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Detection Method for Bean Cotyledon Locations under Vinyl Mulch Using Multiple Infrared Sensors

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Abstract

Purpose: Pulse crop damage due to wild birds is a serious problem, to the extent that the rate of damage during the period of time between seeding and the stage of cotyledon reaches 45.4% on average. This study investigated a method of fundamentally blocking birds from eating crops by conducting vinyl mulching after seeding and identifying the growing locations for beans to perform punching. **Methods:** Infrared (IR) sensors that could measure the temperature without contact were used to recognize the locations of soybean cotyledons below vinyl mulch. To expand the measurable range, 10 IR sensors were arranged in a linear array. A sliding mechanical device was used to reconstruct the two-dimensional spatial variance information of targets. Spatial interpolation was applied to the two-dimensional temperature distribution information measured in real time to improve the resolution of the bean coleoptile locations. The temperature distributions above the vinyl mulch for five species of soybeans over a period of six days from the appearance of the cotyledon stage were analyzed. **Results:** During the experimental period, cases where bean cotyledons did and did not come into contact with the bottom of the vinyl mulch were both observed, and depended on the degree of growth of the bean cotyledons. Although the locations of bean cotyledons could be estimated through temperature distribution analyses in cases where they came into contact with the bottom of the vinyl mulch, this estimation showed somewhat large errors according to the time that had passed after the cotyledon stage. The detection results were similar for similar types of crops. Thus, this method could be applied to crops with similar growth patterns. According to the results of 360 experiments that were conducted (five species of bean × six days × four speed levels × three repetitions), the location detection performance had an accuracy of 36.9%, and the range of location errors was 0-4.9 cm (RMSE = 3.1 cm). During a period of 3-5 days after the cotyledon stage, the location detection performance had an accuracy of 59% (RMSE = 3.9 cm). **Conclusions:** In the present study, to fundamentally solve the problem of damage to beans from birds in the early stage after seeding, a working method was proposed in which punching is carried out after seeding, thereby breaking away from the existing method in which seeding is carried out after punching. Methods for the accurate detection of soybean growing locations were studied to allow punching to promote the continuous growth of soybeans that had reached the cotyledon stage. Through experiments using multiple IR sensors and a sliding mechanical device, it was found that the locations of the crop could be partially identified 3-5 days after reaching the cotyledon stage regardless of the kind of pulse crop. It can be concluded that additional studies of robust detection methods considering environmental factors and factors for crop growth are necessary.

Keywords: IR sensor, Signal processing, Soybean, Spatial variance, Thermal response

Introduction

There has been an increase in the attention given to automation and labor saving in the cultivation of various kinds of field crops with relatively lower levels of mechanization compared to rice cultivation. In the case of pulse crops, the rate of mechanization is low because of the small farm sizes in South Korea, diversity in crops, and working methods, among which seeding/transplanting

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require efforts to save labor. In addition, pulse cultivating farms are suffering from the additional need to re-seed as a result of the damage caused by wild birds immediately after seeding. Pulse crop damage due to wild birds is a serious problem, to the extent that the rate of damage during the period between seeding and the cotyledon stage reaches 54% on average. Table 1 lists soybean seedling emergence rates according to the times of eating damage when seeds were treated with bird repellents after soybean seeding. In the case of eating damage by pigeons, the seedling emergence rate was the lowest when the eating damage occurred immediately after seeding, with a value of 36% compared to 65% for the cotyledon appearance stage and 79% for the cotyledon development stage. Thus, it can be seen that the eating damage caused by wild birds decreases from the time when the cotyledons begin to emerge. In the case of the untreated group, in which no bird damage prevention technology was used, the seedling emergence rate was 54.6% on average from the time of seeding to the cotyledon development stage, with a bird damage rate of 45.4%.

Although measures to prevent damage by birds are necessary from immediately after soybean seeding to the stage of cotyledon development, the various measures that have been attempted thus far have limitations. These measures have included tiger manure, scarecrows, and gunshots, but the birds' learning behavior could not be overcome.

In the present study, to minimize the damage by birds before and after the cotyledon stage and acquire the generally proven benefits (e.g., protection against weeds and maintenance of the soil's water content), a work system for performing vinyl mulching immediately after seeding was devised. In cases where vinyl mulching is carried out after seeding, although damage by birds can be fundamentally blocked, punching is essential for the proper growth of beans. When covered by vinyl mulch, the bean seeding locations cannot be determined by relying on information from the visible light range. In addition, because this determination should be linked with seeding, contactless methods that can continuously determine the locations are necessary.

Conventionally, contactless and nondestructive crop growth information measurements have mainly been studied using methods for detecting a crop's thermal response characteristics. Kim et al. (1999) advised that crop entity recognition should be achieved using contactless and nondestructive methods to prevent additional stress on the crop. This symptom might not be noticeable when observing a crop's responses because it is not severe. They recommended crop temperature analysis using thermal images as a method for the early detection of crop growth impairment. Ceccardi et al. (1995) performed a real-time analysis of the amount of crop temperature change in relation to the air temperature using infrared (IR) sensors and studied the response characteristics of crops in relation to atmospheric air conditions. Inoue (1986) investigated crop colony temperature distributions using thermal image acquisition devices, and the range of temperature variations for the crop colonies was shown to be no larger than 3°C. Using thermal image acquisition devices, Hashimoto et al. (1984) found that the temperature of sunflower leaves under water stress was approximately 3-5°C higher than that of sunflower leaves that were supplied with sufficient water. Blazquez (1989) analyzed the degree of health of peach trees using IR photo analysis and obtained results that were very similar to the health grade judgments of experts. Recently, methods have been studied that use information from the visible light range for weed recognition (Sogaard, 2005; Philipp and Rath, 2002) or methods that use color differences in the visible light range to determine whether diseases have occurred

Table 1. Soybean processing time by applying nap rate after seed treatment with bird repellents (Lim, 2006)

Time of treatment	Pheasant (2 peasants/50 m^2)			Pigeon (6 pigeons/50 m^2)			
	Untreated	Thiram	Average	Untreated	Thiram	Tiger excrements	Average
Immediately after seeding	10.4	33.8	22.1	10.6	84.9	12.1	35.9
Emergence stage	8.3	29.2	18.8	70.9	71.9	51.2	64.7
Cotyledon development stage	48.3	65.4	56.9	82.4	89.2	66.7	79.4
Average	22.3	42.8		54.6	82.0	43.3	60.0
L.S.D. (5%)	Whether treated with thiram: 9.97 Time of treatment: 12.21			Whether treated with thiram : 11.6 Time of treatment: 11.6			

(Camargo and Smith, 2009). These have led to studies to measure the growth rate of citrus trees using multispectral images (Fevaerts, 2001) or laser scanners and ultrasonic sensors in combination (Tumboet et al., 2002).

However, studies to estimate the growth information of crops covered by obstacles such as vinyl mulch using visible information have very rarely been attempted. In particular, it can be said that studies using such methods in the field in real time have never been reported.

Therefore, in the present study, a growing location detection method was studied that uses IR sensors to determine the growing locations of beans that have reached the cotyledon stage but cannot be visually identified because they are growing under vinyl mulch that has not been punched.

Materials and Methods

Crop preparation

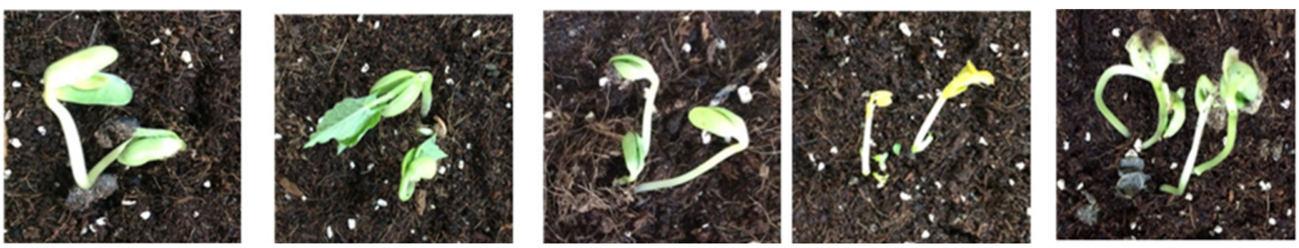
Among the various kinds of beans, kidney beans, black soybeans, peas, black turtle beans, and soybeans were selected to conduct experiments. Figure 1 shows beans in the cotyledon stage 6 days after seeding. Although their sizes and shapes are slightly different, the cotyledons are visually identifiable. Therefore, in the present study, experiments were conducted involving situations where the beans were covered by vinyl mulch when they had reached the visually identifiable level immediately after seeding, that is, when 6 days had passed after seeding.

To grow these crops, a total of five 60 cm × 22 cm × 17 cm plant pots were filled with seven 10 L bags of organic culture soil to maintain the same growth conditions.

Three cultivation experiments were conducted during (1) February 6-20, 2015; (2) March 25-April 5, 2015; and (3) April 9-16, 2015. To maintain the same cultivation environment, a small greenhouse was constructed, as shown in Figure 2(a). To determine the emergence time of the cotyledons, the cultivation environment was constructed so that the vinyl-mulched plant plots and general plant plots could be compared, as shown in Figure 2(b). As illustrated by the round dotted lines in Figure 2(b), the seeds were sown so that three seedlings would be evenly distributed in each pot.

Development of measurement system

A DTS-L300-V2 (Diwell Electronics Co., Ltd., South Korea) was used as a sensor module for detecting the locations of the beans in the cotyledon stage. The DTS-L300-V2 had a resolution of 0.01°C and a measurement



(a) (b) (c) (d) (e)

Figure 1. View of cotyledon stage of five different beans: (a) kidney beans, (b) black soybeans, (c) peas, (d) black turtle beans, and (e) soybeans.

(a) (b)

Figure 2. (a) Small green house cultivating chamber and (b) pots without (up) and with (down) vinyl mulch.

Table 2. Specifications of infrared sensor DTS-L300-V2

Item	Details
Distance ratio	15 : 1
Temperature measurement range (target temperature range)	-30-300°C
Operating temperature (ambient temperature)	-20-70°C
Temperature measuring time	0.5 s
Accuracy	±2%
Digital resolution	0.01°C
Standard starting time	3 s
Stabilizing time	1 min
Communication method	SPI communication

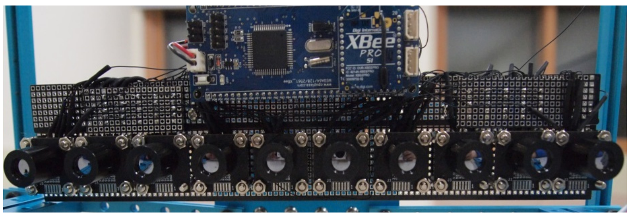


Figure 3. Bottom view of multiple IR sensor array.

cycle of 2 Hz. It communicated with multiple sensors simultaneously using serial peripheral interface (SPI) communication, which is a type of digital communication. Table 2 lists the major specifications of the sensor used in the present study.

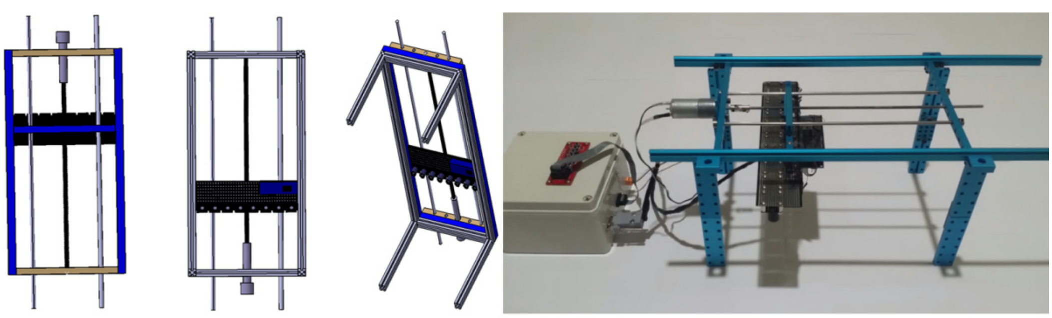
To measure temperatures at many points simultaneously to find the temperature distributions, a measuring system was constructed in the form of a linear array, as shown in the following figure, using multiple DTS-L300-V2 sensors. Each of the individual sensors could detect the representative thermal response of a 2 cm × 2 cm target area in a case where the distance from target was 30 cm. Thus, 10 units could reconstruct an area with a width of approximately 20 cm in a single scan distribution without instructional clearance between units.

A sliding mechanical device was designed, as shown in Figure 4(a), to move the sensors, which were arranged in the form of a 1D linear array, perpendicular to the array using a micro-controller (ATMEGA128, ATMEGA Inc., LTD, UK) integrated with a stepping motor (57BYG, Makeblock Inc., LTD., China), as shown in Figure 4(b). The experiments were conducted while adjusting the moving speed of the IR sensor array to four levels ((1) 2.77 cm/s, (2) 1.40 cm/s, (3) 0.90 cm/s, and (4) 0.70 cm/s) by adjusting the rotational speed of the stepping motor based on a digital pulse width modulation (PWM) signal from the micro-controller. These scan speeds resulted in 20, 40, 60, and 80 scan lines across a mulching length of approximately 55 ± 1 cm.

Data processing method

Two-dimensional temperature distributions could be obtained by moving the information obtained by the 1D array perpendicularly, as shown in Figure 5(a). The obtained data were reconstructed into a grid of spatial information, as shown in Figure 5(b), based on the distance between the sensors and the target and the speed of the sliding mechanical device, before the post processing was carried out. Because there was an insufficient amount of spatial information to represent the information for the actual spaces, depending on the size of each grid, the information was post-processed as shown in Figure 5(c) using two-dimensional spatial interpolation.

Linear interpolation, spline interpolation, and Kriging interpolation were considered for the post-processing of the spatial distribution. Linear interpolation is unable to find actual points with large deviations in areas other than those for the measured points. Although Kriging interpolation may be appropriate as an analysis method



(a) (b)

Figure 4. (a) Schematic design of sliding mechanical device and (b) prototype of implemented IR sensor array with sliding mechanical device.

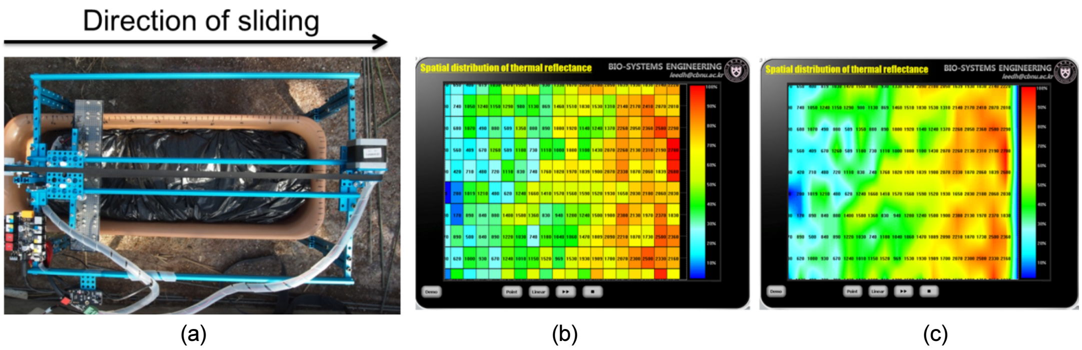


Figure 5. (a) Measuring method using implemented prototype of measurement system, (b) collected two-dimensional thermal distribution without post processing, and (c) post-processed two-dimensional thermal distribution.

for spatial variance, it has the shortcoming of rapid increases in the time required for processing, depending on the amount of information. Thus, it was judged to be inappropriate for real-time signal processing. Therefore, the collected data were first processed using spline interpolation to determine the locations of points where the variance was the largest or smallest in resolution units of 1 cm. In addition, among the various kinds of polynomial interpolation methods, the spline method is relatively faster than the others because it has a lower maximum order of formulation when using a system such as the tridiagonal linear equation system, which provided the capability of real-time processing of the measurement system in this study.

Results and Discussion

Results of detection by time after cotyledon stage

Daily detection results during the cotyledon stage could be obtained for the soybeans as an example. One day after the beginning of the cotyledon stage (March 29, 2015), in cases where the moving speed of the measuring system was 2.77 cm/s (Figure 6(a)), the soybeans located in the center could be identified with an error of 1 cm. In cases where the measuring system moved at a speed of 0.7 cm/s (Figure 6(d)), points could be found in the central region, but the judgment could not be verified. No noticeable information could be found in Figure 6(b) and (d). Nevertheless, there was no foreign object, which was verified after the experimental tests. The inevitable variation in the sensing points when using a resolution of 2 cm for each individual sensor might have led to inconsistent spatial distributions between the moving speeds.

Two days after the beginning of the cotyledon stage (March 30, 2015) (Figure 7), the growing locations of the plants located in the center could be identified with errors that did not exceed 2 cm, but the deviation values necessary for detection were relatively low at one speed (0.90 cm/s). Figure 7(a), (b), and (c) clearly shows the location of a plant in the center. As shown in Figure 7(c), the locations of plants to the left and right could be approximately identified by visual inspection. Meanwhile, although the plants located on the left/right did not show clear deviations compared to the center, their deviations were at the level necessary to identify the locations, and when the average values were taken, the locations could be estimated with errors of around 4 cm.

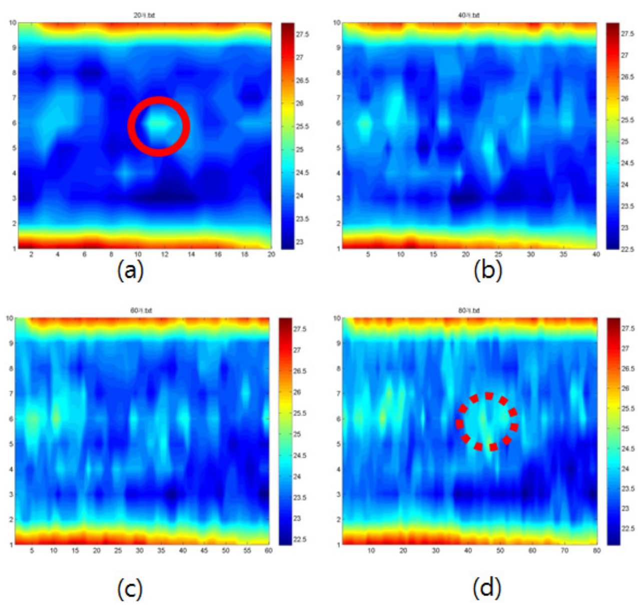


Figure 6. Temperature distributions of soybeans at different measuring speeds one day after beginning of cotyledon stage: (a) 2.77 cm/s, (b) 1.40 cm/s, (c) 0.90 cm/s, and (d) 0.70 cm/s.

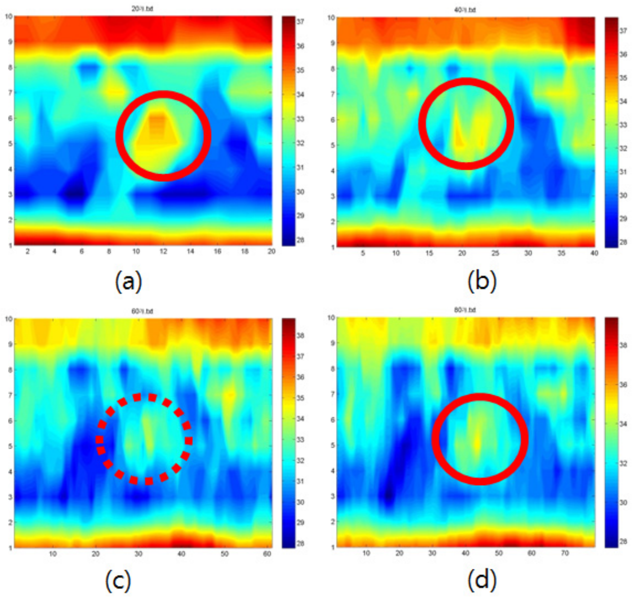


Figure 7. Temperature distributions of soybeans at different measuring speeds two days after beginning of cotyledon stage: (a) 2.77 cm/s, (b) 1.40 cm/s, (c) 0.90 cm/s, and (d) 0.70 cm/s.

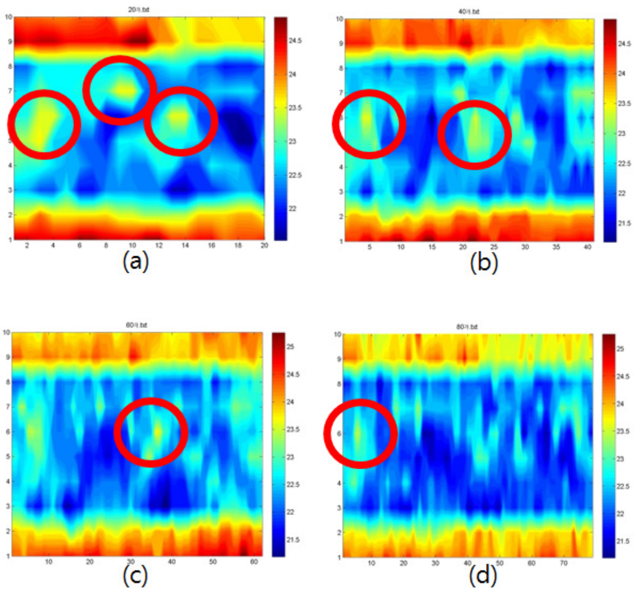


Figure 8. Temperature distributions of soybeans at different measuring speeds three days after beginning of cotyledon stage: (a) 2.77 cm/s, (b) 1.40 cm/s, (c) 0.90 cm/s, and (d) 0.70 cm/s.

Three days after the beginning of the cotyledon stage (March 31, 2015) (Figure 8), much noise was found at a low speed (0.7 cm/s), making it difficult to determine the growing locations. Figure 8(a) clearly shows the locations of three plants with noticeable errors. The relatively large noisy distribution around the assumed location found in Figure 8(c) and (d) leads to uncertainty in the determination across the entire scanning area.

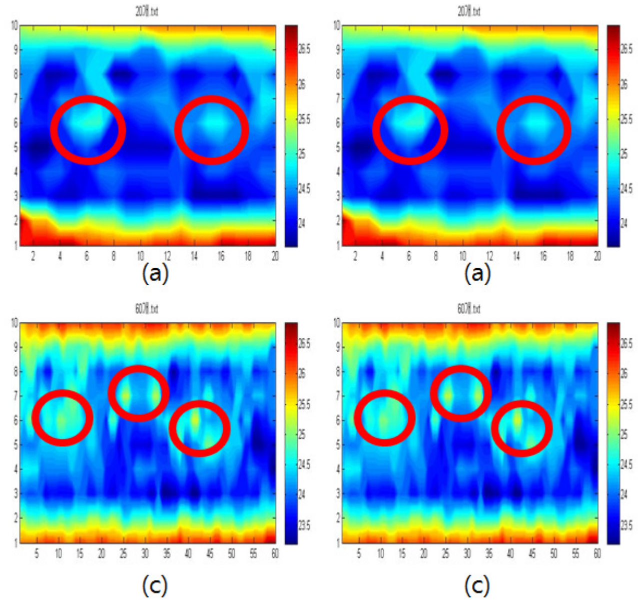


Figure 9. Temperature distributions of soybeans at different measuring speeds three days after beginning of cotyledon stage: (a) 2.77 cm/s, (b) 1.40 cm/s, (c) 0.90 cm/s, and (d) 0.70 cm/s.

Four days after the beginning of the cotyledon stage (April 1, 2015), the locations could be determined the most accurately in cases where the measuring speed was 1.4 cm/s (Figure 9(c)). In the case of the other measuring speeds, relatively large errors were found. The similar noise distribution in Figure 9(c) and (d) compared to Figure 8(c) and (d) shows that a more detailed analysis in relation to the scanning speed of the sensing module should be conducted considering the measurement principle of the sensor used, i.e., DTS-L300-V2.

To summarize the detection results for the different times after the beginning of the cotyledon stage, the location detection became more accurate and the number of omitted plants decreased over time. Meanwhile, noise that made it difficult to identify plant locations was commonly found when measuring at speeds not higher than 1.4 cm/s. Thus, it was determined that signal processing methods to respond to this noise are necessary.

Detection results by kind of pulse crop

A review of the detection results for beans growing below vinyl mulch showed that plants could commonly be detected three days after the beginning of the cotyledon stage. For instance, although there are some entities omitted in Figure 10, the locations of kidney beans at three points, soybeans at two points, black turtle beans at three points, peas at two points, and black soybeans at

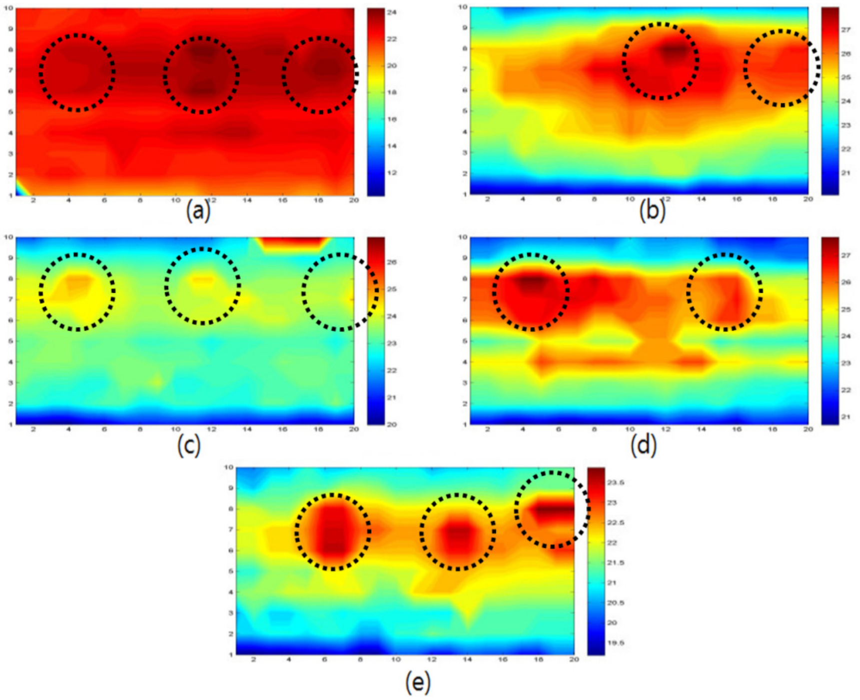


Figure 10. Temperature distributions above vinyl mulch three days after beginning of cotyledon stage: (a) kidney beans, (b) soybeans, (c) black turtle beans, (d) peas, and (e) black soybeans.

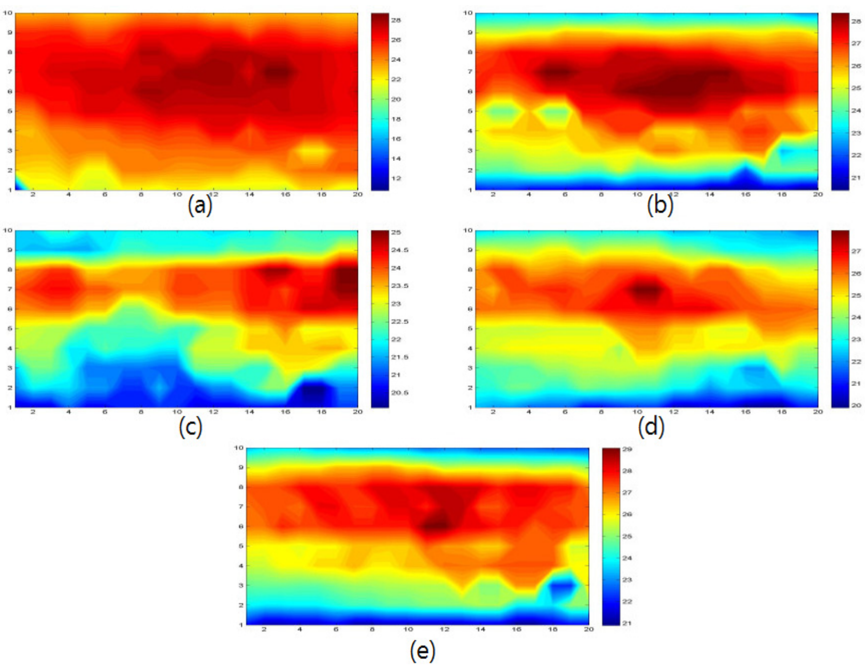


Figure 11. Temperature distributions above vinyl mulch five days after beginning of cotyledon stage: (a) kidney beans, (b) soybeans, (c) black turtle beans, (d) peas, and (e) black soybeans.

three points could be detected, with errors in a range of 2-6 cm, depending on the kind of crop.

As shown in Figure 11, 5 days after the beginning of the cotyledon stage, because of the cotyledon growth, points that show clear deviations cannot be sufficiently determined to identify locations.

Consequently, it can be concluded that, although growing locations below vinyl mulch can be detected regardless of the kind of pulse crop, the growing locations cannot be detected if the appropriate time is missed. This is because as cotyledons grow, the area of contact between the spread cotyledons and vinyl mulch increases, which prevents the information necessary to specify the sown points from being determined.

Detection of soybean seeding locations below vinyl mulch

Experiments to detect the growing locations for beans below vinyl mulch were conducted using five species of beans for six days after the beginning of the cotyledon stage at four speed levels, and the results obtained through a total of three repetitive experiments are summarized in Table 3.

The location detection performance calculated based on the results over the entire period after the beginning of the cotyledon stage had an accuracy of 36.9%, and the range of location errors was 0-4.9 cm (RMSE = 3.1 cm). The point immediately after the beginning of the cotyledon stage was found to have a low detection performance in the range of 8-11% because the amount of cotyledon growth was insufficient, and no contact area appeared between the cotyledons and the vinyl mulch. In addition, the detection performance could be regarded to have declined (26%) 6 days after the beginning of the cotyledon stage because the spread contact surface increased as the cotyledons grew. Thus, the distances between the seeding points and points that showed the largest deviations increased. Therefore, a review of the period from 3 days to 5 days after the beginning of the cotyledon stage, separately excluding the 1st, 2nd, and 6th days based on the growth characteristics of the soybean cotyledons, showed that the detection performance was relatively improved because an average detection accuracy (RMSE = 3.9 cm) of 59% was shown. In particular, the point when four days had passed after the beginning of the cotyledon stage showed the highest detection performance, with a detection accuracy (RMSE = 4.1 cm) of 80%. These results can be explained based on the detection principle of the measuring system developed in the present study. When cotyledons grow and come into contact with the bottom of the vinyl mulch, the thermal transfer characteristics of the contact points will become different from points where no contact occurs. Therefore, when cotyledons come into contact with the vinyl mulch in appropriate

Table 3. Summarized results from three experimental tests

Take	Crop	Elapsed period from cotyledon stage of bean											
		1 day		2 days		3 days		4 days		5 days		6 days	
		Detect[a)]	Error[b)]	Detect	Error	Detect	Error	Detect	Error	Detect	Error	Detect	Error
1	kidney beans	2	1.2	2	1.4	6	3.9	9	4.4	8	4.9	3	2.6
	soybeans	1	2.2	1	2.5	7	3.7	11	3.2	5	4.4	2	2.1
	black turtle beans	1	1.3	1	1.8	5	4.3	8	4.6	6	4.3	3	3.3
	peas	0	NA	1	2.1	6	4.9	10	4.7	4	3.0	3	4.2
	black soybeans	1	2.1	1	2.5	7	3.8	9	4.3	6	4.4	2	2.2
2	kidney beans	1	2.9	1	3.3	5	3.6	10	4.1	7	4.1	3	2.0
	soybeans	0	NA	1	3.2	6	3.6	10	4.1	5	4.9	1	3.0
	black turtle beans	1	2.5	2	3.9	7	4.0	11	3.9	4	2.2	1	2.2
	peas	1	3.2	1	3.3	5	3.6	10	4.7	5	2.2	5	3.8
	black soybeans	1	2.6	1	2.7	6	3.6	11	3.5	8	3.0	5	2.3
3	kidney beans	2	2.5	2	3.2	4	3.8	8	4.5	7	4.0	4	2.9
	soybeans	1	1.9	1	2.5	5	4.7	10	3.5	6	4.2	3	2.7
	black turtle beans	1	2.5	2	2.4	7	4.0	8	3.5	5	4.7	4	2.4
	peas	1	1.3	1	1.4	3	4.8	8	3.2	6	2.4	4	4.8
	black soybeans	1	1.2	2	1.8	6	3.8	11	4.6	5	3.3	5	3.4
	Mean	1		1		6		10		6		3	
	RMSE[c)]		2.1		2.5		4.0		4.1		3.7		2.9
	Hit ratio	8%		11%		47%		80%		48%		26%	

[a)]Detected count from 12 cases derived by multiplying scanning speed (4 steps) by individual seed (3 crops)
[b), c)]Unit is cm

areas (e.g., four days after the beginning of the cotyledon stage), temperature changes will be observed at clearly identifiable points. In contrast, when the growth of the cotyledons is insufficient (at the beginning of the cotyledon stage) or when the amount of growth increases so that the area of contact is excessively large (late stage of cotyledons), the detection of the seeded locations is relatively difficult.

Conclusions

In the present study, to fundamentally solve the problem of damage caused by birds to beans in the early stage after seeding, a working method was proposed in which punching is carried out after seeding, thereby breaking away from the existing method in which seeding is carried out after punching. Methods for the accurate detection of soybean growing locations were studied to perform punching to promote the continuous growth of soybeans that had reached the cotyledon stage. A method was used based on the principle that the thermal transfer characteristics of vinyl mulch surfaces will change when soybean cotyledons come into contact with the bottom of the vinyl mulch, which will lead to changes in the temperature distribution at the top of the vinyl mulch. To implement this principle, a measuring system was developed using multiple IR sensors and a sliding mechanical device. Through repetitive factor experiments conducted under identical environmental conditions, it was found that crop locations could be partially identified under certain conditions after the beginning of the cotyledon stage regardless of the type of pulse crop. A relatively good detection performance was shown three to five days after the beginning of the cotyledon stage. In particular, four to five days after the beginning of the cotyledon stage, a detection performance of approximately 80% was obtained. However, this performance might be insufficient for the introduction of the system into the field of soybean cultivation. In particular, to introduce the system into the field of soybean cultivation, the amount of insolation, temperature, and rainfall with the largest effects on the heat transfer characteristics of the top of vinyl mulch should be carefully considered. Therefore, based on the results of this study on the detection characteristics for soybeans in the cotyledon stage, futures studies on robust detection methods that also consider environmental factors are necessary. A study on a robust segmentation method for the spatial variations derived from concurrent and simultaneous acquisition devices could be attempted using faster preprocessing and proper post processing methods to consider objects in both the spatial and frequency domains.

Conflict of Interest

The authors have no conflicting financial or other interests.

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