. Variation in the yaw angle of the head, which resembles a difference in the timing of button operation. The solid and dotted lines indicate subjects who pressed the button early (Group I) and late (Group II), respectively.

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