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Development of Autonomous Sprayer Considering Tracking Performance on Geometrical Complexity of Ground in Greenhouse

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Abstract

Purpose: Some of the most representative approaches are to apply next generation technologies to save energy consumption, fully automated control system to appropriately maintain environmental conditions, and autonomous assistance system to reduce labor load and ensure operator's safety. Nevertheless, improvement of upcoming method for soil cultured greenhouse has not been sufficiently achieved. Geometrical complexity of ground in protected crop cultivation might be one of the most dominant factors in design of autonomous vehicle. While there is a practical solution fairly enough to promise an accurate travelling, such as autonomous sprayer guided by rail or induction coil, for various reasons including the limitation of producer's budget, the previously developed sprayer has not been widely distributed to market. **Methods:** In this study, we developed an autonomous sprayer considering travelling performance on geometrical complexity of ground in soil cultured greenhouse. To maintain a stable travelling and to acquire a real time feedback, common wire with 80 mm thick and body frame and sprayer boom. To evaluate performance of the prototype, tracking performance, climbing performance and spraying boom's uniform leveling performance were individually evaluated by corresponding experimental tests. **Results:** The autonomous guidance system was proved to be sufficiently suitable for accurate linear traveling with RMS as lower than approximately 10 cm from designated path. Also the prototype could climb 10° of ground's slope angle with 40 kg of water weight. Uniform leveling of spraying boom was successfully performed within 0.5° of sprayer boom's slope. **Conclusions:** Considering more complex pathways and coarse ground conditions, evaluations and improvements of the prototype should be performed for promising reliability to commercialization.

Keywords: Autonomous, Control system, Greenhouse, Soil cultured, Sprayer, Tracking performance

Introduction

There has been a remarkable growth in application and commercial products related with protected crop cultivation systems such as greenhouse and plant factory due to both climate changes and demand on profitability. Generally, protected crop cultivation has advantages in maintaining environmental conditions, such as temperature, humidity, composition of ambient air and solar radiation, to the optimum level determined by producers. Also, perennial crops could provide better profitability due to qualities of being independent on weather conditions in completely sealed facilities. One of the hardest and challenging processes is chemical practices by manual operation. Shin et al. (2004) proposed that a rest area should be located in the middle of greenhouse and ventilation is absolutely required to protect operator's safety from sudden accidental circumstances. Also, the minimum requirement in the size of inner volume of greenhouse was recommended. Both of hazardous chemical and exhaust gas from internal combustion engine during various pro-

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cesses in facilities should be properly managed to avoid various possibility of accidents. Jang and Lee (1991) proposed a remote access control method to operate a speed sprayer on behalf of manual chemical practices.

One of the common methods in development of autonomous vehicle guidance system for greenhouse was to use an induction coil on the ground and corresponding detector in a vehicle (Jang et al., 1995; Jang et al., 1998). Including high cost for initial installation, noisy signal caused by soil water content in near of induction coil was not ignorable in considering innovation from traditional greenhouse. Even though an autonomous vehicle guidance method using rail or coil installed beneath the sealing or on the bottom is one of promising solution to provide safety in chemical practices, most of traditional producers with soil cultured greenhouse have a problem with applying that for various reasons. One of the reasons might be caused by an additional expense for initial installation of additional structure. Another reason is lack of proper place for the installation due to elevated density of crop. Most of autonomous sprayer were operated in only glass structured greenhouse (Um et al., 2007), because the structure was originally designated to utilization of automated chemical practices. Singh et al. (2005) developed a six wheeled autonomous sprayer for soil cultured greenhouse using ultrasonic sensor to measure width of furrow, and fuzzy logic controller to guide vehicle's tracking between furrows.

In this study, new prototype of autonomous sprayer was designed considering geometrical complexity on ground in soil cultured greenhouse. Ultrasonic sensors were used to determine proper travelling direction between ridges and furrows. The prototype was developed considering travelling performance, climbing performance and sprayer boom's uniform leveling performance, and experiments were carried out to evaluate the performances.

Materials and Methods

Review of soil cultured greenhouse

In general, there are two types (i.e. nutrient and soil cultured) of cultivation in protected crop facilities. It depends on use of soil for cultivation. In nutrient cultured cultivation, growing bed is used for planting and more productivity could be expected due to both manipulation of nutrient composition according to growing season and avoiding undesirable conditions caused by various exchange between soil and plants. While there are many outperforming behaviors in nutrient cultured cultivation, a relatively high cost for initial installation of additional facilities is one of the reasons why most of producer could not apply the cultivation method to their greenhouse. Because nutrient cultured cultivation doesn't take soil as a growing bed, a relatively simple and flatted shape of ground could be considered in design of autonomous sprayer. In case of soil cultured cultivation, soil plays a role as both growing bed and nutrient supplier. While soil cultured cultivation could not supply nutrient and water to plants as effective as nutrient cultured cultivation, a relatively low cost for initial installation of additional structures provides higher priority in producers' choice. There are various geometrical shapes of ground in soil cultured greenhouse according to type of plant, density of plant and irrigation method.

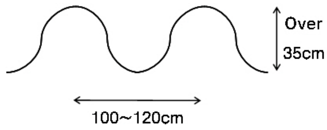
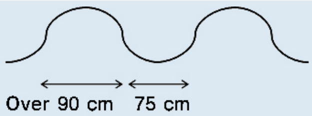
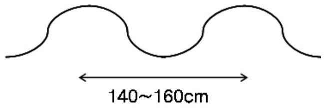
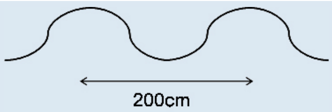
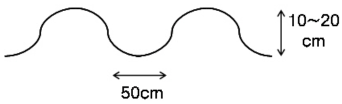
The major reason why it is hard to arrange various geometrical shapes to standardized formations is that soil cultivation depends on the expert knowledge from producer's experience about both preparation of the soil and type of plants. Thus, we summarized soil cultivation forms according to representative plants as listed in table 1.

To maximize yield, the width of furrow varies from 100 mm to 300 mm according to fully grown size of plant. Considering that the width is too narrow for sprayer's tracking, an appropriate vehicle width of sprayer should be larger than two times of the width of furrow. Also the vehicle width could be flexible to provide a stable tracking between furrows. By given fact that the highest height of plants for strawberry was 500 mm, the minimum ground clearance height of sprayer's bottom was determined as 600 mm.

Design of prototype

The major factor in design of sprayer for soil cultured cultivation is ground clearance height of frame's bottom. As previously described, the minimum ground clearance height of sprayer's bottom was determined by 600 mm. Considering probability in wheel sinking into pathway, the height was determined larger than 715 mm as shown in Figure 1(a). Rubber lug wheel with thick rim was chosen to provide more thrust power to the prototype. Radius of tire and tire width were determined as 300 mm and 60 mm, respectively. Other specifications for the prototype are listed in Table 2.

Table 1. Soil cultivation forms for representative greenhouse products

Plants	Cultivation formation	Features
Strawberry		Deepen the furrow for dropping the strawberries to be protected.
Tomato		Curl the stems around the crop for more yield.
Cucumber		Because cucumbers grow high, the ridges are low.
Watermelon		The stems grow wide, so the ridges are also broad.
Flowers		Flowers grow less than 100 cm.

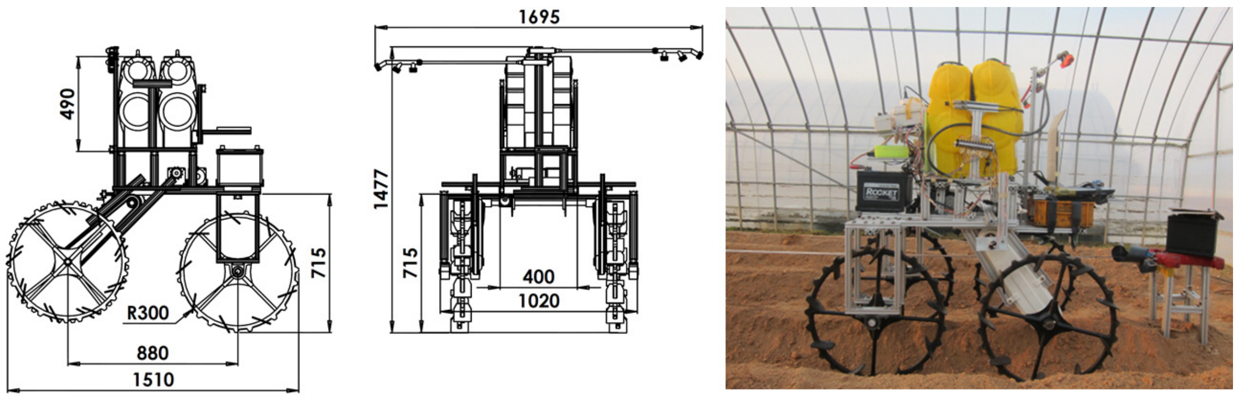


Figure 1. Frame design of the prototype for soil cultured cultivation and the prototype on preliminary experimental ground.

Table 2. Specifications of prototype for soil cultured cultivation

Division		Unit	Details
Body	Overall length	mm	1510
	Overall width	mm	1695
	Overall height	mm	1477
	Max weight	kg	130
Drive System	Drive type		4 wheel (2-wheel drive, rear wheel drive type)
	Max velocity	m/s	0.4
Electric System	Battery		12 V 60 Ah (2 EA)
	Motor		24 V 150 W (2 EA)
Spraying System	Spray type		Vertical horizontal
	Tank capacity	L	40

Total weight of the prototypes' frame was reduced using aluminum profile(NPE 0601-03, Namsun NPS, Korea) and bracket made by aluminum. A battery, a chemical tank and a control box were located above body frame, and driving motor was located beneath body frame. Bearings, shafts and chain were assembled for power transmission.

For spraying boom's uniform leveling performance, a tilt sensor (PIP30, Midotech, Korea) was mounted into the prototype's body frame to measure a tilt of that. The tilt sensor is operated by 12 V DC and measured from -15 to +15 degree angle. Based on the measured tilt angle, a stepping motor (D606-30A, DawHaw, Korea) was controlled to horizontally maintain a level of spraying boom.

Development of Autonomous Sprayer

Method of autonomous guidance

To minimize cost for additional installation for autonomous guidance system in soil cultured cultivation, a new method was developed using two ultrasonic sensors and normal wire. A width of wire was determined as 80 mm to be surely detected by ultrasonic sensor in the preliminary experiments. Two ultrasonic sensors were located beneath body frame of sprayer and detect a distance from the guide wire as shown in Figure 2(a). Among two types (steering wheel and skid steering) of steering method, steering wheel is more common method due to continuous steering and less power requirements. As previously mentioned, elevated density of plants decreases area of unplanted spaces including both ends of furrow could provide appropriate place for a sprayer to turn. Thus, skid steering method was chosen for the prototype because it requires much less space to turn than steering wheel method. In order to minimize space to turn and precisely control steering, two dc motors operated by electrical level were chosen and installed beneath body frame (Fig. 2(b)).

To track a guide wire with 8 mm of width, two ultrasonic sensors were installed beneath of the body frame toward downside. The sensors were continuously scanning the downside of body frame and identifying an approximate offset location of the guide wire from the center of the prototype. Corresponding to this information, PWM method was applied to change the speed of driving motor. Duty cycle of DC power source was manipulated to maintain the center of prototype over the guide wire.

Calibration of ultrasonic sensor

Ultrasonic sensor (P43-T4Y-2D-1C0-130E, PIL Sensoren GmbH, Germany) was used to measure a distance of the guide wire from the bottom of the prototype. The specification of this sensor is shown in Table 3. An operating voltage of this circuit is from 24 V DC, and an operating frequency may be available in a wide band, up to 130 kHz. To calibrate the ultrasonic sensor, a simulated target has

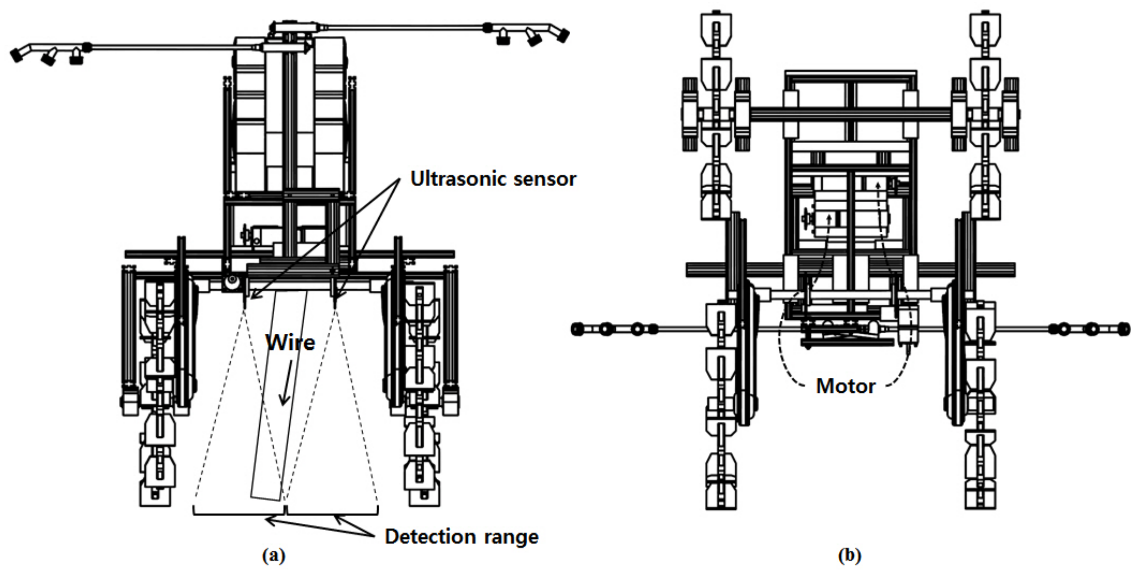
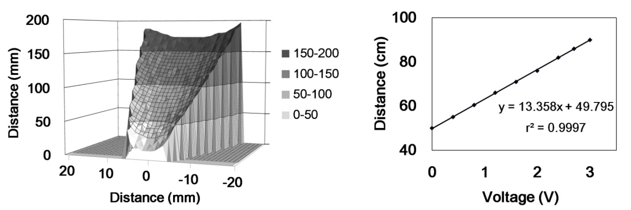


Figure 2. (a) Illustration of the autonomous guidance method using ultrasonic sensors and a guide wire. (b) Top view of illustration for a skid steering method using DC motor.

Table 3. Specifications of ultrasonic sensor used for prototype

Division	Unit	Details
Max. sensing distance	mm	3500
Min. sensing distance	mm	300
Beam angle	°	8
Voltage output	V	0-10
Resolution	mm	1
Response time	msec	400
Linearity	%	<0.5
Temperature range	℃	-20~70
Dimensions	mm	M30 x 125



(a) (b)

Figure 3. (a) Surface plot of detected distance from a target (100 x 100 mm^2) across vertical and horizontal distance (b) Calibration of ultrasonic sensor.

similar shape and dimension as the guide was used. From the calibration tests, the sensitivity and detection range of the ultrasonic sensor was identified as shown in Figure 3(a). From the regression analysis between voltage signal from the sensor and distance of a target (Fig. 3(b)), the ultrasonic sensor was proved to provide high accurate measuring performance. Based on the calibration function, a signal from the ultrasonic sensor played a role as an input parameter of the previously mentioned autonomous guidance system.

Method of spraying boom's uniform leveling

In case with soil cultured cultivation, there is a larger variance in ground's slope angle and it would be relatively hard for sprayer to maintain vehicle's stability through pathway and plants as shows in Figure 4. Two tilt sensors were installed in body frame and spraying boom to measure a sloped angle against geometrically horizontal level. By comparing two tilt angle measured from each part, a control system could operate a step motor installed for horizontal leveling of sprayer boom, which is commonly referred by "feed-back" control system.

Figure 4. Snapshot of the sprayer on highly tilted pathway and uniformly leveled spraying boom.

Implementation of control system

To implement control system for the prototype, driving control, steering control, uniform leveling of spraying boom and nozzle control should be considered together. Automatic or manual mode, forward or backward driving and one way or round way mode were implemented for driving control. A general control method for skid steering by separate turning on and off two motors was implemented for steering control. Basically, a horizontal uniform leveling of spraying boom was performed except the case of a designated tilt by operator. A potentiometer was used to measure the wheel speed of prototype by transforming wheel's rotation into linear displacement in transducer. An optical sensor(PZ-41,Keyence, Japan) was used to identify whether chemical content remains or not in the tank. The optical sensor is operated from 12 to 24 V DC and measured from 0.1 to 1.5 m. Every function in the control system was implemented to be able to provide automatic and manual mode to an operator. Figure 5 presents a schematic diagram of the implemented control system including definition of functions, type of sensors and electronic level according to actuators.

Methods of Performance Evaluation

Method of tracking performance evaluation

Autonomous tracking tests were performed at soil cultured ground. The developed tracking control system

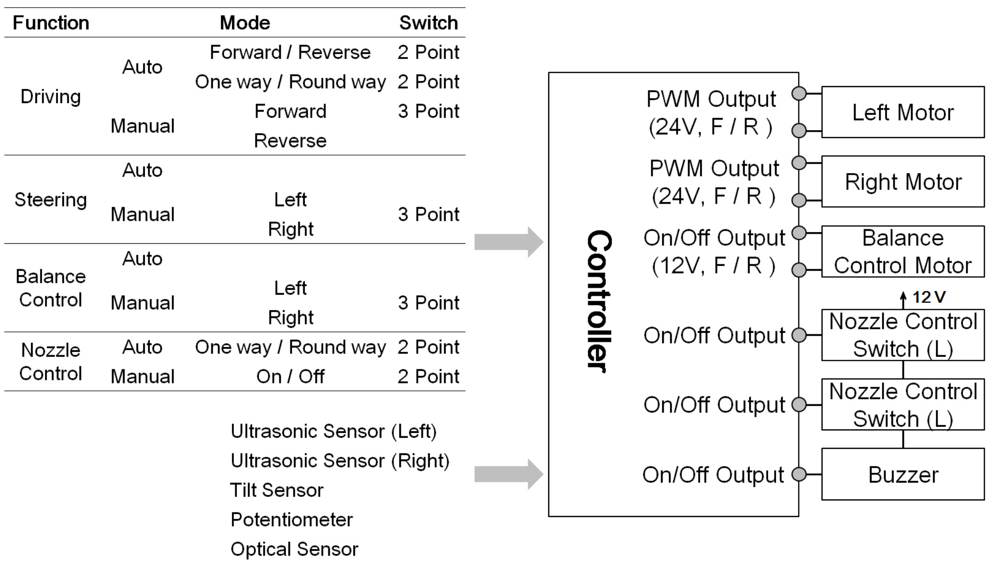


Figure 5. Schematic diagram of the implemented control system.

ideally drives the prototype as same direction and position as by guide wire. Nevertheless, regardless of accuracy in control system, the presence of undershoot or overshoot would be inevitable. Which means tracking errors from the guide wire frequently occurs somewhat more or less. Thus, to quantitatively evaluate the tracking performance of the prototype, the root mean square of error (RMSE) between measured and expected center of the vehicle was calculated using equation 1. Additionally, in order to quantify a slip between the prototype's wheel and soil cultured ground during travelling, slip rate was calculated using equation 2. The location for the test with prototype was one of soil cultured greenhouse located in Ibbook experimental fields at Suwon. Evaluation test with prototype was performed with 8 m distance of round way tracking, 40 kg of water weight, and 0.3 and 0.4 m/s of wheel speed.

$$\text{RMSE} = \sqrt{\sum_{i=1}^{N} \frac{(X_i - x_i)^2 + (Y_i - y_i)^2}{N}} \tag{1}$$

where,

i : observation index

(X_i, Y_i) : expected center position designated by guide wire at i observation

(x_i, y_i) : measured center position by potentiometer at i observation

N : total number of observation

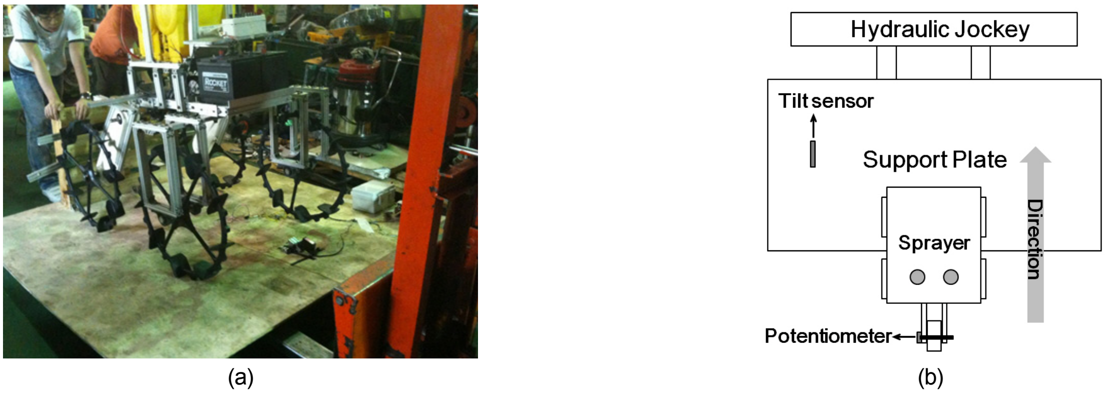
$$Slip\ rate\,(\%) = \left(1 - \frac{Actual\ velocity}{Theortical\ velocity}\right) \times 100 \tag{2}$$

Method of climbing performance evaluation

A climbing test was performed using a potentiometer and a tilt sensor, and wheel speed and tilt of prototype were measured, respectively. Test environment was consist of a support plate, a tilt sensor the tilt of the plate, a hydraulic jockey to change the tilt of plate, a limit switch to prevent overshooting in the tilt of plate. The climbing tests were performed with two experimental factors, i.e. tilt of plate and water weight in chemical tank. A slope angle of plate varied from 0° to 15° with 5° interval. A water weight in chemical tank varied from 0 kg to 40 kg with 20 kg interval. Measured factors were instant tilt and wheel speed of the prototype at the exact moment when slip occurs. Figure 6 shows method of performance evaluation by climbing test.

Method of uniform leveling performance evaluation

In order to elevate geometrical complexity of ground, holes with a slope angle by 6° were artificially prepared with 2 m interval across pathway. Additionally, tilt sensor was installed on spraying boom to compare tilts from body frame and spraying boom of the prototype. A tracking speed was 0.3 m/s during experiment to evaluate performance of uniform leveling of spraying boom. To obtain the measured tilt angle from each part, a data logger was



(a) (b)

Figure 6. Snapshot of performance evaluation by climbing test and experimental configuration.

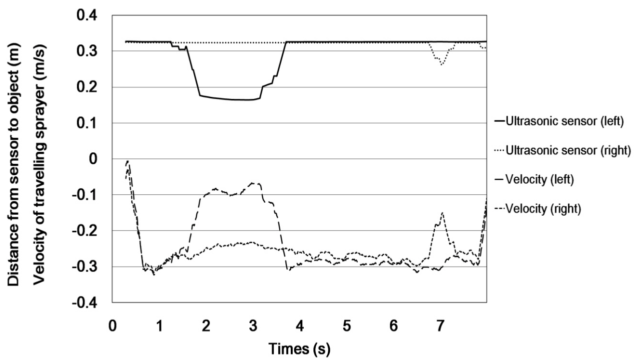


Figure 7. Resulted distance plot from ultrasonic sensors installed on body frame and velocity plot of tracking spraying.

connected between tilt sensors and a laptop computer.

Results and Discussion

Results from autonomous tracking tests

No critical outbound travelling might be resulted by accurate detection of the guide wire by ultrasonic sensors. Figure 7 shows one of possible explanation. A negative value in velocity of travelling sprayer indicates how an activated voltage level was lower than a referenced input level as 24 V. During 7 seconds of travelling, right ultrasonic sensor could clearly detect the guide wire in only two seconds (from 1.5 second to 3.5 second) and a right DC motor's duty cycle proportionally responded to input signal. In case with this outbound, RMSE was resulted greater than 10 cm. However, in most cases, autonomous tracking test s following the straight guide line showed an appropriate performance lower than 10 cm of RMSE. During 10 times experiments of autonomous tracking test, a mean value of RMSE was resulted in 10 cm with 2 cm of standard deviation. Additionally, considering a mean value of response time was identified short than 0.1 second, the developed autonomous control system could be suitable to the future development requires faster response characteristics. Table 4 shows results from autonomous tracking tests with both types of the prototype. Slip ratio was calculated using equation 1 with determined travel speed and actually measured speed as parameters. Greater slip ratio was obviously examined by faster travel speed. Slip ratio of the prototype was greater than that of the prototype as similar as the results from climbing test. Based on these results, we recommended that a proper travel speed with bad condition of ground would be lower than 80% of a design speed with normal condition of ground. In order to sustain slip ratio less than 10%, a travel speed for the prototypes should be same as or less than 0.3 m/s.

Table 4. Results from autonomous tracking tests

Travel speed	Actual speed	Slip ratio
0.30 m/s	0.27 m/s	10%
0.40 m/s	0.35 m/s	12.5%

Results from climbing test

Climbing tests with the prototype resulted that the performance of the prototype was greater than 15° with every case of experimental factors of water weight and slope angle. In case with prototype, a tracking speed with the given experimental factors, which are 0 kg of water weight and all cases of slope angle, was maintained with 0.18 m/s. However, the absence of the capability was found in the prototype for climbing with 20 kg and 40 kg of water weight and 15° slope angle of support plate as

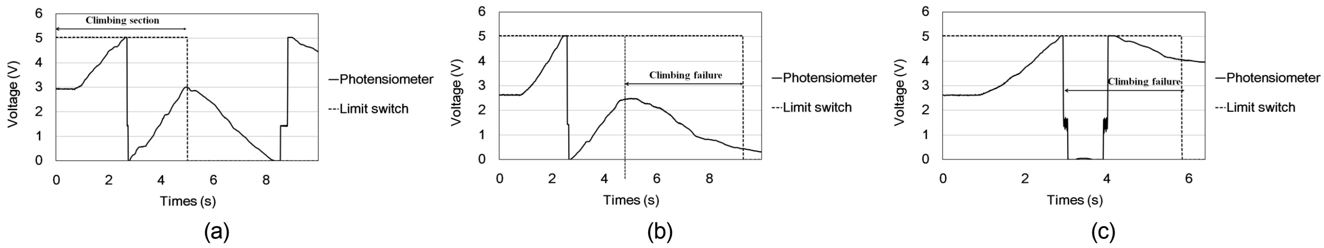


Figure 8. Resulted plots of electrical level from tilt sensor and limit switch for climbing test. Measured electric level from the prototype during climbing times (a) 0 kg of water weight and 15 degree of slope angle, (b) 20 kg of water weight and 12 degree of slope angle and (c) 40 kg of water weight and 12 degree of slope angle.

Table 5. Results from autonomous climbing tests at speed 0.18 m/s. (◯ and X means success and failure, respectively)

Water weight	Slope angle		
	5°	10°	15°
0 kg	◯	◯	◯
20 kg	◯	◯	X
40 kg	◯	◯	X

shown in table 5. Figure 8(b), (c) show resulted plots of electrical level from tilt sensor and limit switch of prototype with 20 kg and 40 kg of water weight as one of experimental factors. The black dotted line indicates 5 seconds that was the time when climbing failure occurs. Regarding relatively less friction coefficient of rubber lug wheel with thick rim, the evaluation test considerably showed a logical result of climbing failure. Considering more coarse ground condition than a plat in experimental test, there might be the possibility of greater climbing angle of the prototype.

Results from spraying boom's uniform leveling tests

Figure 9 shows result from an experiment to evaluate the performance of uniform leveling of spraying boom. The symmetry of measured slope angle was clearly examined between body frame and spraying boom of the prototype. This symmetry represents that uniform leveling of spraying boom was successfully performed, and the difference between absolute value of tilt angles could be useful to quantitatively evaluate the performance, which was less than 0.5°. Even though geometrical complexity of ground was elevated by manipulation as previously described, uniform leveling of spraying boom was satisfactorily accomplished by the developed control system.

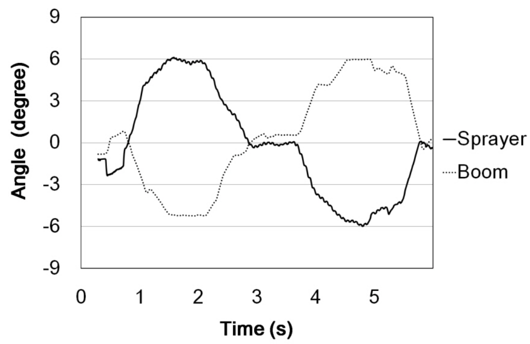


Figure 9. Resulted tilt plots from tilt sensor installed on body frame and spraying boom.

Conclusions

In this study, we developed the autonomous sprayer considering geometrical complexity of soil cultured cultivation in greenhouse. To minimize an initial installation cost for additional structure, a common wire was used instead of rail and induction coil. Various control components for driving control, steering control, uniform leveling of spraying boom and nozzle control were concurrently considered in the development of an integrated control system. The study summary is as follows:

(1) The prototype for soil cultured cultivation was developed. Radius of tire and tire width were determined as 300 mm and 60 mm, respectively. Wheelbase is flexible to be suitable for tracking on geometrically complex ground.

(2) Total weight of the prototypes' frame was reduced using profiles and bracket made by aluminum. A battery, a 40 L of chemical tank and a control box were located above body frame, and two driving motor and two ultrasonic sensors were located beneath body frame. A line tracer method for autonomous guidance was developed using 80 mm of wire width.

(3) Autonomous tracking tests following the straight guide line showed an appropriate performance as lower than 10 cm of RMSE.
(4) The prototype could not climb with 20 kg and 40 kg of water weight and 15° slope angle of the plate. Commonly in case of the prototypes, greater slip ratio was obviously examined by faster travel speed.
(5) Uniform leveling of spraying boom was successfully performed within 0.5° as a difference between body frame and spraying boom of the prototype.

Considering more complex pathways and coarse ground conditions, evaluations and improvements of the prototype should be performed for promising reliability to commercialization.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

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References

Singh, S., T. F. Burks and W. S. Lee. 2005. Autonomous robotic vehicle development for greenhouse spraying, American Society of Agricultural Engineers 48(6): 2355-2361.

Jang, I. J., T. H. Kim and M. D. Cho. 1995. Development of autonomous speed sprayer(I): Remote control and guidance cable system. Journal of Biosystems Engineering 20(3):226-235 (In Korean, with English abstract).

Jang, I. J., T. H. Kim and S. H. Um. 1998. Development of autonomous speed sprayer(II): Control algorithm for tracking direction using image processing method. Journal of Biosystems Engineering 23(3):291-304 (In Korean, with English abstract).

Jang, I. J. and K. M. Lee. 1991. Development of remote control speed sprayer(I): Development of prototype. Agricultural Resource of Kyungbook University (9): 11-20 (In Korean, with English abstract).

Shin, Y. S. 2004. Health management of operators in greenhouse. Suwon: Rural Development Administration (In Korean).

Um, Y. C. 2007. Current and future of the development of high-tech horticultural industry. Rural and Environmental Engineering Journal 96:123-140. (In Korean).