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Novel attitude control of Korean cabbage harvester using backstepping control

Yonghyun Park[1,2] · Hyuck-Joo Kim[3] · Hyoung Il Son[1,2]

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Abstract
This study proposes a backstepping control-based attitude control system for cutting devices to improve the performance of Korean cabbage harvesters. If the Korean cabbage is not cut at an optimal cutting position, the quality of the cabbage deteriorates because of head damage. However, attitude control of the harvester body has limitations in maintaining an optimal cutting position. In this study, a mechanism was designed to independently control cutting devices depending on the variety of crops during harvesting. However, the environment of Korean cabbage fields is irregular and nonlinear, making it difficult to predict the gradient changes. Therefore, a backstepping nonlinear control method was used to reduce the load on the hydraulic system caused by the dynamic characteristics of the harvester. A field test was conducted on a Korean cabbage field to validate the proposed controller. A total of 60 heads were harvested for the experiment, and a score was calculated to evaluate the cabbage cutting surface quantitatively. The proposed method yielded a cutting performance of 86.6%. The attitude maintenance performance was validated by measuring the change in attitude during harvesting. The root mean square errors (RMSEs) of the pitch angle and cutting height position were 0.73° and 11.20 mm and the mean absolute errors (MAEs) were 0.53° and 8.97 mm. The results confirmed that the cutting angle and height were maintained within ± 2° and ± 25 mm. The proposed backstepping-based attitude control system enabled accurate harvesting of Korean cabbage, which is expected to improve the harvest success rate.

Keywords Attitude control · Automatic cabbage harvesting · Backstepping control · Korean cabbage harvester · Nonlinear control

Introduction

Korean cabbage (*Brassica rapa* L. ssp. Pekinensis) cultivation has been decreasing because of a labor shortage caused by a decrease in the agricultural worker population in rural areas and the aging of the population. The labor shortage is even more pronounced among cabbage growers because the domestic cabbage cultivation process can only be conducted

✉ Hyoung Il Son
hison@jnu.ac.kr

Extended author information available on the last page of the article

manually by five to six humans. However, machine development for Korean cabbage cultivation is insufficient and the mechanization rate is meager, especially in harvest work, which requires the most labor (Yu et al., 2015). Therefore, it is essential to develop a cabbage harvester to reduce labor requirements.

Research on precision agriculture and labor force problems is being conducted to increase the efficiency of agricultural work and minimize labor by considering spatio-temporal variability and uncertainty within the agricultural system (Kim et al., 2020). This approach improves quality and efficiency by combining sensors, information systems, machines and information management, such as in autonomous agricultural vehicles or robots (Lowenberg-DeBoer et al., 2020). Research on autonomous agricultural vehicles is being conducted to improve the accuracy of side positioning required for control (Zhang et al., 2021).

Several researchers have developed Korean cabbage harvesters to increase the mechanization rate (Song et al., 2000). These include a walking-type structure in which people can walk around and steer the harvester (El Didamony & El Shal, 2020), a tractor-attached type in which a cutting device is installed on the side of the tractor for harvesting (Ali et al., 2019; Lee et al., 2020; Reza et al., 2021) and a crawler combine type for harvesting (Ali et al., 2021; Hachiya et al., 2004). In most cases, a single-row harvester has been developed that cuts and transfers crops individually. However, during harvesting, the cutting position varies depending on the variety of crops and cutting beyond the desired range damages the crop. Effects such as a lack of cutting, excessive cutting and breaking of cutting have been reported (Du et al., 2016, 2019). Inaccurate root cutting occurs when the attitude of the cutting blade, reaching the Korean cabbage, is incorrect (Cao & Miao, 2020)—a significant cause of difficulties in harvester development.

The Korean cabbage is not easy to cut because of its unique structure. The cabbage, a head-leafy vegetable similar to Korean cabbage, is relatively easy to cut because its stem and root are located outside the head (Cui et al., 2019). In contrast, the stems and roots of Korean cabbages are located inside their heads—if they are cut above a certain height, their quality deteriorates because of head damage. Therefore, Korean cabbage harvesters should be able to accurately cut within the optimal cutting area range through attitude control based on crop characteristics.

Research on attitude-control systems has been actively pursued to mitigate the risk of accidents and damage to crops (Kise & Zhang, 2006). A header height control system was developed for soybean harvests. This method analyzed the soil density of soybean growing plots and designed an adaptive header-height adjustment system using a linear fitting method (Ni et al., 2021). Another study improved the accuracy of navigation control using a correction method according to the attitude of implementation when a rice transplant was tilted (He et al., 2020). A method was developed to measure height using a scraper and laser sensor with water surface as the benchmark in paddy fields (Tang et al., 2018). Many studies have been conducted to stabilize unstable systems in response to weather variables (Kim et al., 2020; Michels et al., 2021). The crawler-type Korean cabbage harvester can control the attitude of the body using an adjustable lift (Sun et al., 2020a, 2020b) but has difficulty controlling the overall attitude of the cutting device. The tractor-mounted type is also complicated because it operates separately from the cutting device. Even if controlled, many trial-and-error attempts were required to achieve the desired cutting position through additional manipulation. Therefore, an attitude-control system that overcomes these limitations is required to solve this problem.

A recent study developed a mechanism to control the cutting devices of Korean cabbage harvesters (Park et al., 2021). The cutting position of the cabbage was maintained at a constant level to improve the harvesting success rate by attitude control of the cutting device using Kalman filter-based sensor fusion and proportional-integral-derivative (PID) control. Although the proposed PID control demonstrated improved performance, a more effective control algorithm is still required to overcome the nonlinearity of the harvester's hydraulic actuators. In a previous study (Park et al., 2021), Korean cabbage was planted on flat land and a test environment was created under the guise of a real-world cabbage field. Therefore, more field experiments must be conducted on real-world farmlands because their environments are irregular and unstructured. The mechanical specifications of the Korean cabbage harvester and its dynamic characteristics should also be considered in the control design.

This study proposes backstepping-based attitude control of a Korean cabbage harvester for accurate harvesting (Fig. 1). The proposed nonlinear backstepping controller was designed to operate the hydraulic cylinder of the attitude-control system. The objectives of this study were to (a) confirm the performance of the Korean cabbage harvester by applying the attitude control system of the cutting device, (b) confirm the performance of the backstepping control considering the dynamic characteristics of the attitude control system and (c) conduct field tests to determine whether it achieves the objectives stated in (a) and (b). This study hypothesized that the proposed attitude control system would perform similarly to the previous study even in a real-world, irregular cabbage field. Field experiments were conducted in real-world fields to confirm this hypothesis.

General Korean cabbage harvester

Structures

As shown in Fig. 2, the stems and roots of the cabbage are inside the head. Thus, cabbages should be cut within the optimal cutting height because the number of separated outer leaves depends on the cutting height, as shown in Fig. 3, which affects the size of

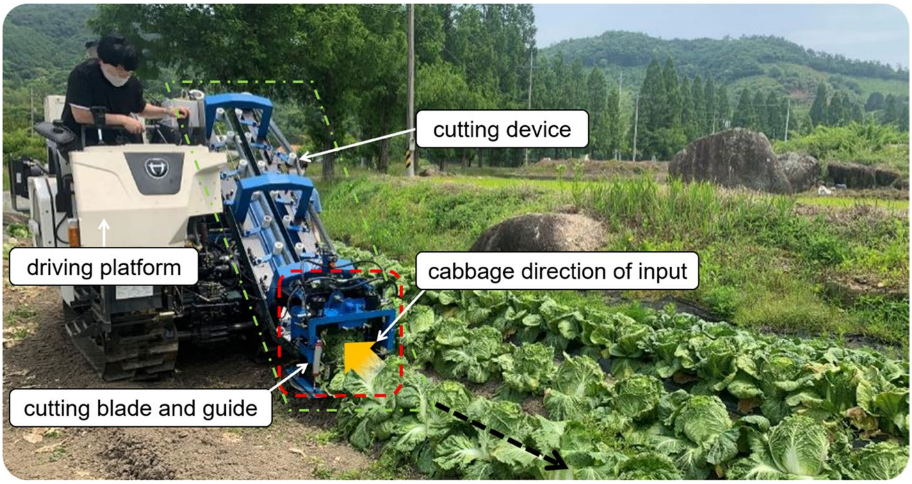

Fig. 1 Korean cabbage harvester with proposed attitude control system for cutting device

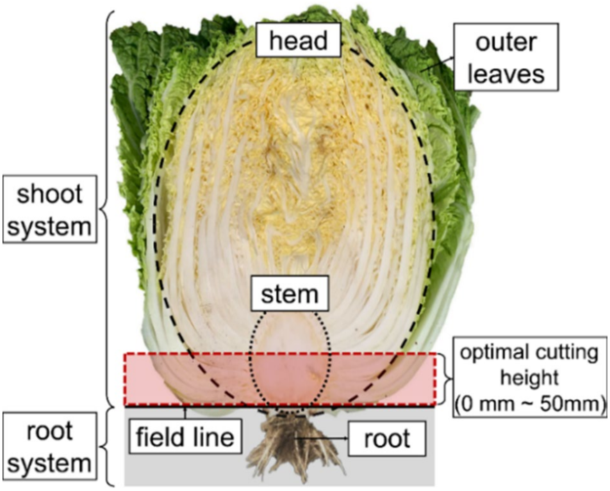

Fig. 2 Structure of Korean cabbage

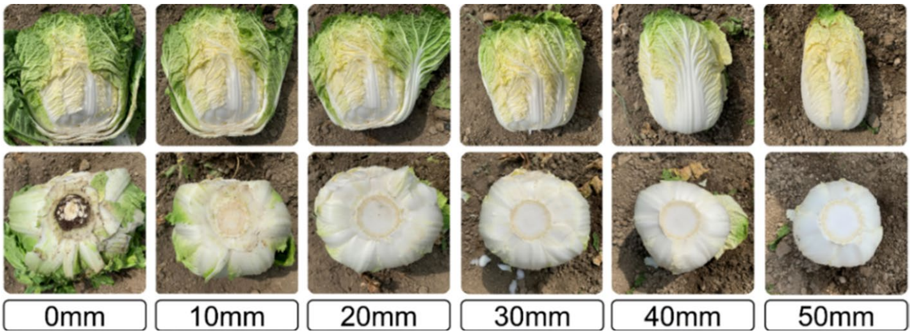

Fig. 3 Cabbage size according to cutting height

the harvested cabbage. Furthermore, this cutting is directly related to the quality of the cabbage; therefore, the cabbage should be cut at an optimal height. The structure of the harvester cutting device is shown in Fig. 4a.

The harvest sequence is as follows. First, the cut cabbage is transferred from the cutting blade to the top using a rotating belt. Second, the belt tensioner enables the cabbage to be held on the belt to move with the belt. Finally, the transferred cabbage can be trimmed, packed and loaded.

Limitations

The roll and pitch of general Korean cabbage harvesters are shown in Fig. 4b. Because of uneven fields, the slope of the harvester body changes irregularly during harvesting, which changes the cutting position of the cutting device and interferes with cutting at the optimal height, as shown in Fig. 2. This may cause problems such as missed cutting (Fig. 5b), overcutting of the head caused by excessive cutting height (Fig. 5c) and side cutting caused by the failure of the cutting device to remain level (Fig. 5d). These problems adversely affect the quality of cabbages during harvesting.

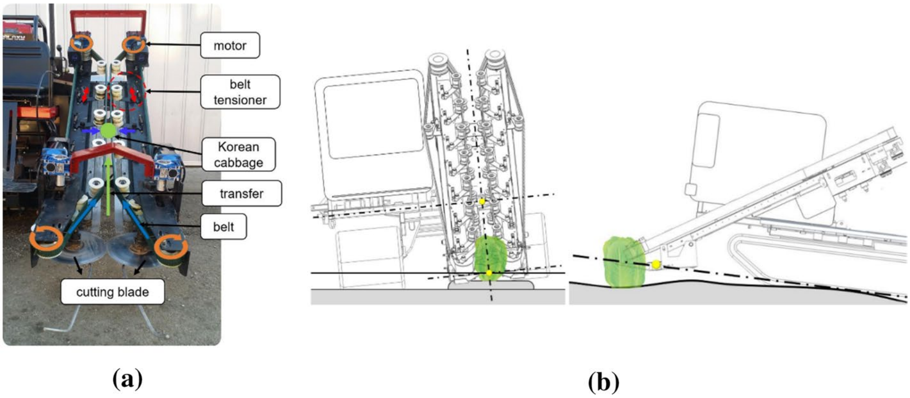

Fig. 4 Structure of general harvesters: **a** components and **b** problems of harvester body slopes

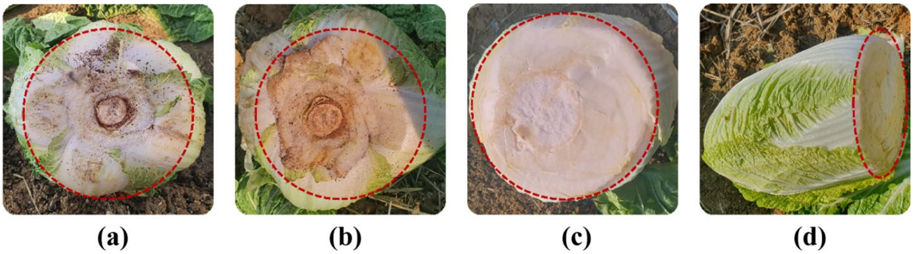

Fig. 5 Different classifications of cutting: **a** good cut, **b** missed cut, **c** overcut and **d** side cut

The track-laying harvester has a built-in device that controls the height. However, they have limited body control and additional control is required to create the desired attitude. Because of the difficulties faced by inexperienced operators, the harvest time may increase. Thus, it is necessary to control the attitude of the cutting device of the harvester to adopt the correct attitude throughout the harvest.

Attitude control of the cutting device

Korean cabbage grows perpendicular to the sun and sky. However, the physical environment of the fields can vary. The irregularity, relative tilt and height difference in the field interfere with the cutting process of the harvester. The blade must be maintained at a specific position to ensure accurate cutting. Consequently, the parameters that require control are defined as follows:

- Roll angle (ϕ): Level of the cutting blades
- Pitch angle (θ): Angle of the cutting device
- Cutting-position height (C_h): Cutting position of the cutting device

These controls operate simultaneously for optimal cutting. The attitude control mechanism is shown in Fig. 6.

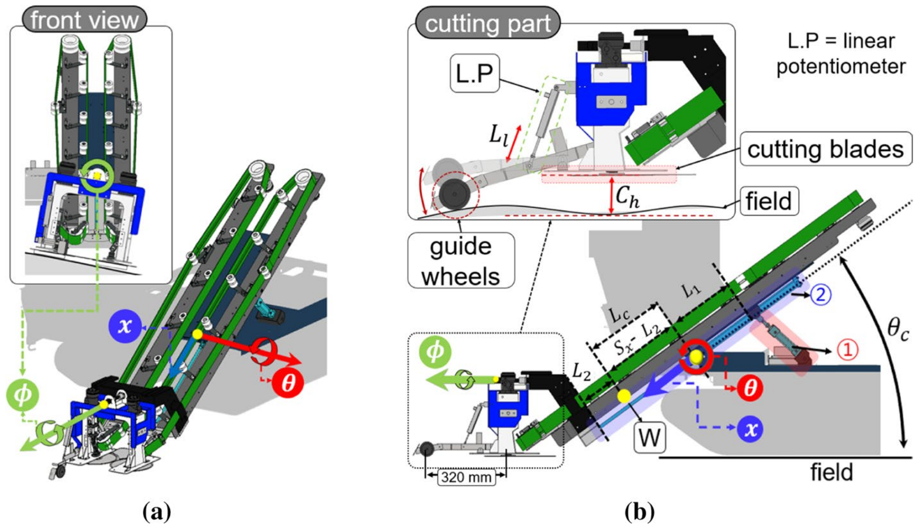

Fig. 6 Cutting device of Korean cabbage harvester with an attitude control system: **a** isometric and **b** right side elevation

Rotation control of roll angle

The cutting device must be able to travel along the slope of the ridge regardless of the field slope. As shown in Fig. 6, the blade of the cutting device could be operated alone. When the guide part is grounded, the rotations along the ϕ ensure that the cutting blade remains at the field slope level. The attitude of the cutting device is changed autonomously using ground traction and gravity. The advantage of this mechanism is that stable harvesting of Korean cabbage is possible because cutting is performed while the cutting blade remains parallel to the ridge.

Rotation control of pitch angle

During harvesting, the attitude of the harvester changes in the front and rear depending on the surface profile. This case is shown on the right side of Fig. 4b. These problems affect the cutting angle and height, varying the cutting angle of the cutter. Therefore, it is necessary to maintain a constant angle. Figure 6 shows the rotation of θ by controlling the 1-cylinder stroke (S_θ) to maintain the angle control reference value, requiring calibrating the measured S_θ to a θ. The calibration is expressed as a linear equation, Eq. 1:

$$\theta = A_\theta \times S_\theta + B_\theta. \tag{1}$$

For calculating θ with a S_θ, linear equation parameters A_θ and B_θ were obtained using the design value and calibration $[A_\theta, B_\theta]$ = [-0.03, 54.86], where θ_c is the goal position of the θ and the angle between the ground and cutting device is maintained by θ_c. Hence, the cutting device is operated regardless of the angle of the drive platform body.

Length control of cutting height

In the case shown on the right side of Fig. 4b, the exact harvesting process cannot be performed by adjusting only the angle of the cutting device using the θ control because the cutting-point height of the cutting device changes as the angle changes. Therefore, height control is necessary. The approach depicted in Fig. 6 was used to control the length of the device x-axis by controlling the 2-cylinder stroke (S_x) to achieve the height control objective. It uses a height control mechanism for measuring the height between the ground and blade because non-contact sensors, such as ultrasonic, laser and infrared, would be obstructed by soil, dust, mud and the outer cabbage leaves. Therefore, a linear potentiometer, a contact sensor capable of measuring length, was used. When driving, the guide wheel is driven into the ground and the length of the linear potentiometer (L_l) attached varies, resulting in data corresponding to the ground height. The linear equation for determining the C_h using the L_l installed in the cutting blade is shown in Eq. 2:

$$C_h = A_c \times L_l + B_c. \tag{2}$$

For calculating C_h with a L_l, linear equation parameters, A_c and B_c were obtained using the design value and calibration $[A_c, B_c] = [0.33, 109.56]$. C_{hc} is a goal position of the cutting blade height. This device maintains the C_{hc} of the C_h and operates the cutting device regardless of the angle of the drive platform body.

Backstepping control-based hydraulic system

Backstepping control

The control algorithm is divided into linear control and nonlinear control according to the mechanical characteristics and requirements of the control. Linear control is theoretically easy to access and the structure of the controller is simple. However, even if the performance is verified through analysis, the uncertainty cannot be predicted and unstable if it moves nonlinearly. Therefore, research on a robust nonlinear control algorithm (even with uncertainty) has been conducted (Kokotovic, 1992).

In this study, the hydraulic system for cutting device attitude control used backstepping to contend with nonlinearity and uncertainty problems (Ahn et al., 2013; Guo et al., 2016; Kaddissi et al., 2007). As shown in Fig. 7, The backstepping control replaces the virtual control input (x_d) with feedback to design complex nonlinear controls in stages. Based on Lyapunov stability theory, the error (z) between the state variable (x) and x_d is gradually controlled to converge to zero. This backstepping control applies the Lyapunov theory

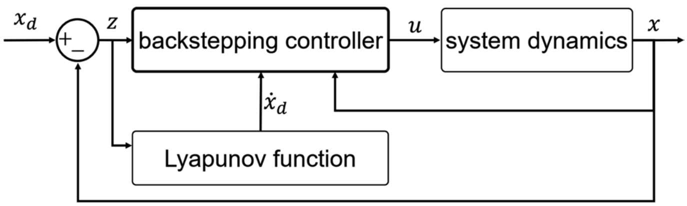

Fig. 7 Block diagram of backstepping control

step-by-step so that the overall stability can be easily secured and controlled. However, because of incorrect parameters, there is a limit to accurate control. The proposed attitude control system changes parameters using real-time control. Therefore, the controller was designed considering the dynamic characteristics of the attitude control system.

System dynamics model

The hydraulic system of the attitude control system is shown in Fig. 8. According to Newton's second law, the dynamics of cylinders are as shown in Eq. 3:

$$\begin{aligned} m_\theta \ddot{x} &= A_p P_1 - A_T P_2 \\ m_x \ddot{y} &= A_p P_3 - A_T P_4. \end{aligned} \tag{3}$$

where m is the equivalent mass, $x = S_\theta$ and $y = S_x$ are the system displacements of the 2-cylinders and A_P and A_T are the actuating areas. The cylinders used had the same actuating area because their strokes were different. P_1, P_2 and P_3, P_4 are the pressures in the two chambers. The dynamics of the cylinder oil flow are shown in Eq. 4:

$$\begin{aligned} \dot{P}_1 &= \frac{K}{A_P S_\theta}\left(Q_1 - A_P \dot{S}_\theta\right) \\ \dot{P}_2 &= \frac{K}{A_T S_\theta}\left(Q_2 + A_T \dot{S}_\theta\right) \\ \dot{P}_3 &= \frac{K}{A_P S_x}\left(Q_3 - A_P \dot{S}_x\right) \\ \dot{P}_4 &= \frac{K}{A_T S_x}\left(Q_4 + A_T \dot{S}_x\right). \end{aligned} \tag{4}$$

where K is the effective bulk modulus of the hydraulic fluid, Q_1 and Q_3 are the supply flow rates to the cylinder end and Q_2 and Q_4 are the supply flow rates to the rod end. The cylinder load resulting from operating the attitude control system is shown in Eq. 5:

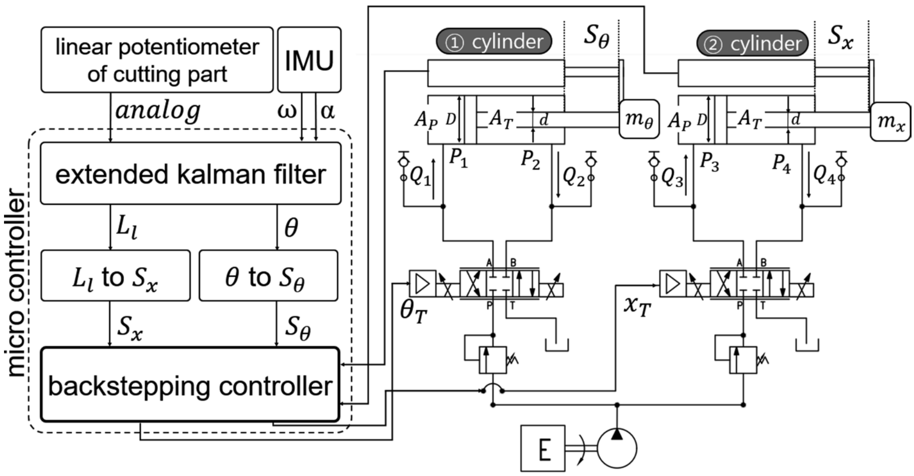

Fig. 8 Schematic of the attitude control system

$$m_\theta = \frac{L_c \times m_a \times \cos\theta_c}{L_1} \tag{5}$$
$$m_x = m_a \cos\theta_c.$$

where m_θ and m_x are the loads on each cylinder, m_a is the total weight of the cutting device, L_c is the difference between the S_x and L_2, as shown in Fig. 6b and L_2 is the length between the center of weight W of the cutting device and the end of the 2-cylinders. The pressure obtained from Eq. 4 is used as the input for Eq. 3. The state variables are defined as shown in Eq. 6 to express these relationships as state-space expressions:

$$\begin{aligned} x &= \left[x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6 \ x_7 \ x_8 \right]^T \\ &\equiv \left[S_\theta \ \dot{S}_\theta \ P_1 \ P_2 \ S_x \ \dot{S}_x \ P_3 \ P_4 \right]^T \end{aligned} \tag{6}$$

The state-space expressions, Eq. 7, are obtained using Eqs. 3, 4 and 5:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dfrac{L_1}{L_c m_a \cos\theta_c}\left(A_P x_3 - A_T x_4\right) \\ \dot{x}_3 = \dfrac{K}{A_P x_2}\left(Q_1 - A_P x_1\right) \\ \dot{x}_4 = \dfrac{K}{A_T x_2}\left(Q_2 + A_T x_1\right) \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = \dfrac{1}{m_a \cos\theta_c}\left(A_P x_7 - A_T x_8\right) \\ \dot{x}_7 = \dfrac{K}{A_P x_6}\left(Q_3 - A_P x_5\right) \\ \dot{x}_8 = \dfrac{K}{A_T x_6}\left(Q_4 + A_T x_5\right). \end{cases} \tag{7}$$

Control design

The backstepping control is then designed for the state-space model (Eq. 7) of the attitude-control system's hydraulic system. First, the system-tracking errors are defined by Eq. 8:

$$z_1 = x_1 - x_{1d}. \tag{8}$$

The differential of the tracking error, $\dot{z}_1$ is calculated in Eq. 9:

$$\dot{z}_1 = x_2 - \dot{x}_{1d}. \tag{9}$$

The virtual control input for converging Eq. 9 to zero is Eq. 10:

$$x_{2d} = \dot{x}_{1d} - k_1 z_1, \left(k_1 > 0\right). \tag{10}$$

The tracking error (Eq. 9) and virtual control input (Eq. 10) are substituted for the state error in Eq. 11:

$$\begin{aligned} z_2 &= x_2 - x_{2d} \\ &= \dot{z}_1 + k_1 z_1. \end{aligned} \tag{11}$$

Based on the Lyapunov function (Kanellakopoulos et al., 2019), the state error (Eq. 11) is defined by Eq. 12:

$$\begin{cases} V_1 = \frac{1}{2} z_1^2 \\ \dot{V}_1 = z_1 \dot{z}_1 = z_1 z_2 - k_1 z_1^2. \end{cases} \tag{12}$$

From Eq. 12, if an error, z_2 converges to zero, the tracking error, z_1 is likely to converge to zero. Therefore, the next step is to control, z_2 to be as close to zero as possible (Eq. 13).

$$\begin{aligned} \dot{z}_2 &= \dot{x}_2 - \dot{z}_{2d} \\ &= \dot{x}_2 - \ddot{x}_{1d} - k_1 \dot{z}_1. \end{aligned} \tag{13}$$

The virtual control input for converging Eq. 13 to zero is Eq. 14:

$$x_{34d} = \dot{x}_2 + \ddot{x}_{1d} + k_1 \dot{z}_1 - k_2 z_2, \quad \left(k_2 > 0\right). \tag{14}$$

The tracking error (Eq. 13) and the virtual control input (Eq. 14) are substituted for the state error in Eq. 15:

$$\begin{aligned} z_{34} &= x_{34} - x_{34d} \\ &= x_{34} + \dot{x}_2 - \ddot{x}_{1d} - k_1 \dot{z}_1 + k_2 z_2. \end{aligned} \tag{15}$$

The state error is defined below. Based on the Lyapunov function, the following state error (Eq. 15) is defined by Eq. 16:

$$\begin{aligned} V_2 &= V_1 + \frac{1}{2} z_2^2 \\ \dot{V}_2 &= \dot{V}_1 + z_2 \dot{z}_2 = -k_1 z_1^2 - k_2 z_2^2 + z_2 \dot{z}_2. \end{aligned} \tag{16}$$

The backstepping control inputs for following the cylinder displacement are shown in Eq. 17:

$$\begin{aligned} \dot{\theta}_T &= \frac{h_1(x)\left(\ddot{x}_{1d} - k_1 \underset{1}{z} - k_2 \dot{z}_2 - z_2 - k_{34} z_{34}\right) + h_2(x)}{g_1(x)} \\ \dot{x}_T &= \frac{h_3(x)\left(\ddot{x}_{5d} - k_5 \ddot{z}_5 - k_6 \dot{z}_6 - z_6 - k_{78} z_{78}\right) + h_4(x)}{g_2(x)} \end{aligned} \tag{17}$$

where

$$\begin{cases} g_1(x) = x_1\left(A_p A_T\right) \geq 0 \\ h_1(x) = \dfrac{L_1 A_P K}{L_c m_a \cos\theta_c} + \dfrac{L_1 A_T K}{L_c m_a \cos\theta_c} \\ h_2(x) = \dfrac{L_1 A_P K}{L_c m_a \cos\theta_c}\left(A_T x_1\right)\left(\theta_P - A_P x_2\right) \\ \qquad - \dfrac{L_1 A_T K}{L_c m_a \cos\theta_c}\left(A_P x_1\right)\left(\theta_T + A_T x_2\right), \end{cases} \tag{18}$$

$$\begin{cases} g_2(x) = x_5\left(A_p A_T\right) \geq 0 \\ h_3(x) = \dfrac{A_P K}{m_a \cos\theta_c} + \dfrac{A_T K}{m_a \cos\theta_c} \\ h_4(x) = \dfrac{A_P K}{m_a \cos\theta_c}\left(A_T x_5\right)\left(\theta_P - A_P x_6\right) \\ \qquad - \dfrac{A_T K}{m_a \cos\theta_c}\left(A_P x_5\right)\left(\theta_T + A_T x_6\right). \end{cases} \tag{19}$$

According to Lyapunov stability theory, Eq. 17 must be negative definite to stabilize the system, rendered negative definite by control error. The system-tracking errors are expressed in Eq. 20:

$$\begin{cases} z_1 = x_1 - x_{1d} \\ z_2 = x_2 - \dot{x}_{1d} + k_1 z_1 \\ z_{34} = x_{34} + \dot{x}_2 - \ddot{x}_{1d} - k_1 \dot{z}_1 + k_2 z_2 \\ z_5 = x_5 - x_{5d} \\ z_6 = x_6 - \dot{x}_{5d} + k_5 z_5 \\ z_{78} = x_{78} + \dot{x}_6 - \ddot{x}_{5d} - k_5 \dot{z}_5 + k_6 z_6. \end{cases} \tag{20}$$

where x_d is the reference value for the location and the backstepping control gain (k). The control inputs $\dot{\theta}_T\, and\, \dot{x}_T$ are entered for each hydraulic cylinder to use the designed backstepping control.

Field test of Korean cabbage harvester

Control parameter settings

The hydraulic parameters of the attitude control system used in this study are listed in Table 1. These parameters are input into the designed controller. A reference signal is introduced to tune k in Eq. 20 of the backstepping controller and compared with the PID controller used in previous studies (Park et al., 2021). Both controllers were driven using the maximum cylinder strokes of the attitude control system and designed according to a trial-and-error approach. The PID control gain (r) is shown in Eq. 21.

Table 1 Parameter list of the attitude control system

Parameters	Specification
Cutting device, L_1	480 [mm]
Cutting device, L_2	320 [mm]
Cylinder diameter, D	40 [mm]
Rod diameter, d	22 [mm]
Cylinder stroke, S_θ	120 [mm]
Cylinder stroke, S_x	800 [mm]
1-Cylinder, Q_1	2.41 [lpm]
1-Cylinder, Q_2	1.68 [lpm]
2-Cylinder, Q_3	1.45 [lpm]
2-Cylinder, Q_4	1.01 [lpm]
Effective bulk modulus, K	1.37×10^9 [Pa]
Weight of cutting device, m_a	250 [kg]
Goal position, θ_c	35 [deg]
Goal position, C_{hc}	250 [mm]

$$
\begin{aligned}
r_\theta &= \left[r_{p1},\ r_{i1},\ r_{d1}\right] = [3.0,\ 0.8,\ 0.5] \\
r_x &= \left[r_{p2},\ r_{i2},\ r_{d2}\right] = [3.0,\ 0.0,\ 0.5],
\end{aligned}
\tag{21}
$$

k is shown in Eq. 22,

$$
\begin{aligned}
k_\theta &= \left[k_1,\ k_2,\ k_{34}\right] = [30,\ 30,\ 10] \\
k_x &= \left[k_5,\ k_6,\ k_{78}\right] = [10,\ \ 1,\ \ 1].
\end{aligned}
\tag{22}
$$

The reference signal was entered as a sine wave at a frequency of 1 Hz. For verification, the reference signal is input to the θ_c and C_{hc} in the hydraulic proportional control valve. The results are shown in Fig. 9. Furthermore, Fig. 10 shows the relative errors between the reference signal and actual θ and C_h. When calculating the root mean square errors (RMSEs) of the θ, the differences between the backstepping and PID controls were 0.61° and 3.09° and those of the cutting height had differences of 1.09 and 2.77 mm (Chai & Draxler, 2014). The relative error of the backstepping controller is smaller than that of the

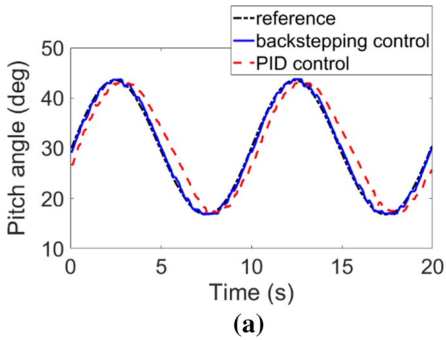

Fig. 9 Backstepping controller and PID controller reference tracking performance: **a** pitch angle (θ) and **b** cutting height (C_h)

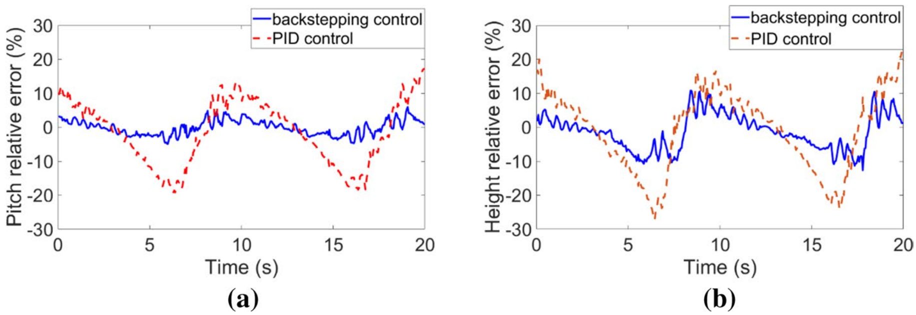

Fig. 10 Relative errors in backstepping and PID controller: **a** pitch angle (θ) and **b** cutting height (C_h)

PID controller, indicating that the overall follow accuracy of this backstepping control is high and the backstepping controller is faster and more accurate than the PID controllers.

Experimental design

The experiment was conducted in a field (Fig. 11). The harvest sequence is shown in Fig. 12. Sixty cabbages were harvested, their cutting surfaces were qualitatively evaluated and the results were scored by referring to Fig. 5. The scoring criteria were as follows:

1. Three points for a good cut (Fig. 5a)
2. Two points for cabbages that required some trimming (less than 0 mm, roots were cut, Fig. 5b)
3. One point for over-cutting (cutting height greater than 50 mm, roots not cut, minor head damage)

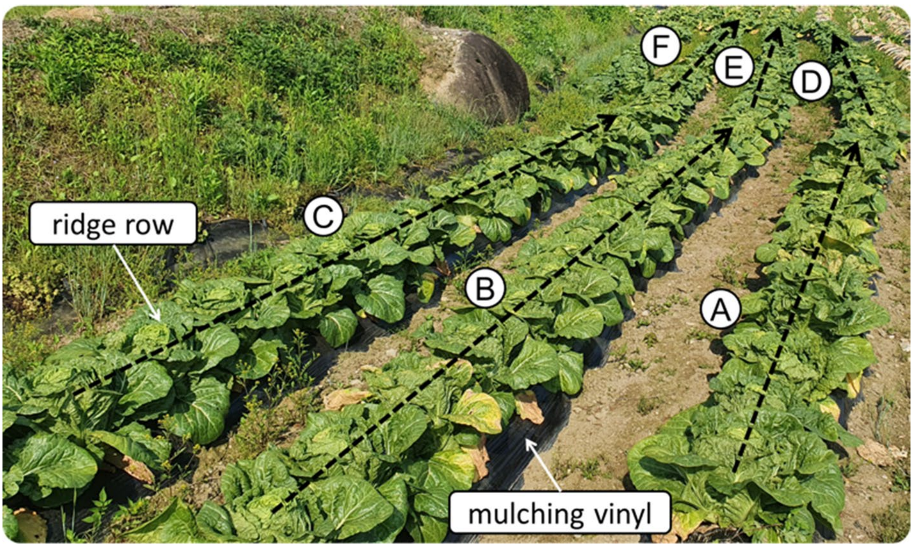

Fig. 11 Field test environment

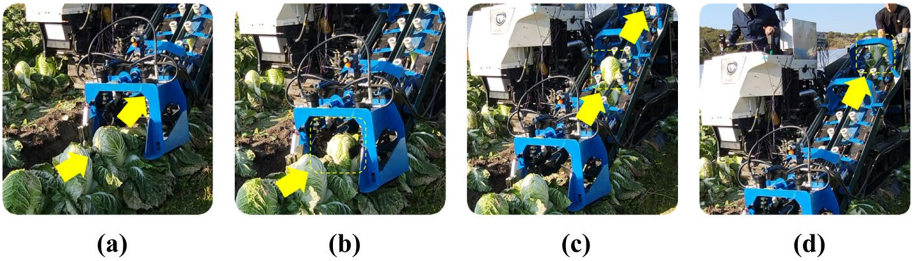

Fig. 12 Sequence of Korean cabbage harvester with attitude control system applied: **a** controlling attitude of cutting device, **b** entering and cutting the Korean cabbage, **c** transfer and **d** completion

4. Zero points for those that had to be discarded (roots not cut, head damage, Fig. 5b, c).

Next, one ridge row was measured to determine whether the reference position was followed accurately. Cabbages were harvested in the ridge row of E, as shown in Fig. 11. The measurement method used a linear potentiometer attached to the 2-cylinder, as shown in Fig. 6b, to measure the ridge height (H_p) of the field. The linear equation for determining the H_p using S_x is shown in Eq. 23:

$$H_p = A_h \times S_x + B_h. \tag{23}$$

For calculating H_p with S_x linear equation parameters A_h and B_h were obtained using the design value and calibration $[A_h, B_h]=[-0.71, 596.03]$. H_p is the height between the ground and cutting blade in the same manner as C_h. However, this differs from C_h depicted in Fig. 6b. C_h is the height measured by the guide wheel and contributes to maintaining the distance between the ground and the cutting blade as much as the C_{hc}. However, the purpose of H_p is to measure the height between the cabbage ridge and cutting blade, with the harvester placed in a flat field during calibration (Eq. 21). H_p measures the height of the cabbage ridge. H_p is used to measure the ridge height and C_h is used to measure the gap between the field and the cutting blade.

Result and evaluation

The results are shown in Fig. 13 and the scoring results are presented in Table 2. Good cut was observed for 38 cabbage heads, some trimming was needed for 18 heads and over-cutting and missed cuts were observed in only four heads. There were no cabbages with zero product value. The average harvest performance score was 2.57 out of 3.00, or 85.7%. The evaluation of cabbage harvesters is typically divided into good cuts, missed and insufficient cuts, over and excessive cuts and harvest loss (Du et al., 2019; Hong et al., 2001). Table 3 summarized the results and quantified cutting rates for each case in Table 2 using based on this evaluation method. After harvesting, the remaining soil or outer leaves are removed and grooming is repeated. Therefore, good cutting and trimming can be considered successful. The experimental results show that 93.3% of cabbages are good without damage.

Attitude control for harvesting the one ridge row of the field was verified. Maintenance performance was verified by measuring the changes in attitude during harvesting. The

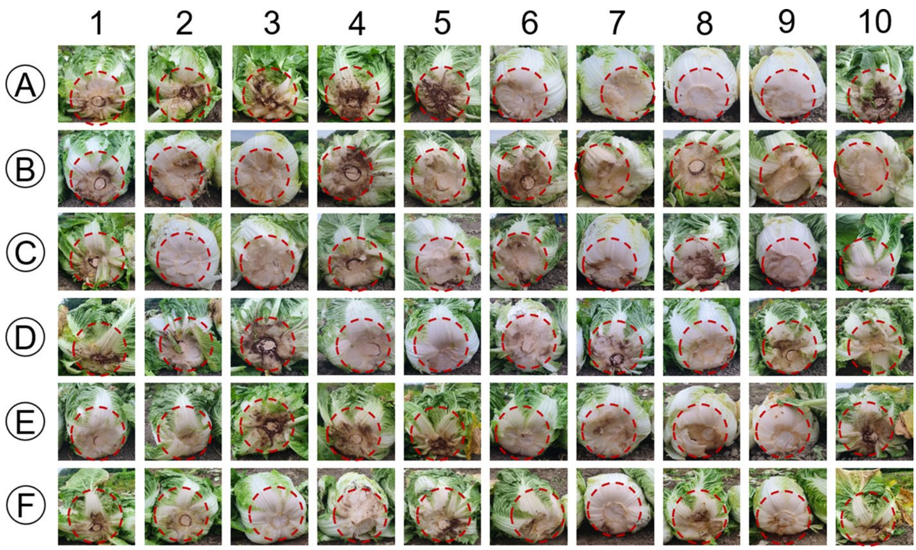

Fig. 13 Korean cabbage cutting surface

Table 2 Calculated scores of Korean cabbages cutting surface

	1	2	3	4	5	6	7	8	9	10
A	3	2	2	2	2	3	3	3	3	2
B	3	2	3	3	3	3	3	3	1	2
C	2	3	2	3	1	1	3	3	3	3
D	2	2	2	3	3	3	3	3	2	2
E	3	3	2	3	2	3	3	2	1	2
F	3	3	3	1	3	3	3	3	3	3
Average	2.57 out of 3.00									

Table 3 Harvesting quality in field test

Ridge row	A	B	C	D	E	F	Total
Harvest cabbage (head)	10	10	10	10	10	10	60
Qualified cutting rate							
Good cutting (%)	50.0	70.0	60.0	50.0	60.0	90.0	63.3
Needed some trimming (%)	50.0	20.0	20.0	50.0	40.0	0.0	30.0
Over-cutting or missed cutting (%)	0.0	10.0	20.0	0.0	0.0	10.0	6.7
Needed to be discarded (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

results are shown in Fig. 14. The harvester can be viewed as driving while maintaining the height of the measured ridge using a linear potentiometer. For robust verification, it confirmed that the reference position was followed, as graphed in Fig. 15. The result is shown in Fig. 15a, which demonstrates a tracking accuracy of approximately $\pm 2.0°$ with

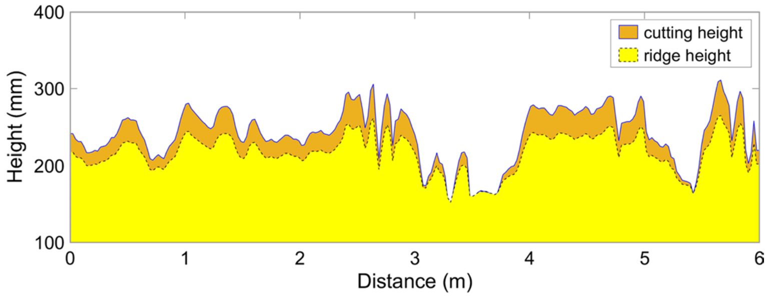

Fig. 14 Harvesting Korean cabbage using the attitude control system

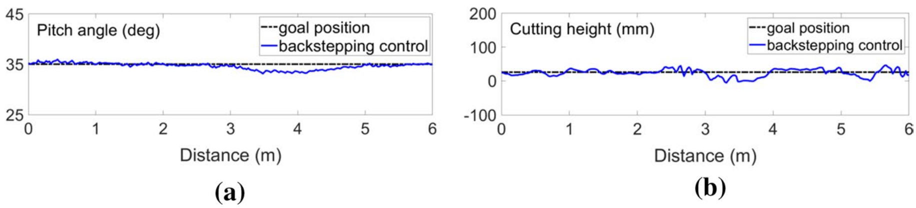

Fig. 15 Verification of goal position following: **a** pitch angle (θ) control and **b** cutting height (C_h) control

Table 4 Statistics of deviation of goal position

Position error			
Pitch angle, θ (deg)		Cutting height, C_h (mm)	
RMSE	MAE	RMSE	MAE
0.73	0.53	11.20	8.97

the cutting angle of the cutting device. The shown in Fig. 15b demonstrates a tracking accuracy of approximately ± 25.0 mm with C_h of the cutting device. The harvesting success rate was increased by maintaining the cutting angle and height.

Table 4 summarizes the statistics of the deviation in the position of the cutting device, as shown in Fig. 15. The RMSEs of the error θ and C_h were 0.73° and 11.20 mm and the mean absolute errors (MAEs) were 0.53° and 8.97 mm (Chai & Draxler, 2014). These findings suggest that an attitude control system using backstepping control to stabilize attitude changes prevents relatively large positioning errors at the goal position. The experimental results demonstrated that when the harvester's body is sloping, the attitude control system can improve the position and cutting accuracy of the cutting device of the harvester.

Discussion

The factors that caused cabbage damage during harvesting were analyzed. These experiments and previous studies have confirmed that a cabbage-harvester cutting device with an attitude control system can significantly reduce harvest failure. However, some of the harvested cabbages were damaged. As shown in Table 3, four incidents out of the 60 were of over or missed cutting. Two factors can cause this type of damage.

First, generally in Korea, cultivation methods using mulch vinyl are used to suppress weeds, maintain moisture and prevent manure or soil loss (Fig. 16). The vinyl caught by the guide wheel hinders the measurements and as shown in Fig. 16a, the guide wheel is grounded on the vinyl rather than on the ground. Consequently, an error occurred in the height measurements. In some parts, harvested cabbages were damaged by old vinyl, causing inaccurate measurements. In some cases, the harvested cabbage and vinyl were cut together and additional trimming was conducted. From a design perspective, the vinyl catching can be solved if the guide wheel is designed by minimizing sharp parts or corners and if the guide tension is adjusted and pressed to reduce the space between the vinyl mulch and the ground. From a control perspective, it will be possible to cope with the vinyl-catching situation by flexibly adjusting C_{hc} in Table 1.

Second, as shown in Fig. 6b, there is a problem caused by the gap between the guide wheel measuring the ground's height and the cutting blade's central axis. From a design perspective, the guide wheel was constructed with a gap to prevent breakage by contacting the blade. Furthermore, the guide wheel was produced in a long-stretched form to measure the height of the ground nearby, avoiding the outer leaves of the cabbage as much as possible. However, with this 320 mm gap, errors may occur in the cut and measured heights. As shown in Fig. 14, the harvester is driven while maintaining a constant height from the ground, but the attitude maintenance performance is poor in parts with frequent slope changes. This problem can be solved by verifying the ground height of the cutting blade using previous data. If past data are to be used, the velocity must be calculated to determine the time difference between the guide wheel and the cutting blade. Therefore, the velocity of the harvester is measured. The time difference was calculated by dividing the velocity by 320 mm. Accordingly, it is possible to improve harvest performance by controlling the attitude using the correct ground height data of the cutting position.

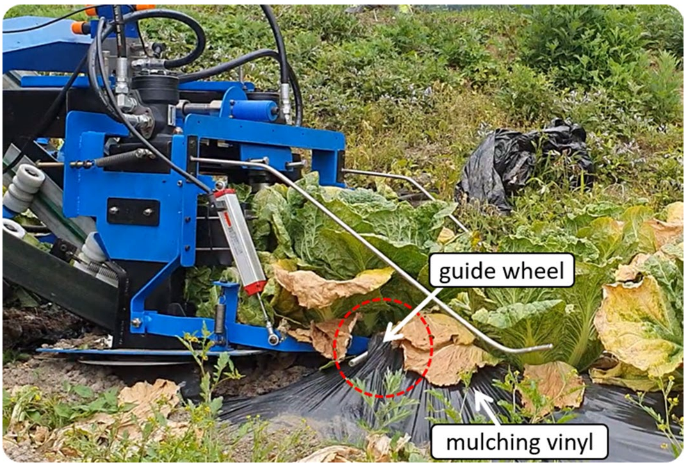

Fig. 16 Problems caused by mulching vinyl during harvesting

Conclusions

This study proposed a backstepping control-based system to control the attitude of a Korean cabbage harvester's cutting device by improving harvesting performance. The performance of the proposed controller was verified experimentally in a domestic cabbage field. Sixty cabbages were harvested, with an average cutting quality of 86.6% (a score of 2.57 out of 3.00), indicating cutting performance. This performance was similar to or higher than previous studies conducted on test beds, even in irregular cabbage fields. The attitude maintenance performance based on the reference position was also verified. The RMSE and MAE were calculated to confirm the attitude maintenance performance of the cutting device, with RMSEs of 0.73° and 11.20 mm in θ and cutting height and MAEs of 0.53° and 8.97 mm. The experimental results demonstrated that, as shown in Fig. 3, the cutting can be conducted within a range of 0–50 mm when the harvester body tilts; the attitude control system can improve the position and cutting accuracy of the cutting device of the harvester. In the future, robust backstepping controllers should be designed to increase the stability of Korean cabbage harvesters. This study is expected to facilitate the future mechanization of cabbage harvesters.

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Declarations

Competing interests 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.

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Authors and Affiliations

Yonghyun Park[1,2] · Hyuck-Joo Kim[3] · Hyoung Il Son[1,2]

Yonghyun Park
dk03378@jnu.ac.kr

Hyuck-Joo Kim
agrihj@sunchon.ac.kr

1 Department of Convergence Biosystems Engineering, Chonnam National University, 77 Yongbong-ro, Gwangju 61186, Republic of Korea

2 Interdisciplinary Program in IT-Bio Convergence System, Chonnam National University, 77 Yongbong-ro, Gwangju 61186, Republic of Korea

3 Department of Industrial Mechanical Engineering, Sunchon National University, 255 Jungang-ro, Suncheon 57922, Republic of Korea