Optimization of an installation angle of a root-cutting blade for an automatic spinach harvester

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Abstract. This paper presents an optimization of the installation angle of a root-cutting blade relative to the arm of an automatic spinach harvester. In the harvesting operation, the blade, which is a rigid body, moves under the planted rows in soil of powder consistency to cut the roots of the spinach and to harvest the spinach on a conveyor. Therefore, the interaction between a rigid body and powder is an important consideration. Experiments were conducted on the design of the harvester. The experiments revealed that a certain path of the blade is more favorable for both harvesting spinach easily and minimizing the amount of soil removed by the blade. In this paper, without revising the favorable path, the optimum installation angle of the blade is derived. To derive the installation angle, a nonlinear optimization problem is solved as an evaluation function consisting of the volume of soil pushed by the blade and the installation angle, which is a design parameter. The utility of the installation angle is confirmed by the Discrete Element Method (DEM), which analyzes the interaction between a rigid body and powder.

1. Introduction

In recent years, mechanisms for replacing the manual labor in harvesting in agriculture have become a requirement. For example, in spinach production, harvesting accounts for up to 80 \[%\] of the overall labor cost [1]. To reduce the burden of harvesting, many automatic spinach harvesters have been developed [2, 3, 4, 5, 6, 7]. Among them, the automatic harvester developed by Chida [7] does not damage the stems and leaves of spinach. The harvester harvests spinach in the following way: a root-cutting blade is placed under the ground surface, cuts the roots of the spinach, and then a conveyor lifts and collects the spinach. In the automatic harvester, the path of the root-cutting blade in the soil is important for the successful harvesting of spinach. The favorable path is the one in which the lesser soil is pushed forward by the root-cutting blade [8]. However, studies so far have been conducted with the root-cutting blade installed vertically, which is an easy and arbitrary position. Modification of the installation angle of the root-cutting blade can decrease the amount of soil pushed by the root-cutting blade. Although other studies have studied the interaction of a rigid body and soil, they do not apply to our specific situation. Kimura et al. [9] analyzed the interaction between powder and a bowl-mill, which is a machine that blends fluid or powder, or both, in order to optimize the form of the bowl-mill. You et al. [10] carried out experiments using several forms of tiller blades to optimize the shape of the blade. The optimal form minimized the torque acting on it in the soil. Shmulevich et al. [11] simulated soil motions with the Discrete Element Method (DEM). The
Figure 1. Schema of a developed automatic spinach harvester.

Figure 2. Schema of the spinach-harvesting steps: (1) The root-cutting blade makes a path in the soil with the advancing crawler (2) The root-cutting blade cuts a spinach root (3) The conveyor pushes and picks up the root-cut spinach.

The purpose of their simulation, which included four kinds of blades, was to model the interaction between the soil and the rigid body. Yamamoto et al. [12] simulated soil motions with the Moving Particle Semi-implicit (MPS) method to verify the validity of a soil-motion simulator. The focus of these studies was the wide movement of soil, and micro movement of the soil was not considered. In contrast, Iizuka et al. [13] studied a suitable design of a wheel for driving in the sand on the moon. Iizuka and Kubota [14] discussed the micro movement of sand by two kinds of driving wheels. But, these studies were intended for rigid body motion in sand, not soil. This paper focuses on the micro movement of soil due to the motion of a root-cutting blade, which is a rigid body, and discusses optimization of the installation angle, which is a design parameter of the automatic spinach harvester. A nonlinear optimization problem is derived and solved to optimize the installation angle of the root-cutting blade to the arm. The effectiveness of the installation angle is verified by motion analyses of soil using DEM, which analyzes the interaction between the soil and the blade.

2. Developed automatic harvester and the motion path of the root-cutting blade

2.1. Developed automatic harvester

This paper examines the automatic harvester developed by Chida [7]. Figure 1 shows a schema of the automatic spinach harvester and Fig. 2 shows the steps of automatic harvesting for the automatic harvester. The automatic harvester is composed of an arm, a root-cutting blade attached to the arm, an arm-angle control system, an arm-length control system, a crawler and a conveyor. The automatic harvester harvests spinach in the following way. First, the root-cutting blade is lowered into the soil in a spinach field by advancing the crawler and the angle of the root-cutting blade, which is downward-sloping from the ground surface. The arm-angle control system tilts the arm with the root-cutting blade. Second, the root-cutting blade moves in the soil with a path and cuts a spinach root by the driving force of the advancing crawler. During that time, the arm-length control system keeps the root-cutting blade at a constant depth in the soil. The arm-angle control system of the harvester is a two degree-of-freedom system that controls the attitude and the position of the root-cutting blade. Finally, the conveyor pushes the root-cut spinach and picks it up. A specification of the root-cutting blade is shown in Fig. 3: "d", "T" and "w" indicate the thickness, width and length of the root-cutting blade, respectively. The blade is mounted on the tip of the arm with the installation angle, "θ_b", as shown in Fig. 4. The installation angle is the free parameter for the design of the harvester. A conventional installation angle is vertical to the arm and is represented as θ_b = 0 [7].
2.2. Background of the problem

Two different paths of the root-cutting blade are compared [8]. One is shown in Fig. 5: the path is generated by the root-cutting blade, which turns to the downward direction and advances in the soil, and by the crawler, which advances with constant speed. Then the root-cutting blade pushes the soil forward and the root-cut spinach is advanced with the pushed soil, so the root-cut spinach cannot be picked up by the conveyor behind the root-cutting blade. Therefore, the path shown in Fig. 5 is not suitable for automatic spinach harvesting by the harvester shown in Fig. 1. Another path is shown in Fig. 6. A later subsection explains the detail of this path. The path is generated by the swinging arm, in which a sinusoidal wave is inputted in the arm-angle control system, while the crawler advances with constant speed. This path is suitable for spinach harvesting because the root-cutting blade moves forward in the soil but pushes a lesser amount of soil. Moreover, the installation angle, $\theta_b$, can improve the amount of soil pushed by the root-cutting blade. Figure 7 and Fig. 8 show sectional views of the passage volume. The root-cutting blade is installed on the arm in the downward directions of 45 [deg] and 0 [deg] in Fig. 7 and Fig. 8, respectively. The amount of soil pushed by the root-cutting blade is proportional to the passage volume of the blade. The passage volumes are $11434w$ [mm$^3$] and $2336w$ [mm$^3$], respectively: a smaller value of the passage volume can be calculated by improvement of the installation angle, $\theta_b$. This paper discusses the improvement of the installation angle, $\theta_b$, to
Figure 9. Arm motion for automatic harvesting.

Figure 10. Path of the root-cutting blade.

Table 1. Parameters of the path of the root-cutting blade.

| Parameter | Description                                      | Value   |
|-----------|--------------------------------------------------|---------|
| \(x(t), y(t)\) | Position of the root-cutting blade               |         |
| \((x_0, y_0)\) | Initial position of rotation center of the arm   | (0, 485) [mm] |
| \(\theta_0\) | Center angle of the conventional motion          | 5 [deg] |
| \(\alpha\) | Amplitude of the swinging arm                     | 5 [deg] |
| \(f\) | Frequency of the swinging arm                     | 0.35 [Hz] |
| \(l\) | Arm length                                        | 508 [mm] |
| \(v_c\) | Crawler speed in the harvesting motion           | 60 [mm/s] |

To decrease the passage volume of the root-cutting blade.

2.3. Path of the root-cutting blade

This subsection explains the motion that generates the path shown in Fig. 6. This study employs the path of the root-cutting blade analyzed by Fujisawa et al. [8]. To realize the path of the root-cutting blade, the crawler advances with the arm-angle control system, which is inputted as a sinusoidal wave. Figure 9 shows the parameters of the automatic harvester, where \(t\) is time, \((x_0, y_0)\) is the initial position of the rotation axis of the arm, \(v_c\) is the constant speed of the crawler, \(\alpha\) and \(f\) are the amplitude and frequency of the input sinusoidal wave, respectively, \(\theta(t)\) is the arm angle from the vertical line, \(\theta_0\) is the center of the amplitude of the sinusoidal wave, and \(l\) is the arm length. The position of the blade, \(\left(\begin{array}{c} x(t) \\ y(t) \end{array}\right)\), is described as

\[
\begin{align*}
  x(t) &= x_0 - l \sin \theta(t) + v_c \cdot t \\
  y(t) &= y_0 - l \cos \theta(t). 
\end{align*}
\]

Equations (1), (2) and (3) generate the path shown in Fig. 10 based on Table 1. The root-cutting blade moves in the direction of the location \(x\), by the crawler and cuts the root of the spinach in \([t_0, t_1] = \left[0, \frac{1}{2f}\right]\) shown in Fig. 10. The root-cutting blade in the range of the path pushes the soil forward. On the other hand, if the root-cutting blade does not move toward location \(x\), in \([t_1, t_2] = \left[\frac{1}{2f}, \frac{1}{f}\right]\) shown in Fig. 10, then the root-cutting blade does not push soil forward. The path of the root-cutting blade pushes a lesser amount of soil than does the path shown in Fig. 5 [8]. The soil displaced by the root-cutting blade pushes and covers the root-cut spinach.
so the spinach becomes hard for the conveyor to pick up. Thus, the path generated by Eq. (3) and shown in Fig. 6 favors harvesting by the automatic harvester.

3. Calculation method for the passage volume of the root-cutting blade

3.1. Outline of this section

The aim of this study is to reduce the amount of soil pushed forward by the root-cutting blade. The root-cutting blade cuts the root of the spinach in the range \([t_0, t_1]\). Therefore, the amount of soil pushed forward by the root-cutting blade can be found in the interval \([t_0, t_1]\). The amount of soil pushed by the root-cutting blade is proportional to the passage volume of the root-cutting blade advancing in the soil. The passage volume means that the necessary volume to move the root-cutting blade, which is illustrated in Figs. 7 and 8. The next section describes the passage volume depending on the installation angle of the root-cutting blade. The calculation method for the passage volume and the modification of the installation angle that effectively decreases the passage volume of the root-cutting blade are then discussed.

3.2. Evaluation method for the passage volume of the root-cutting blade

This subsection describes the calculation method for the passage volume of the root-cutting blade in soil in the range \([t_0, t_1]\), in which the root-cutting blade pushes the soil forward. Fujisawa et al. [15] previously showed the calculation method of the passage volume of the root-cutting blade. However, their method cannot calculate the passage volume correctly if the root-cutting blade moves in the pattern shown in Fig. 11. This paper introduces a new method that can calculate the passage volume, even if the root-cutting blade moves in the pattern shown in Fig. 11. The passage volume can be calculated by integrating the passage volume per unit time. The passage volume per unit time is calculated by multiplying the norm of the velocity of the root-cutting blade, \(v_b(t)\), and the projection area in the movement direction, \(S(t, \theta_b)\) shown in Fig. 12. First, \(v_b(t)\) is described as follows.

\[
\begin{align*}
  v_b(t) &= (\dot{x}(t), \dot{y}(t)) \\
  \dot{x}(t) &= -\dot{l}(t) \sin \theta(t) - l(t) \dot{\theta}(t) \cos \theta(t) + v_c \\
  \dot{y}(t) &= -\dot{l}(t) \cos \theta(t) + l(t) \dot{\theta}(t) \sin \theta(t).
\end{align*}
\]

From Eq. (4), \(|v_b(t)|\) is derived as

\[
|v_b(t)| = \sqrt{\dot{x}(t)^2 + \dot{y}(t)^2}.
\]
Figure 13. Definitions of points O, A, B and C: these points indicate the corner points of the root-cutting blade.

Also, the direction of movement of the root-cutting blade, $\angle v_b(t)$, is

$$\angle v_b(t) = \tan^{-1} \frac{y(t)}{x(t)}.$$

Next $S(t, \theta_b)$, which indicates the projection area in the direction of movement of the root-cutting blade, is derived as follows. Corner points, ”O", ”A", ”B" and ”C", are defined on the root-cutting blade shown in Fig. 13. Each point is described as

$$O = (0, 0)$$
$$A = (0, d)$$
$$B = \left( T - \frac{d}{\tan \frac{\pi}{6}}, d \right) = (T - \sqrt{3}d, d)$$
$$C = (T, 0).$$

Figure 14 shows the rotating coordinate transform indicated by ”R" from A, B and C to ”A", ”B" and ”C", respectively, where

$$R := \begin{pmatrix}
\cos(\theta(t) + \theta_b + \angle v_b(t)) & \sin(\theta(t) + \theta_b + \angle v_b(t)) \\
-\sin(\theta(t) + \theta_b + \angle v_b(t)) & \cos(\theta(t) + \theta_b + \angle v_b(t))
\end{pmatrix}$$

$$A^T = R \cdot A^T = R \begin{pmatrix} 0 \\ d \end{pmatrix} = \begin{pmatrix} -d \sin(\theta(t) + \theta_b + \angle v_b(t)) \\ d \cos(\theta(t) + \theta_b + \angle v_b(t)) \end{pmatrix}$$

$$B^T = R \cdot B^T = R \begin{pmatrix} T - \sqrt{3}d \\ d \end{pmatrix}$$

$$C^T = R \cdot C = R \begin{pmatrix} T \\ 0 \end{pmatrix} = \begin{pmatrix} T \cos(\theta(t) - \theta_b + \angle v_b(t)) \\ -T \sin(\theta(t) - \theta_b + \angle v_b(t)) \end{pmatrix}$$

$$OA'(t, \theta_b) = |d \cos(\theta(t) + \theta_b + \angle v_b(t))|$$
$$OB'(t, \theta_b) = |(T - \sqrt{3}d) \sin(\theta(t) + \theta_b + \angle v_b(t)) + d \cos(\theta(t) + \theta_b + \angle v_b(t))|$$
$$OC'(t, \theta_b) = |T \sin(\theta(t) + \theta_b + \angle v_b(t))|$$
$$A'B'(t, \theta_b) = |(T - \sqrt{3}d) \sin(\theta(t) + \theta_b + \angle v_b(t))|$$
$$A'C'(t, \theta_b) = |d \cos(\theta(t) + \theta_b + \angle v_b(t)) - T \sin(\theta(t) + \theta_b + \angle v_b(t))|$$
$$B'C'(t, \theta_b) = |- \sqrt{3}d \sin(\theta(t) + \theta_b + \angle v_b(t)) + d \cos(\theta(t) + \theta_b + \angle v_b(t))|. $$
Thus, \( S(t, \theta_b) \) is derived as

\[
S(t, \theta_b) = w \cdot \max \{ OA'(t, \theta_b), OB'(t, \theta_b), OC'(t, \theta_b), A'B'(t, \theta_b), A'C'(t, \theta_b), B'C'(t, \theta_b) \}
\]

and the passage volume per unit time, \( \dot{V}(t, \theta_b) \), is derived as

\[
\dot{V}(t, \theta_b) = |v_b(t)| \cdot S(t, \theta_b).
\]

Therefore, the passage volume in \([t_0, t_1]\), \( V(\theta_b) \), is

\[
V(\theta_b) = \int_{t_0}^{t_1} \dot{V}(t, \theta_b) dt.
\]  

(5)

4. Procedure to decrease the passage volume of the root-cutting blade

The passage volume of the root-cutting blade can be decreased as shown in Fig. 15. The decrease is realized by modification of the installation angle, \( \theta_b \). To confirm the effectiveness of the modification, a derivative of \( V(\theta_b) \) is examined. It is not easy to differentiate \( V(\theta_b) \), because \( V(\theta_b) \) includes a function, \( \max \). So, the central difference described as

\[
\frac{\partial V(\theta_b)}{\partial \theta_b} \approx \frac{V(\theta_b + \Delta \theta_b) - V(\theta_b - \Delta \theta_b)}{2\Delta \theta_b}
\]

is a substitute for the derivative of \( V(\theta_b) \), where \( \Delta \theta_b \) indicates a minute change of the installation angle. The central derivative is calculated as

\[
\left. \frac{V(\theta_b + \Delta \theta_b) - V(\theta_b - \Delta \theta_b)}{2\Delta \theta_b} \right|_{\theta_b = 0} = 240.0 > 0.0
\]

(6)

where \( \Delta \theta_b = 0.01 \). Equation (6) shows that the passage volume with the default installation angle is not a minimum value. Then, modification of the installation angle can decrease the passage volume of the root-cutting blade.

5. Optimization of the installation angle for decreasing the passage volume

5.1. Definition of the optimization problem

The smallest passage volume is derived in this section by modifying the installation angle, \( \theta_b \), without changing the path, which is described in Subsection 2.3. The root-cutting blade must turn to the front because the blade cuts the spinach with the driving force of the crawler. The installation angle has the constraints: \(-90 < \theta_b < 90 \) [deg]. The optimization problem for minimizing the passage volume, \( V(\theta_b) \), is defined as

\[
\min V(\theta_b) \text{ s.t. } \theta_b
\]

\[
-90 < \theta_b < 90 \text{ [deg]}
\]

(7)

(8)

The optimization problem is nonlinear because \( V(\theta_b) \) includes the function, \( \max \).
5.2. Optimization method

This subsection solves the optimization problem defined in Eqs. (7) and (8). The optimization problem is nonlinear and the parameter is a real number. Thus, particle swarm optimization (PSO) [16] can be used to solve the optimization problem, because this method is highly versatile for solving nonlinear optimization problems. For the PSO, the number of particles and the number of times to search must be determined, so the general form of Eq. (7) is used. Figure 16 shows the general form of Eq. (7) calculated every 1 [deg]. This figure represents a form similar to a convex function, so the PSO for solving Eq. (7) is not likely to produce a local solution. Therefore, ten particles determined by trial and error are used in the PSO. A pseudo-random number determines the initial values of the particles, as shown in Table 2. The number of times to search is determined as 40 times by trial and error.

### Table 2. Initial numbers for the PSO.

| No. | Initial number |
|-----|----------------|
| 1   | -10.00         |
| 2   | -52.17         |
| 3   | -4.81          |
| 4   | -1.15          |
| 5   | -1.11          |
| 6   | -73.19         |
| 7   | -60.91         |
| 8   | -6.01          |
| 9   | -46.71         |
| 10  | -1.30          |

5.3. Result of the optimization

Figure 17 shows the result of the optimization defined by Eqs. (7) and (8). The obtained value is $\theta_b = -2.2$ [deg]. That is, the passage volume for the optimum installation angle is $V(-2.2) = 2090w$ [mm$^3$], whereas the passage volume for the conventional installation angle is $V(0.0) = 2336w$ [mm$^3$] from Eq. (5). This result represents that the optimum installation angle $\theta_b = -2.2$ [deg] can be obtained the smaller passage volume than that with the conventional angle $\theta_b = 0.0$ [deg].
### Table 3. Parameters of particles in the DEM simulation.

| Parameter | Value |
|-----------|-------|
| $D_p$ | Diameter of particle | 3 [mm] |
| $\rho_s$ | Density of particle | 2550 [kg/m$^3$] |
| $K$ | Spring constant | 44800 [N/m] |
| $E_r$ | Coefficient of restitution | 0.0001 [-] |
| $\mu_{sp}$ | Static friction coefficient between particles | 0.9 [-] |
| $\mu_{dp}$ | Dynamic friction coefficient between particles | 0.85 [-] |
| $\mu_{sb}$ | Static friction coefficient between particle and the root-cutting blade | 0.4 [-] |
| $\mu_{db}$ | Dynamic friction coefficient between particle and the root-cutting blade | 0.25 [-] |
| $\mu_{sc}$ | Static friction coefficient between particle and the square container | 0 [-] |
| $\mu_{dc}$ | Dynamic friction coefficient between particle and the square container | 0 [-] |

### 6. Verification method for the installation angle using DEM

DEM has good results for the analysis of the interaction between the soil and the rigid body [8, 11, 15]. The effectiveness of the optimum installation angle is discussed in Section 5. DEM replaces soil in the spinach field with a lot of particles, so the motion of particles must represent the motion of soil in the spinach field. Moreover, the root-cutting blade moves in the $(x, y)$ coordinate plane in Fig. 1: the blade does not move in the shear direction. Therefore, the verification environment suggested by Fujisawa et al. [8] is used to analyze the two-dimensional motion of soil with the 3D-DEM package software. Figure 18 shows the environment for the DEM analysis. The environment is generated by Particleworks®, which is general-purpose package software. The particles representing the spinach field are laid out in a rectangular surface of 165 [mm] times 800 [mm] in two layers in a virtual container, and the striped pattern of particles appears every 50 [mm]. The size of the container is over 165 [mm] in height, 800 [mm] in length and 6 [mm] in thickness. The long length of the rectangular surface is used to reduce the influence of a virtual container. The striped patterns indicate the behavior of particles, which are used to evaluate the behavior of soil between the conventional installation angle and the optimum installation angle. The specification of the root-cutting blade for the analysis is the same as the specification for the blade installed in the automatic harvester introduced in Section 2. For analyzing the motion of soil, the following ten parameters must be set: diameter of particle, $D_p$, density of particles, $\rho_s$, spring constant of particle, $K$, coefficient of restitution, $E_r$, static friction between particles, $\mu_{sp}$, dynamic friction between particles, $\mu_{dp}$, static friction between particles and root-cutting blade, $\mu_{sb}$, dynamic friction between particles and root-cutting blade, $\mu_{db}$, static friction between particles and virtual container, $\mu_{sc}$, and dynamic friction between particles and virtual container, $\mu_{dc}$. The parameters reproduce the behavior of soil in the real spinach field. This paper uses the values shown in Table 3. These values were determined by Fujisawa et al. [8].

### 7. Result of the verification by DEM

#### 7.1. Overview of the analyses

Figure 19 and Fig. 20 show the results of the simulation in the cases of $\theta_b = 0.0$ [deg] and $\theta_b = -2.2$ [deg], respectively. In Figs. 19 and 20, the point, p, indicates the top of the uplifted particles of the bank and the point, q, represents the base corner point of the root-cutting blade. The maximum vertical distances between p and q in Fig. 19 and Fig. 20 are 49.4 [mm] and 46.5 [mm], respectively. The results are evaluated by using the difference of the striped patterns of particles in Figs. 19 and 20 in the following subsection.
Figure 19. Result of DEM for the conventional installation angle: $\theta_b = 0.0$ [deg].

Figure 20. Result of DEM for the proposed installation angle: $\theta_b = -2.2$ [deg].

Figure 21. Leaning angle of the conventional installation angle of the root-cutting blade, $\theta_b = 0.0$ [deg]: Leaning angle is $\phi_c = 21$ [deg].

Figure 22. Leaning angle of the proposed installation angle of the root-cutting blade, $\theta_b = -2.2$ [deg]: Leaning angle is $\phi_p = 6$ [deg].

7.2. Evaluation of the leaning angle of the boundary line between the striped patterns

The evaluation method shown by Fujisawa et al. [8] is used in this subsection. This method uses the leaning angle of the boundary line between the striped patterns of the particles. The boundary lines, "s-t", shown in Figs. 21 and 22 are drawn from Figs. 19 and 20, respectively. In Figs. 21 and 22, $\phi_c$ and $\phi_p$ indicate the leaning angles from the vertical line and $\phi_c = 21$ [deg] and $\phi_p = 6$ [deg], respectively. The angle is proportional to the volume of soil pushed forward by the root-cutting blade: the smaller the angle, the less likely that soil is pushed forward by the root-cutting blade. Thus, $\phi_c > \phi_p$ shows that automatic harvesting using the optimized installation angle decreases the amount of soil pushed forward by the root-cutting blade.

7.3. Evaluation of the horizontal compression between the striped patterns

This subsection evaluates the horizontal compression of soil on the root-cutting blade. The evaluation method shown by Fujisawa et al. [8] is used in this subsection. This method uses the distances between the striped patterns of the particles. The additional lines "l1" to "l4" shown in Figs. 23 and 24 are drawn from Figs. 19 and 20. The lines are drawn in the following way. The striped patterns are defined as $D$ to $G$. Line $l_1$ is drawn from the corner point $a_1$ to the boundary line between $D$ and $E$ vertically. Line $l_2$ is drawn from $a_1$ to the boundary line between $F$ and $G$. Lines $l_3$ and $l_4$ are drawn from the corner points, $b_1$ and $b_2$, to the boundary line between $E$ and $F$, respectively. The average length of $l_1$ and the minimum line between $l_2$...
and $l_4$ in Figs. 23 and 24 are defined as $l_c$ and $l_p$, respectively. Here, $l_c$ and $l_p$ correlate with the horizon compression thickness. So, the compression ratios, $\beta_c$ and $\beta_p$, which use the initial pattern thickness of 50 [mm], and the horizon compression thickness are defined as

$$\beta_c = \frac{50 - l_c}{50} \times 100 \,[\%] , \quad \beta_p = \frac{50 - l_p}{50} \times 100 \,[\%] .$$

Then, the compression ratios are calculated as $\beta_c = 32 \,[\%]$ and $\beta_p = 24 \,[\%]$. Therefore, $\beta_c > \beta_p$ shows that the automatic harvesting using the proposed installation angle ($\theta_b = -2.2 \,[\text{deg}]$) decreases the amount of soil pushed forward by the root-cutting blade.

8. Conclusion
The present paper describes a modification for the installation angle of the root-cutting blade in an automatic spinach harvester. In the nonlinear optimization problem, the modified installation angle derived minimizes the volume of soil pushed forward by the root-cutting blade. DEM verified the motion of soil in the automatic harvester using the modified installation angle. As a result, it is clear that the amount of soil pushed forward by the root-cutting blade installed in the arm with the modified installation angle is less than that of the conventional installation angle. Future work includes finding the path for the root-cutting blade that minimizes the amount of soil pushed by the root-cutting blade in consideration of the modified installation angle.

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