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Autonomous Self-Propelled Napa Cabbage Harvester: Cutting, Attitude Control, and Loading Modules

Yonghyun Park [1,2], Myeong-Sin Kim [3], Juwon Shin [4], Yongjin Cho [4,5,*], Hyuck-Joo Kim [3,*] and Hyoung Il Son [1,2,6,*]

1 Department of Convergence Biosystems Engineering, Chonnam National University, Yongbong-ro 77, Gwangju 61186, Republic of Korea; dk03378@jnu.ac.kr
2 Interdisciplinary Program in IT-Bio Convergence System, Chonnam National University, Yongbong-ro 77, Gwangju 61186, Republic of Korea
3 Department of Convergence Biosystem Mechanical Engineering, Sunchon National University, Jungang-ro 255, Suncheon 57922, Republic of Korea; audtlsgp@naver.com
4 Department of Bio-Industrial Machinery Engineering, Jeonbuk National University, Hyeonmu 2-gil 13, Jeonju 55000, Republic of Korea; jw970429@naver.com
5 Institute of Agricultural Machinery ICT Convergence, Jeonbuk National University, Hyeonmu 2-gil 13, Jeonju 55000, Republic of Korea
6 Research Center for Biological Cybernetics, Chonnam National University, Yongbong-ro 77, Gwangju 61186, Republic of Korea
* Correspondence: choyj@jbnu.ac.kr (Y.C.); agrihj@sunchon.ac.kr (H.-J.K.); hison@jnu.ac.kr (H.I.S.)

Abstract: This paper introduces an autonomous self-propelled Napa cabbage harvester, designed to significantly improve the efficiency and effectiveness of the traditionally labor-intensive harvesting process. The harvester integrates three key modules: a cutting, an attitude control, and a loading module. The cutting module is equipped with an attitude control module that ensures precise severance of the Napa cabbage stems, minimizing damage to the crop and maintaining product quality. The attitude control module employs a backstepping-based force control that continuously adjusts the cutting angle and height to ensure consistent cutting precision, even on uneven terrain, thereby optimizing the quality of the Napa cabbages. The loading module automates the collection and transfer of harvested Napa cabbages into storage, significantly reducing the physical burden on workers and improving operational efficiency. Field experiments demonstrated improvements, including a 42–66% reduction in task time compared to manual harvesting, as well as a 37% increase in cutting accuracy through the use of autonomous control. The proposed system presents a comprehensive solution for enhancing productivity, reducing labor demands, and maintaining high crop quality in Napa cabbage harvesting, offering a practical approach to modernizing agricultural practices.

Keywords: autonomous harvester; agricultural mechanization; backstepping control; Chinese cabbage harvester; precision agriculture

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1. Introduction

Napa cabbage (*Brassica rapa* L. ssp. Pekinensis) is a significant crop, particularly in East Asia, where it is widely cultivated in countries such as China, Japan, and the Republic of Korea [1]. In the Republic of Korea, Napa cabbage is a crucial ingredient in Kimchi, a staple food in the local diet [2]. Between 2012 and 2017, the production volume increased from 2 million tons on 295.24 km^2 to 2.4 million tons on 324.16 km^2, reflecting growth rates of approximately 10% and 20%, respectively. Napa cabbage cultivation represents 68% of the total area dedicated to leaf-stalk vegetables in Korea. Despite its importance, mechanization for Napa cabbage cultivation remains limited, particularly for labor-intensive harvesting operations [3].

The labor-intensive nature of Napa cabbage harvesting presents significant challenges for farmers, particularly in the face of a decreasing agricultural workforce and an aging rural population [4,5]. In this context, there has been a push towards developing autonomous agricultural systems to enhance efficiency and reduce labor dependency [6–10]. Research has explored various technologies, such as autonomous agricultural vehicles, swarm robotics, and deep learning applications for precision agriculture [11–16]. Despite these advancements, Napa cabbage cultivation, especially harvesting, remains challenging to automate due to the complex crop structure and the variability of outdoor cultivation environments

These diverse research efforts span the fields of smart farming, horticulture, and robotics. However, the mechanization of Napa cabbage cultivation, which is typically performed outdoors, remains challenging owing to the unique structure of Napa cabbage and non-uniformities in the cultivation environment [17] . Optimal cutting height is crucial for Napa cabbage, as the number of separated outer leaves depends on the cutting height, affecting the size and quality of the harvested cabbage (Figure 1). The harvesting of Napa cabbages, which involves more complex conditions than cabbages, has not yet been automated and is typically grown manually.

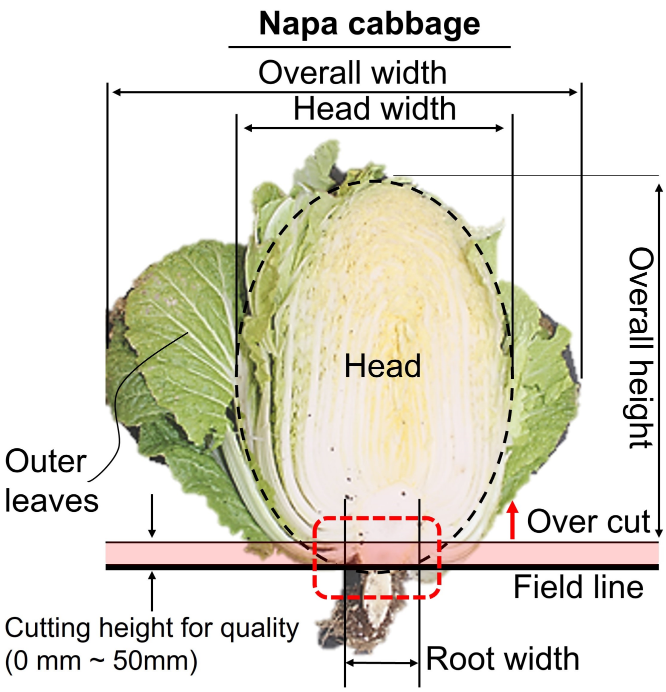


Figure 1. Structure of Napa cabbage [18].

The current manual harvesting method, depicted in Figure 2, involves multiple labor-intensive steps, as follows: (1) after laying down the Napa cabbage head, cut off the stem with a knife and remove the outer leaves; (2) in packaging the cabbage heads, discard those with defects and pack high-quality cabbages in nets; (3) packaged Napa cabbage is loaded onto small trucks for primary loading; and (4) Napa cabbage is transferred from small trucks to larger trucks for secondary loading and distribution. This process, which typically involves five to six workers, is labor-intensive and highly susceptible to labor shortages. It can also lead to worker injuries, low product quality, and a high prevalence of musculoskeletal disorders (MSDs) [19–21].

Agricultural mechanization is crucial in reducing physical strain on workers and enhancing efficiency. Hachiya et al. (2004) reported that mechanized systems reduced labor requirements by over 50% compared to traditional hand-harvesting methods [22]. Automated unloading systems in harvesters further reduced manual labor by over 80%, minimizing worker fatigue and improving efficiency.

Figure 2. Steps involved in the manual labor harvesting of Napa cabbage.

The mechanization devices include tractor-mounted grain harvesters [23–25] and self-propelled one-row designs [26,27]. Tractor-mounted harvesters are advantageous for large-scale operations but require multiple tractors, and their large size poses challenges for Napa cabbage harvesting [28]. Therefore, most Napa cabbage harvesters have been developed as standalone, self-propelled one-row configurations [17,29–32].

Recently, Park et al. (2021) developed a compact harvester for Napa cabbage [33]. Despite some success, field tests showed sub-optimal performance in lifting, cutting, and transporting cabbages [34]. Specifically, the Type A harvester had a 50% success rate for lifting and only 35% for cutting, while Type B showed improved lifting (78%) but poor cutting performance (7.7%).

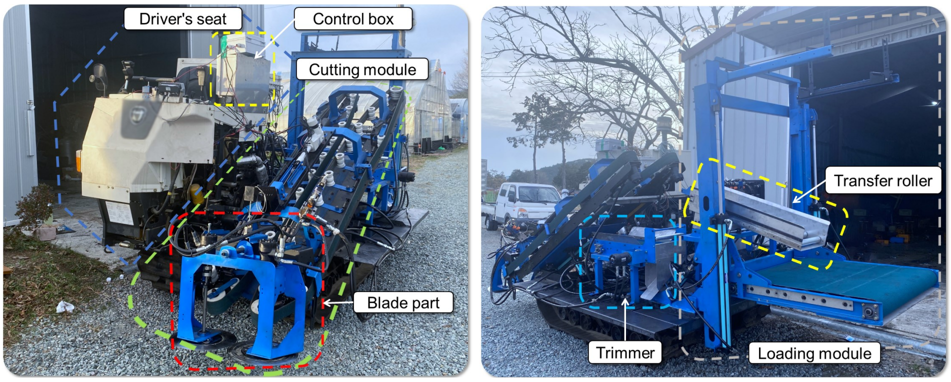
To address these issues, Park and Son (2022) introduced an attitude control system in the cutting module of Napa cabbage harvesters, significantly improving accuracy [18]. The implementation of this system led to a 37.0% improvement in cutting accuracy and efficiency, reducing errors, missed cuts, over-cuts, or side-cuts, thereby underscoring the crucial role in precise Napa cabbage harvesting, as shown in Figure 3.

Figure 3. Different classifications of Napa cabbage cutting results [35].

As part of follow-up research, a nonlinear backstepping controller was designed to enhance the performance through precise attitude control [35]. Field experiments demonstrated a 40.0% increase in the efficiency and precision of the Napa cabbage harvesting process when using the attitude control module, compared with methods without it. Additionally, 85.7% of the cabbages harvested with this system were damage-free, indicating a significant improvement in product quality. However, issues remain with measurement accuracy due to obstacles such as mulching vinyl. These issues must be addressed to optimize the mechanized harvesting process, and an integrated Napa cabbage harvester should be developed.

In this paper, we propose a self-propelled harvester for autonomous Napa cabbage harvesting, as shown in Figure 4. It integrates three key modules—cutting, attitude control, and loading, into the Napa cabbage harvester. The harvester includes enhancements to the cutting module, an optimized attitude control module, and a mechanized loading module. Key improvements include the following: (1) refining the conveyor and cutting mechanisms for better performance, (2) optimizing the attitude control module for more precise cutting, (3) designing a ton bag-type loading system for efficient handling, and

(4) validating these improvements through field tests. The proposed harvester is expected to outperform manual labor in efficiency and effectiveness.



(**a**) (**b**)

Figure 4. Proposed integrated Napa cabbage harvester: (**a**) front view and (**b**) rear view.

This paper is structured as follows: In Section 2, we present the materials and methods, detailing the overall design and functionality of the integrated cutting, attitude control, and loading modules. Section 3 provides the results and analysis of the field experiments, comparing the proposed harvester's performance with manual labor. Section 4 discusses the limitations and proposes future enhancements for post-harvest automation. Finally, Section 5 concludes the study by summarizing the key findings and outlining the contributions of the autonomous Napa cabbage harvester.

2. Materials and Methods

2.1. Overall Design

The proposed Napa cabbage harvester, depicted in Figure 5, integrates cutting, attitude control, and loading mechanisms to streamline and enhance harvesting efficiency. The harvester moves in the direction indicated by the arrow-labeled operation direction. It features a driver's seat and a worker's station, enabling semi-autonomous operation. The driver controls the movement of the harvester while the worker assists with manual tasks such as trimming.

At the front of the harvester is the cutting module, equipped with a blade that precisely cuts the Napa cabbage stem. After the cabbage is cut, it is transferred to a conveyor belt for further handling. In the middle section, a worker manually trims the Napa cabbage, removing excess leaves or imperfections to improve its marketability. The transfer roller ensures that the Napa cabbages are evenly distributed into the ton bag, allowing them to be stacked properly without damage or deformation.

The right-side view illustrates the operational flow, from cutting, transferring, and trimming to transferring again and finally loading (Figure 5). This flow shows how the cabbage moves through each phase of the harvesting process, demonstrating the efficiency and integration of each module in the system.

The harvesting sequence is illustrated in Figure 6, starting with cutting Napa cabbage using the cutting module blade. The attitude control module ensures that the cabbage is cut at the optimal angle. After cutting, the cabbage is conveyed to the worker via a conveyor belt system. Once trimming is completed, the cabbage is loaded into a ton bag using the transfer roller of the loading module.

The hardware architecture, depicted in Figure 7, is built around a microcontroller (Arduino Mega 2560, Arduino.cc , Ivrea, Italy) that controls the entire system. Force control is provided by a load cell (CSBA-200L, CURIOTEC Co., Ltd., Paju, Republic of Korea) attached to the cutting device, while attitude feedback is given by an inertial measurement unit (IMU) sensor (MPU-6050, TDK InvenSense, San Jose, CA, USA) mounted on the cutting device. The hydraulic system features a manifold block with a proportional valve

(4WREE 6E 32-re29061, Bosch Rexroth, Lohr am Main, Germany) and a directional valve (4WE6G6X/EG24N9K4, Bosch Rexroth, Lohr am Main, Germany). This system operates a 20 cc/rev hydraulic pump, drawing from a 170 L hydraulic tank, and powers the pitch and slide actuators, blade, conveyor, trimmer motor (120 rpm with 50 cc displacement), and the tilt and up-down actuators of the loading module (with 120 mm and 1000 mm strokes, respectively). These components ensure precise and reliable operation throughout the harvesting process.

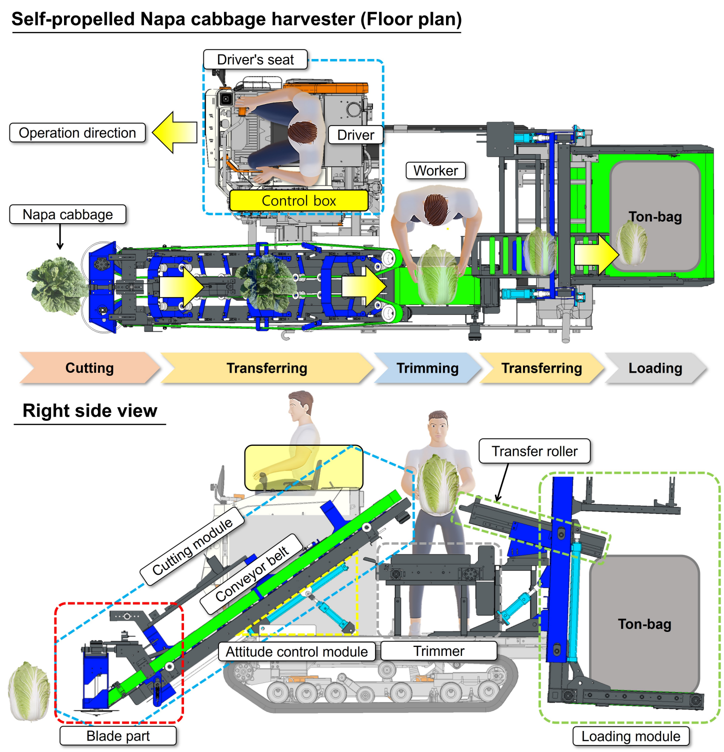


Figure 5. Structure of the proposed Napa cabbage harvester.

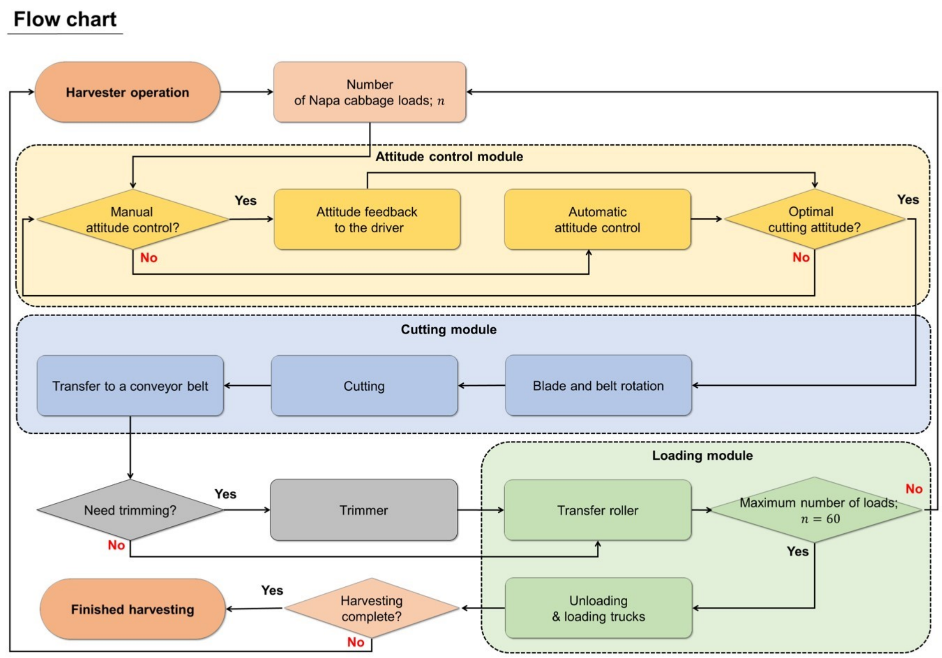


Figure 6. Flow chart of the proposed harvester.

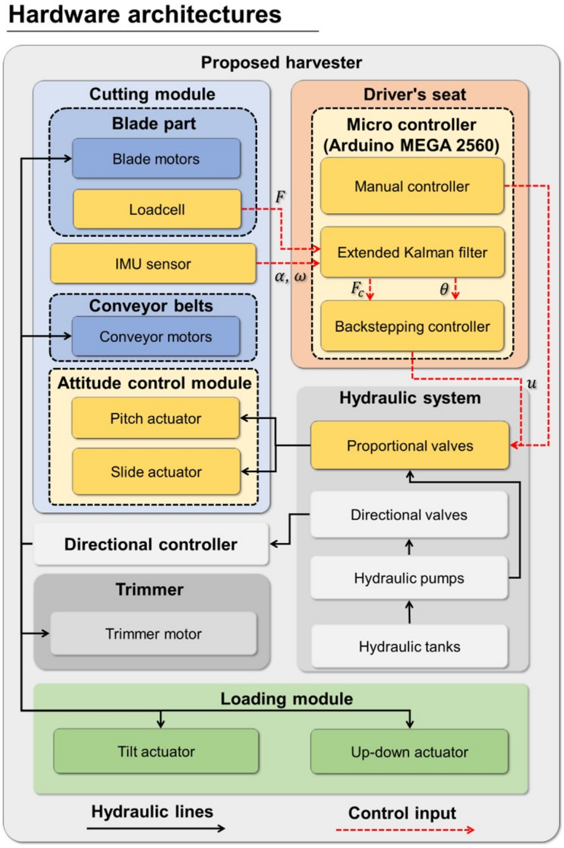


Figure 7. Hardware architectures of the proposed harvester.

The main components of the proposed Napa cabbage harvester are as follows:

- Cutting module: This module consists of a blade part that cuts the Napa cabbage stems and a conveyor part that transports the cut Napa cabbage.
- Attitude control module: This module adjusts the attitude of the cutting module to ensure precise cuts. It uses sensors and actuators to maintain the optimal cutting angle and height.
- Loading module: This module is designed to transport harvested Napa cabbage from the cutting module through the transfer roller and load it into ton bags for storage. It also includes a tilt/up-down actuator for efficient unloading after harvest.
- Control system: The control system serves as the central component of the harvester, integrating and coordinating the functions of the cutting, attitude control, and loading modules, as well as the self-propelled platform. It receives sensor data and uses control algorithms to optimize performance. As shown in Figure 7, the system mainly consists of a microcontroller that drives the proportional valve for the attitude control module and a directional controller for the cutting and loading modules. The attitude control allows switching between backstepping-based automatic control and manual control modes.

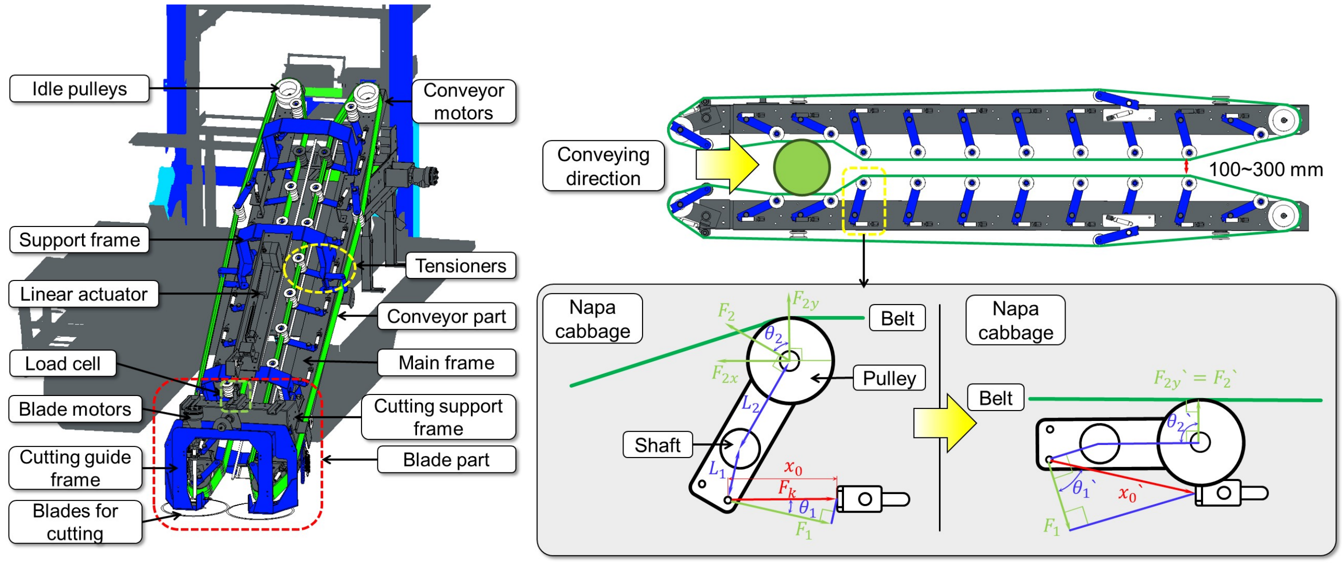
2.2. Cutting Module

The cutting module, a critical component for efficient Napa cabbage harvesting, has undergone significant enhancements in the latest design (Figure 8a). Based on insights from previous research [33,34], several key improvements were made:

Blade part design optimization: The blade part was redesigned to achieve a more precise and gentle cut, minimizing crop damage. The angle of the blade was calibrated to enhance cutting efficiency while preserving the quality of the Napa cabbage.

Conveyor part enhancement: The conveyor part was re-engineered for smoother operation. Adjustments to the conveyor belt tension ensure consistent and safe transport of cabbages post-cut, reducing the risk of bruising or dropping.

These modifications were aimed at minimizing crop damage and improving the overall efficiency of the harvesting process, representing an advancement over previous designs. Preliminary simulation confirmed the effectiveness of these improvements.



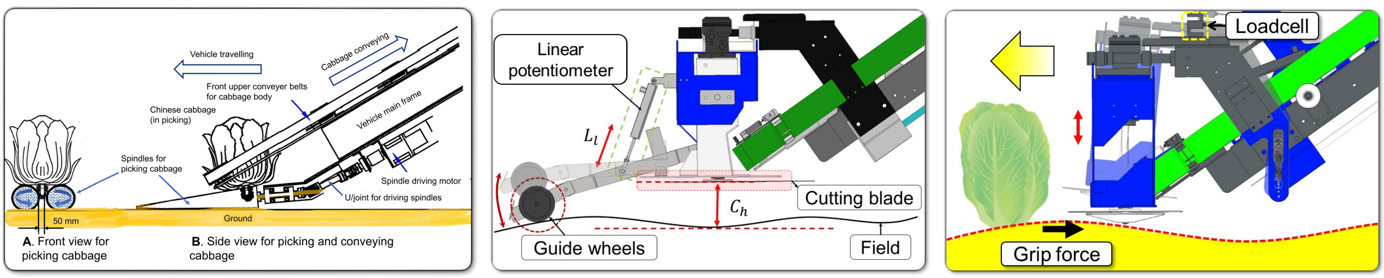
(**a**) (**b**)

Figure 8. Structure of the cutting module: (**a**) structure and (**b**) changes in the force of the tensioner to push the belt (F_{2y}) to hold the Napa cabbage.

2.2.1. Blade Part Design

In a previous prototype cutting module, Napa cabbages were first uprooted and then cut [34]. In this prototype, the blade was tilted at approximately 25–35° (Figure 9a). This orientation posed challenges for one-row harvesters, as the Napa cabbages needed to be transported upward for loading after harvesting, which often led to instability. Yang et al. (2022) conducted experiments with different blade angles, but increasing the blade angle often caused the Napa cabbages to fall over, limiting cutting accuracy [34].

To address these issues, Park et al. (2023) redesigned the cutting module with the blade positioned at 0°, completely horizontal to the ground (Figure 9b) [35]. This modification was based on practical testing, which demonstrated that a horizontal blade orientation provided greater stability during cutting. By maintaining a consistent horizontal position, the blade achieved a more precise cut while reducing the risk of damaging the Napa cabbage.



(**a**) (**b**) (**c**)

Figure 9. Structure of the blade part: (**a**) Yang et al. [34], (**b**) Park et al. [35], and (**c**) proposed blade part.

Previous research identified an issue with attitude control along the pitch axis: the horizontal blade could inadvertently tilt when the posture was adjusted, causing side-cutting and reducing precision. The proposed design effectively addresses this problem. As shown in Figure 9c, the blade maintains consistent contact with the ground using a force-controlled mechanism. If the disc disengages from the ground, a spring mechanism allows the blade to tilt slightly but ensures that it returns to a horizontal position once ground contact is re-established. This mechanism effectively resolves the side-cutting issue, ensuring accurate and effective cutting while adapting to uneven terrain.

2.2.2. Conveyor Part Design

To prevent the cut Napa cabbages from falling or being damaged during transfer via the conveyor for loading, the optimal grasping force should be applied. The belt is made from a flexible, non-abrasive material to reduce friction and avoid damaging the cabbage during transport. The forces acting on the tensioner are analyzed to select the appropriate spring specifications, ensuring the tensioner can securely grip the cabbage while maintaining its shape on the transfer belt, as depicted in Figure 8b.

The force exerted by the tensioner on the belt, F_{2y}, is influenced by the force moving the tensioner, F_2, a component of the elastic force of spring, F_k, and the spring length, x_0. It can be expressed as:

$$F_{2y} = F_2 \cdot \sin\theta_2 \quad = \frac{L_1 \cdot F_k \cdot x_0 \cdot \cos\theta_1}{L_2} \cdot \sin\theta_2. \tag{1}$$

Here, it is crucial to consider the dynamic nature of the problem, including vertical accelerations caused by field roughness, which affect the actual force experienced by the cabbages during conveyance. To accurately calculate the grasping force, F_f, dynamic vertical forces resulting from conveyor motion and field conditions were incorporated into the proposed model.

F_f is initially calculated as the product of F_{2y} and the friction coefficient μ. To adjust for dynamic conditions, a correction factor, α, was introduced to account for vertical acceleration and field roughness:

$$F_f = 2 \cdot \mu \cdot F_{2y} \cdot \alpha. \tag{2}$$

Here, the inclusion of α ensures that F_f accurately reflects dynamic conditions during harvesting. This means that the Napa cabbage may drop if F_f is less than its weight, $W = m_c g$. Therefore, F_f must be greater than or equal to W. Given that the heaviest Napa cabbage weighs 4.5 kg (Table 1), the system should exert a grasping force capable of supporting at least 44 N. Additionally, considering the upper limit of failure and deformation under transverse compression for Napa cabbage (approximately 580.9 N and 50.8 mm, respectively), the cabbages should be gripped with a force less than 580 N to avoid damage [36]. Thus, the optimal range for F_f is 44–580 N, accounting for dynamic conditions.

Table 1. Weight comparison of Napa cabbage.

Type	Average Weight [kg]	Average Weight After Trimming Outer Leaves [kg]
Spring Napa cabbage	4.54	3.37
Highland Napa cabbage	2.67	1.87

Incorporating dynamic vertical forces into the calculation provides a more accurate and reliable measure of the grasping force required to ensure the safe and damage-free conveyance of Napa cabbages during the harvesting process.

2.2.3. Preliminary Simulation

A dynamic simulation of post-harvest transport of Napa cabbage was conducted using dynamic analysis software (RecurDyn 2022, MHS, Seoul, Republic of Korea) to optimize the cutting module (Figure 10). F_f was calculated by substituting the parameters listed in Table 2 into Equations (1) and (2). The friction coefficient μ was set at 0.76, based on the experimental results by Zheng et al. (2023), who studied the friction between cabbage and ethylene vinyl acetate [37]. To select a spring that yields optimal F_f, three springs with differing stiffness values (F_k = 0.69, 1.57, and 8.43 N/mm) were considered.

Table 2. Parameters of the conveyor part.

Parameter	Specification
L1 [mm]	46
L2 [mm]	100
x_0 [mm]	88–136
μ	0.76
θ_1 [°]	41–70
θ_2 [°]	46–90
α [N]	1

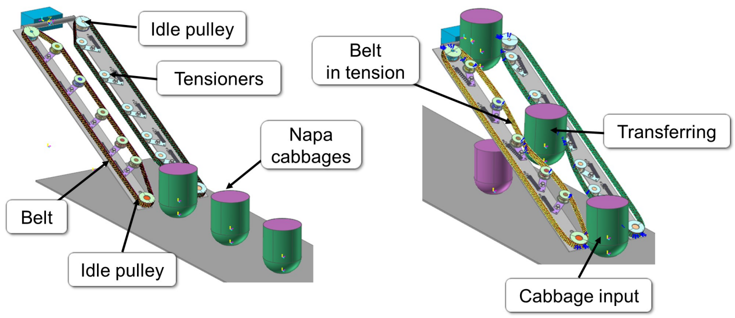


Figure 10. Dynamic simulation model of the conveying part.

According to the simulation results (Figure 11), all three springs with different F_k can be gripped within the optimal F_f (44–580 N). Finally, a spring (F_k = 1.57 N/mm) with an intermediate F_f value is selected to prevent the destruction.

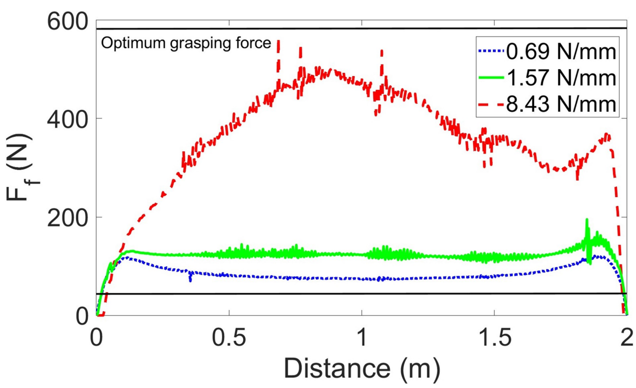


Figure 11. Results of preliminary simulation for optimal spring selection of conveyor belt. The black line on the graph denotes the optimum grasping force range (44–580 N), resulting in no damage to Napa cabbage.

2.3. Attitude Control Module

Previously, an attitude control system was developed to prevent missed cuts, over-cuts, or side-cuts during the harvesting of Napa cabbage, enhancing the overall harvest performance [18]. Furthermore, a backstepping controller was introduced to enable precise harvesting on uneven fields, ensuring high-quality Napa cabbage [35]. However, when using these frameworks, the accuracy of height measurement decreased in the presence of obstacles such as cabbage leaves, rocks, or mulching vinyl, negatively affecting harvesting precision.

To address this issue, measuring height from the ground was replaced with a force control that maintains constant grip force. The improved module performs harvesting by pressing down obstacles with blades that touch the ground. This approach creates a consistent cutting environment by effectively leveling the ground, ensuring uniform cutting of Napa cabbage stems. By maintaining a constant grip force on the ground, the harvester can adapt to irregular surfaces and maintain a consistent cutting height, which allows for precise cutting regardless of terrain variations.

2.3.1. Design of the Attitude Control Module

The attitude control system, shown in Figure 12, ensures that the cutting edge is leveled to the field and performs cutting at a constant height, thereby achieving stable harvesting of Napa cabbages.

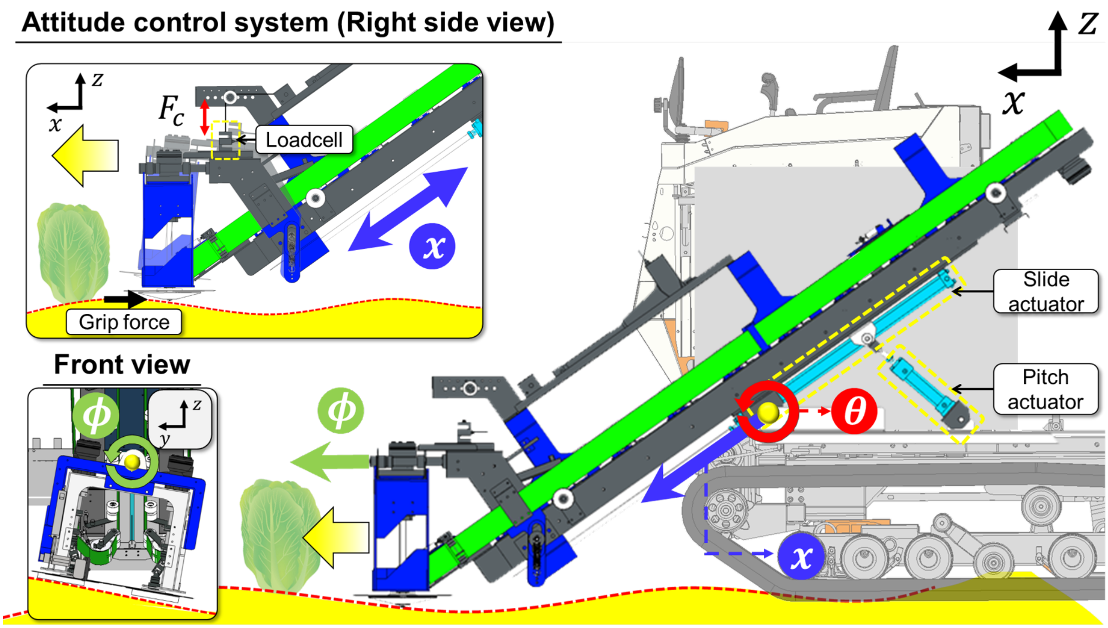


Figure 12. Design of the attitude control module.

The following parameters need to be controlled:

- Roll angle (ϕ): The blade part of the cutting module can operate independently. The guide part beneath the blade maintains contact with the ground and rotates to keep the blade level. The orientation of the cutting module is adjusted autonomously using the grip force on the ground along with gravity, ensuring the blade remains level.
- Pitch angle (θ): To ensure accurate harvesting, the blade must maintain a horizontal position relative to the ground. However, uneven terrain can cause the body to rock, necessitating pitch angle adjustments. The desired pitch angle, θ_d, is maintained by controlling the pitch actuator, which stabilizes the attitude in such environments.
- Grip force (F_c): Napa cabbage must be cut at a consistent height to prevent over-cutting and under-cutting. Therefore, the blade must remain in contact with the ground and

adjust for an optimal cut. F_c is continuously measured to maintain the desired cutting height. By controlling the slide actuator, the desired grip force, F_{cd} can be achieved, ensuring effective and precise cutting.

2.3.2. Backstepping-Based Force Control

Backstepping control, commonly used for controlling nonlinear systems, is essential for ensuring precise attitude control in unstructured Napa cabbage fields. A backstepping control was designed and verified for its performance [35]. However, issues arose when the guide wheel, which measures height, was obstructed by cabbage leaves, rocks, or mulching vinyl, reducing accuracy. The gap between the guide wheel and blade further complicated precise measurement.

In this section, we utilize a backstepping control approach, which is commonly applied for controlling nonlinear systems. We aim to ensure precise attitude control of the cutting module while harvesting Napa cabbage. The backstepping control framework allows us to maintain a constant force on the cutting device while compensating for terrain irregularities and other disturbances.

To address these challenges, a backstepping-based force control strategy is implemented to improve performance. Instead of relying on height measurements, force control maintains F_{cd} by adjusting the stroke of the slide actuator along the x-axis. A backstepping controller is used to verify the effectiveness of this force control. The primary objective is to minimize this error to ensure stable and accurate cutting. The backstepping control involves the following steps (Figure 13):

Error definition: we first define the tracking error, z_f, as the difference between F_c and F_{cd}:

$$z_f = F_c - F_{cd}. \tag{3}$$

z_f represents the deviation from F_{cd}.

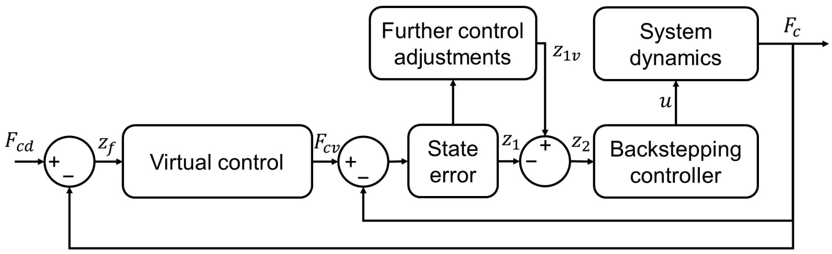


Figure 13. Block diagram of backstepping-based force control.

Virtual control input, F_{cv}: To correct this error, F_{cv} is designed to drive the error towards zero. The equation for F_{cv} is:

$$F_{cv} = k_1(z_f - \dot{z}_f)(k_1 > 0), \tag{4}$$

where k_1 is a positive gain constant. This input helps regulate the grip force to bring the error to zero.

State error definition and derivative: the state error, z_1, is then defined between F_{cv} and F_c, with its derivative calculated as follows:

$$\begin{aligned} z_1 &= F_{cv} - F_c, \\ \dot{z}_1 &= \dot{F}_{cv} - \dot{F}_c = k_1\dot{z}_f + \dot{z}_f. \end{aligned} \tag{5}$$

Lyapunov function: a Lyapunov function ensures that z_1 converges to zero over time. The Lyapunov function for this system is defined as:

$$\begin{aligned} V_1 &= \frac{1}{2}z_1^2, \\ \dot{V}_1 &= -k_1 z_1^2 - z_1\dot{z}_f. \end{aligned} \tag{6}$$

The negative definiteness of $\dot{V}_1$ ensures that the error will decrease over time.

Further control adjustments: To enhance stability, a second virtual control input, z_{1v} is introduced:

$$z_{1v} = k_2 z_1 + \dot{z}_1 (k_2 > 0), \tag{7}$$

followed by the definition of another state error (z_2):

$$z_2 = z_{1v} - z_1. \tag{8}$$

The introduction of z_1 and z_2 allows for a robust control scheme, ensuring that not only the force is regulated but that the convergence of these errors is stable and leads to a decrease in z_f.

These steps were used to modify the controller by adjusting the backstepping control input, u to maintain F_c. Constants k_1, k_2, and k_3 were selected based on system dynamics and requirements. The force applied to the slide actuator, m_a, considering the dynamic characteristics during harvester operation, is given by:

$$m_a = m_{all} \cos\theta. \tag{9}$$

where m_{all} is the total weight of the cutting device and varies with θ. For this system, m_{all} is 250 kg. u is designed as follows:

$$\begin{aligned} u &= k_2 z_1 + k_3 z_2 + m_a \dot{z}_1 (k_3 > 0), \\ k &= [k_1, k_2, k_3] = [10, 3, 3]. \end{aligned} \tag{10}$$

2.3.3. Preliminary Simulation

A Preliminary Simulation was conducted to verify the effectiveness of the designed attitude control module. A simulation program (Unity 2020.3.46f1, Unity Technologies, San Francisco, CA, USA) was used to create a virtual arable field environment, in which a Napa cabbage harvester equipped with the designed attitude control module was implemented (Figure 14). F_{cd} was set to 20 N, and θ_d was set to 35°. The control performance was evaluated by comparing height and pitch angle changes between the harvester with and without the attitude control module.

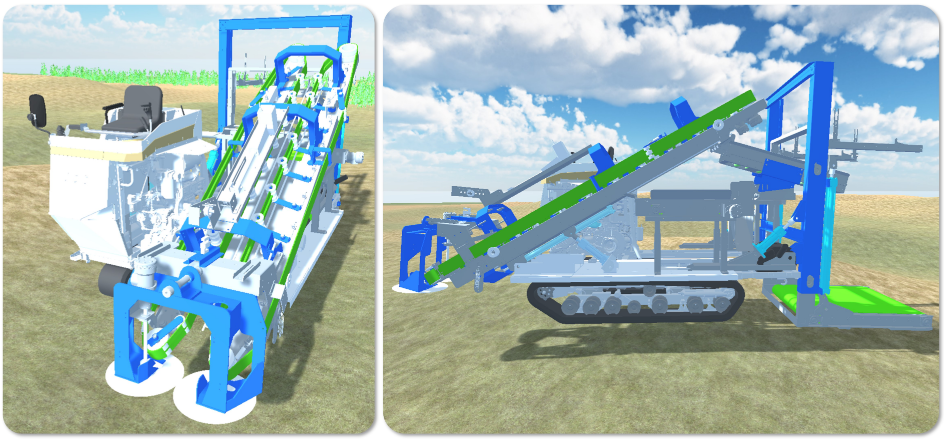


Figure 14. Preliminary simulation of attitude control system.

The results (Figure 15) show that the proposed module consistently maintains a pitch angle of 35°, unlike the system without attitude control, which experienced variations. This indicates that the attitude control module can stabilize the cutting module regardless of terrain variations, thereby improving the accuracy of Napa cabbage harvesting.

Furthermore, as shown in Figure 15, F_c was maintained at 20 N, resulting in a consistent cutting height of 25 mm. This value falls within the optimal range of 0 to 50 mm, as defined by Park et al. (2023), which is crucial for minimizing crop damage and maximizing cutting performance [35].

Notably, Figure 15 includes data extending beyond −200 mm. This occurred because the blade of the cutting module moved through the virtual arable field, leading to values measured beyond the intended range. Conducting similar tests in a real arable field could result in accidents, such as ground excavation, damage to the harvester, or personal injury. The preliminary simulation results confirm that the attitude control module effectively prevents such risks, ensuring safe and precise harvesting.

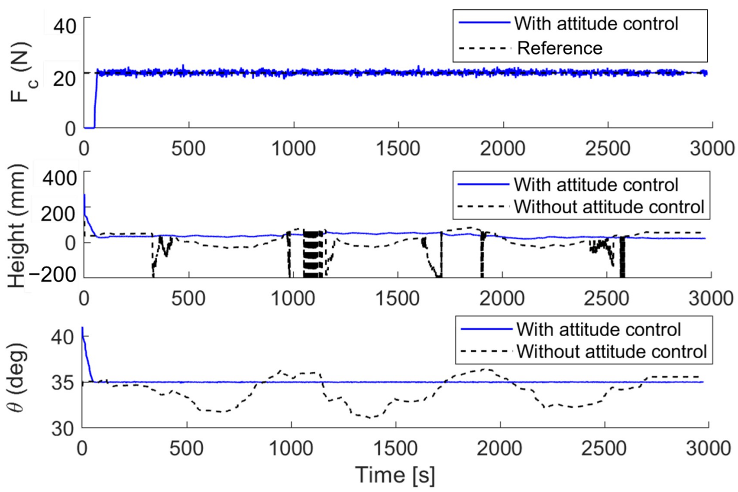


Figure 15. Preliminary results of the attitude control system.

2.4. Loading Module

The loading module reduces the burden on agricultural workers by automatically transferring harvested cabbages from the cutting module to a built-in storage area. This automation eliminates the need for manual labor during loading, significantly reducing labor costs. Moreover, the mechanization of this task minimizes physical strain on workers, thereby reducing the risk of injuries and MSDs. Automating the transfer and loading processes also accelerates the harvesting operation, enabling more cabbages to be harvested in a shorter time. Overall, the loading module is a critical component of the proposed self-propelled Napa cabbage harvester, providing a streamlined, efficient, and less labor-intensive solution.

Design of the Loading Module

The proposed loading module comprises a loading guide plate, a tilt mechanism, up–down actuators, and a transfer roller. The tilt, up–down, and transfer roller control mechanisms adjust the angle and height of the loading module (Figure 16). The parameters of the loading module are summarized in Table 3.

First, tilt control is performed to unload the ton bag when it reaches its capacity. Specifically, the loading guide plate, equipped with a conveyor, adjusts its angle to facilitate the unloading task. This automatic unloading feature can reduce the need for manual handling, thereby mitigating the risk of crop damage and worker fatigue.

Second, the up–down control mechanism directly loads the harvested cabbages onto a truck at an optimal height. This feature also enables the unloading of the ton bag onto the ground. Furthermore, up–down control can minimize potential damage to the cabbages during loading. Specifically, the mechanism adjusts the loading height to prevent the cabbages from being dropped from large heights onto the loading guide plate, thereby reducing the risk of bruising or other forms of damage.

Third, the transfer roller, manually operated by a worker, distributes the harvested cabbages evenly within the ton bag. This distribution strategy prevents the cabbages from being concentrated in an area, which may lead to pressure-induced damage. Consequently, the cabbages are stacked sequentially, ensuring their quality.

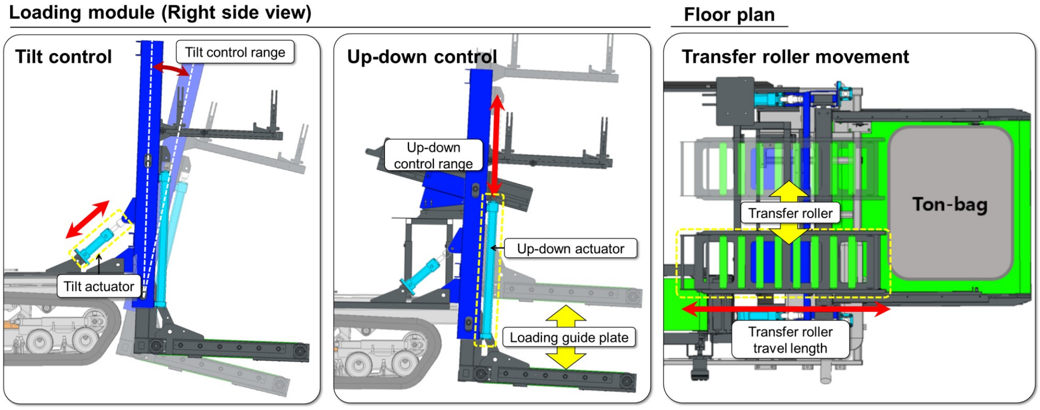


Figure 16. Design of the loading module.

Table 3. Parameters of the loading module.

Parameter	Specification
Length [mm]	1300
Width [mm]	1340
Height [mm]	1900
Maximum load [kg]	250
Tilt control range [°]	15–25
Up–down control range [mm]	200–1000
Transfer roller travel length [mm]	585

2.5. Field Experimental Design

A field experiment was conducted to evaluate the performance of the proposed Napa cabbage harvester, incorporating various systems as shown in Figure 4. The experiment took place in a 280 m^2 Napa cabbage field located in Suncheon, Republic of Korea (Figure 17). A total of 145 Napa cabbage heads were harvested during the experiment.

Figure 17. Field experiment environment.

The quality of the cutting surface was assessed using the scoring system proposed by Park et al. (2023) [35]:

- Three points were awarded for good cutting,
- Two points if some trimming was needed,
- One point for over-cutting,
- Zero points if the cabbage was deemed unusable and discarded.

The evaluation focused on several aspects:

- Time required for harvesting: The total time taken was measured to compare efficiency.
- Comparison of manual and automatic attitude control: Differences between manual and automatic control modes for the attitude control module were analyzed.
- Performance of attitude control module: The ability of the attitude control module to maintain optimal cutting conditions was also evaluated, focusing on cutting precision and stability.

This comprehensive evaluation aimed to assess the overall efficiency, quality, and performance improvements achieved using the proposed harvester, particularly highlighting the benefits of automated systems compared to manual methods.

3. Results and Analysis

3.1. Field Experimental Result

3.1.1. Comparison with Manual Labor

The results of the field experiments, summarized in Table 4, indicate a substantial improvement in harvesting efficiency due to the introduction of the proposed integrated cabbage harvester. According to a 2021 survey by the Korea Rural Development Administration, the harvesting process for each 1000 m^2 typically requires significant labor: 19.7 h for harvesting, 5.9 h for sorting and packing, and 2.6 h for transportation, with at least five workers involved. These tasks, executed sequentially, often include additional loading time, contributing to the overall labor intensity.

Table 4. Results of the field experiment of the proposed Napa cabbage harvester.

		Manual Labor	**Proposed Harvester**	
			Manual Control	**Automatic Control**
Task time [h/1000 m^2]	Harvesting	19.7	15.4	8.5
	Packaging and loading	5.9		
	Transporting	2.6	1.0	1.0
	Total	28.2	16.4	9.5
No. of workers [persons]		5	3	2
Harvest cabbage [head]			75	70
Yield area [100 m^2]			1.45	1.35
Traveling speed [m/s]			0.04	0.07
Quantified cutting rate [%]	Good cutting		89.3	85.7
	Needed some trimming		5.3	0.0
	Over-cutting or missed		5.3	14.3
	Needed to be discarded		0.0	0.0
Cutting surface quality (scores) [%]			94.7 (2.8)	90.0 (2.7)

The proposed harvester, as depicted in Figure 18a, not only performs harvesting but also handles tasks such as sorting and packing, reducing the overall task time by 11.8–18.7 h/1000 m^2 compared with conventional manual labor. This corresponds to a task time reduction rate of 42 to 66%. According to Hachiya et al. (2004), an 8 h work shift should include a 1.5 h break, resulting in an actual task time of approximately 6.5 h [22]. The experimental results demonstrate that the proposed harvester allows for a larger yield to be harvested without excessive worker strain compared to manual labor.

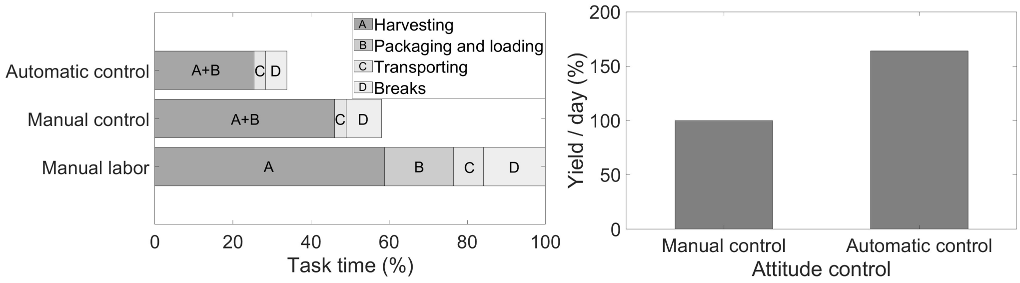


Figure 18. Efficiency of the proposed harvester: (**a**) comparison with manual labor, (**b**) comparison of manual and automatic attitude control strategies.

Additionally, the automated loading system of the harvester significantly reduces the labor and time required for packing and transportation, improving overall labor efficiency. During mechanical harvesting, 60 Napa cabbages can be stored in ton bags, which considerably reduces the time needed for harvesting, sorting, and packing compared with manual methods. The workforce requirement can also be reduced to 2–3 people. When operated by skilled workers, the harvester can perform tasks effectively with minimal labor, thereby enhancing both productivity and efficiency.

The efficiency improvements of the proposed harvester in comparison with manual labor, as well as the differences between manual and automatic attitude control, are presented in Figure 18.

3.1.2. Comparison of Manual and Automatic Attitude Control

The results presented in Table 4 highlight the efficiency of automatic attitude control for autonomous harvesting tasks. Unlike manual control, automatic control requires a lower task time of 6.9 h/1000 m^2. In manual control strategies, the operator must accurately assess whether the Napa cabbage has entered the cutting module with the correct attitude, which is challenging. Consequently, additional personnel may be required to monitor the attitude and provide feedback to the operator. The operator then adjusts the attitude based on the feedback, which increases the task time.

Nevertheless, the quality score of the cutting surface for manual control (94.7%) is slightly higher than that (90.0%) observed in automatic control. Thus, a *t*-test was conducted to verify the statistical significance of the mean difference between the two groups. The results indicate that the difference is insignificant. As shown in Figure 18a, automatic control is more efficient than manual control, resulting in enhanced efficiency for attitude control. The calculated task time was used to compute the yield area and yield harvested in a day, defined as 12.0 h, corresponding to daylight hours. Assuming that the workers are provided 1.3 h of break time during this period, the actual task time is 10.0 h (excluding breaks).

The yield/day is illustrated in Figure 18b. Under manual control, 3065 heads can be harvested in an area of 610 m^2, whereas automatic control enables the harvesting of 5026 heads over 1000 m^2. The difference is statistically significant, as demonstrated by the *t*-test results. Moreover, automatic control enables operation with one less worker compared with manual control, thereby facilitating shift-based operations. These results highlight that harvesting based on automatic attitude control is more efficient than manual control.

3.1.3. Performance of Attitude Control

To thoroughly evaluate the performance of the automatic attitude control system, the measured values of θ and F_c are meticulously analyzed. As demonstrated in Figure 19, θ

and F_c are consistently maintained at 35° at 0 N, respectively, showcasing the robust tracking performance of the system. The precision of these measurements is further substantiated by the root mean square errors (RMSEs) and mean absolute errors (MAEs) listed in Table 5. The results confirm that both θ and F_c closely adhere to the desired values of θ_d and F_{cd}, maintaining the efficiency and integrity of the harvesting process within an acceptable margin of error. These results were benchmarked against a previous study by Park et al. (2023) to validate their significance and reliability [35].

Table 5. Deviation statistics for attitude control.

	Pitch Angle, θ [°]	**Grip Force, F_c [N]**
RMSEs	0.31	22.65
MAEs	0.27	17.10

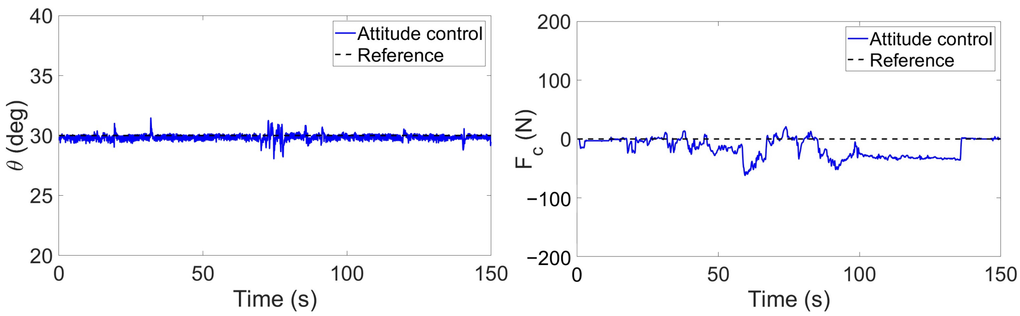


Figure 19. Accuracy of the automatic attitude control module.

Furthermore, the efficacy of the automatic attitude control system is underscored by the cutting surface score, a metric that reflects the quality of the harvested Napa cabbage. By employing the same evaluation scheme used in the previous study for a fair comparison, the proposed harvester achieves a cutting surface score of 2.7 points, translating to 90.0%, as detailed in Table 4. This score notably surpasses the 2.57 points (85.7%) reported by the existing study, providing empirical evidence of the superiority of the proposed harvester. This performance enhancement demonstrates the effectiveness of the improved attitude control system, particularly the implementation of force control, which ensures a more precise and consistent cutting process. By integrating these advanced control mechanisms, the harvester not only improves the quality of the harvested produce but also sets a new benchmark in Napa cabbage harvesting.

3.1.4. Validation of Conveyor Part in the Cutting Module

During the design phase of the cutting module, an appropriate spring was selected through simulations, exerting a clamping force that securely holds the Napa cabbage without causing damage. Furthermore, throughout the experiments, 145 Napa cabbages were harvested under both manual and automatic control, as detailed in Table 4. These experiments were continuously conducted over an area of 280 m². Notably, there was no loss or detachment due to the clamping force in the conveying part during this period. These results affirm the reliability of the clamping force of the conveying mechanism in the cutting module, indicating that it functions effectively without compromising the integrity of the Napa cabbage.

4. Discussion

4.1. Limitations

The advancements made in agricultural mechanization by this study, particularly regarding the autonomous Napa cabbage harvester, are significant. However, several limitations need to be addressed.

4.1.1. Challenges in Napa Cabbage Harvesting

The unstructured and variable nature of the Napa cabbage harvesting environment introduces complex dynamic characteristics that pose significant challenges. Although the study incorporates a correction factor α to adjust for vertical acceleration due to field roughness, the real-time prediction of these dynamic characteristics is not feasible within the scope of this research. This limitation impacts the precision of force calculations crucial for the optimal operation of the vertical force and clamping force of the conveying mechanism, thereby potentially affecting the harvesting efficiency and effectiveness.

Moreover, while field experiments were conducted, the system still requires further validation under a wider range of field conditions and with different Napa cabbage varieties. Comprehensive validation is essential to ensure robustness and generalizability across diverse agricultural scenarios, thereby establishing the reliability and effectiveness of the harvester in various environments.

Additionally, this study focused primarily on the harvesting process, with limited attention given to the automation of post-harvest tasks such as cleaning, trimming, and quality inspection. Automation of these subsequent stages represents a significant opportunity for future research and development, potentially enhancing the overall efficiency and productivity of Napa cabbage harvesting.

4.1.2. Damage to Napa Cabbage by Ton Bag Loading

Using ton bags, designed to carry up to 1000 kg, may lead to Napa cabbages being damaged by compression during the loading process. To mitigate damage from falling, up–down control is incorporated into the loading design, as illustrated in Figure 16. Additionally, implementing a transfer roller aims to distribute the Napa cabbages more evenly within the bags. Despite these measures, the inherent nature of loading into ton bags still results in discrepancies in quality between the cabbages at the bottom and those at the top. The cabbages loaded initially may suffer from bruises, deformation, or tears in the leaves, negatively impacting the overall quality and shelf life.

Furthermore, loading into ton bags presents challenges in accurately counting and weighing the harvested cabbages, leading to potential discrepancies in harvest quantities. The ability to adapt to the natural variations in cabbage dimensions due to growth or other factors is also limited.

In contrast, the traditional manual harvest sequence involves packing cabbages in groups of three and loading them onto transport trucks. This method allows the Napa cabbages to be tightly bound, minimizing deformation and damage. The increased density also enables the cabbages to withstand higher weights, offering a more protective solution than loading into ton bags.

4.2. Future Directions and Automation Enhancement

The introduction of an innovative automated Napa cabbage harvester that integrates cutting, attitude control, and loading modules is presented in this paper. The satisfactory performance and efficiency have been demonstrated through field experiments. However, several areas for future development have been identified, with a focus on addressing current limitations and enhancing the system automation capabilities.

A key direction for future work is the automation of decision-making criteria for each stage of the harvesting process. Currently, these decisions are largely subjective and rely on human operator judgment. To address this, an intelligent system is envisioned that leverages sensors, data analytics, and machine learning techniques to autonomously determine the optimal conditions for each sequence. This approach aims to enhance the accuracy, efficiency, and stability of the harvesting process.

Furthermore, the need to automate post-harvest processes, which are currently labor-intensive and time-consuming, has been recognized. Post-harvest tasks, including cleaning, trimming, and quality inspection, require significant manual effort. The goal is to incorporate automated systems for these processes, integrating technologies for cleaning, trimming, and quality inspection into the automated harvester system. This integration is expected to significantly streamline the post-harvest phase, reducing the time and labor needed to prepare the harvested Napa cabbages for the market.

By addressing these areas, the goal of future work is to deliver a comprehensive solution that automates not only the harvesting process but also the subsequent post-harvest tasks. The ultimate vision is to create a fully autonomous system that covers the entire process, from field to transportation, providing a revolutionary approach to Napa cabbage harvesting and setting a new benchmark in agricultural mechanization.

5. Conclusions

This paper proposes an autonomous self-propelled Napa cabbage harvester that integrates cutting, attitude control, and loading modules. This study aimed to mechanize the Napa cabbage harvesting process, which is currently labor-intensive and inefficient. Preliminary simulation validated the designed modules, and subsequent field experiments demonstrated the effectiveness of the proposed harvester.

The effectiveness of the attitude control module was evaluated through simulation experiments. The module maintained a consistent θ of 35° and an F_c of 20 N, achieving an optimal cutting height of approximately 25 mm. Furthermore, it prevented excessive blade penetration into the ground, ensuring safety and performance.

Field experiments were conducted to compare the proposed harvester's performance and efficiency with manual labor and attitude control. A total of 145 Napa cabbage heads were harvested in a field in Suncheon, Republic of Korea. The proposed harvester reduced the harvest time by 11.8 to 18.7 h/1000 m^2, corresponding to a reduction of 42% to 66% compared to manual labor. Additionally, the number of workers required was reduced to two or three, compared with the typical five workers needed for manual harvesting.

The performance of manual versus autonomous attitude control was also compared. Automatic control reduced the task time by 6.9 h/1000 m^2, representing a 42% improvement over manual control. Although the cutting surface quality achieved with manual control (2.8 out of 3) was slightly better than that achieved with automatic control (2.7 out of 3), the difference was not statistically significant. This suggests that automatic control can enhance harvesting speed and efficiency without compromising quality.

The performance of the automatic attitude control was evaluated, with root mean square errors (RMSEs) of 0.31° for θ and 22.65 N for F_c, and mean absolute errors (MAEs) of 0.27° and 22.65 N, respectively. The harvesting scores improved by 5% (from 2.57 to 2.7) compared with previously reported results [35], demonstrating the effectiveness of the force-based attitude control.

The proposed harvester represents the first successful integration of cutting, attitude control, and loading modules for Napa cabbage harvesting, offering a solution to address issues associated with traditional methods, such as worker injuries, low productivity, and high costs. Future work will focus on optimizing the harvester by automating decision-making criteria for various sequences using intelligent tools such as sensors, data analytics, and machine learning. Additionally, system efficiency will be evaluated across diverse scenarios, including different varieties and sizes of Napa cabbage, varying soil types and slopes, and different seasons and weather conditions.

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