Advancing Agricultural Automation: Innovative Product Design and Research for Carrot Harvesters

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Abstract. Many industrial areas benefit by applying product design strategies in their applications, and agriculture is one of the most challenging of them. We design a novel carrot harvester equipped with an adaptive spring-loaded belt clamping system designed to adjust to varying densities of carrot, thus ensuring effective harvesting without damaging the crop. Our design incorporates a multi-angular soil disruption structure, enabling the harvester to adapt to different soil hardness and moisture levels. This feature is facilitated by linear actuators that adjust the tiller angle, we address the critical issue of soil adhesion which affects the cleanliness and quality of the harvested carrots. Field tests and simulation analysis have validated the functionality of our design, demonstrating notable improvements in harvesting efficiency and a reduction in labor requirements. The design providing a scalable solution that can be adapted for various root crops beyond carrots.

Keywords: Innovative Design, Product Design, Agricultural Robot.

1 Introduction

In numerous countries, traditional field management tasks represent labor-intensive operations. This labor intensity presents significant challenges as the agricultural sector is currently witnessing a notable decline in its workforce. Concurrently, the integration of autonomous robots into agricultural practices is accelerating, primarily driven by their potential to significantly boost food security and sustainability. Some studies[1] have concluded that the robotic systems enhance resource use efficiency, reduce chemical handling, and decrease the reliance on manual labor. The rapid development of agricultural robotics is predominantly focused on optimizing field management processes including spraying, fertilization, crop phenotyping, and selective harvesting. Meanwhile in China, carrot cultivation practices exhibit substantial variability influenced by local conditions such as soil, topography, and climate. This variability fosters decentralized, small-scale farming methods, such as flat, row, and border planting, which often lack uniform standards across different regions.This diversity in cultivation practices complicates the development and adoption of mechanized planting and harvesting technologies. As a result, the level of mechanization in carrot planting and harvesting remains low [2]. The scenario leads to high labor intensity and inefficiency, escalating costs and diminishing the economic benefits of carrot farming [3]. Consequently, this discourages farmers from expanding carrot production.Recent findings suggest that autonomous field robots can significantly mitigate many detrimental environmental impacts and reduce the reliance on manual labor [4]. For instance, weeding robots that reduce or

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eliminate the use of herbicides have been commercialized, leveraging advanced AI techniques to ensure targeted agrochemical application and improved crop management [5].

The robots discussed are primarily deployed for functions including the application of pesticides, fertilizing crops, analyzing soil, and gathering data on crop phenotypes. Essential to their operation are technologies such as mobile chassis systems, advanced positioning and navigation, and precision control mechanisms. Currently, agricultural machinery often fails to account for regional variations in soil conditions such as hardness and moisture content, significantly impacting their effectiveness. For example, differences in soil properties can lead to variations in the performance of carrot harvesting equipment, as seen in studies that evaluate the impact of soil conditions on root crop production [6].Furthermore, during carrot harvesting, the adherence of soil to the surface of the carrots affects their cleanliness and appearance, presenting additional challenges for existing harvesting equipment. Unfortunately, most current machinery does not effectively clean the soil from the carrots, as the design of these machines often does not consider the specific soil and crop parameters that affect the cleaning process [7]. This article presents the design of an agricultural robot capable of collecting carrot fruits and dislodging soil. The robot is designed for future applications in tasks such as harvesting and gathering crop data. We outline our design approach and provide a detailed description of the analysis and implementation methods.

2 Analysis Requirements for Carrot Harvesters

2.1 Carrot Harvesters Positioning

Carrots, known scientifically as Daucus carota, are highly regarded for their nutritional and medicinal benefits, functioning both as a healthy dietary staple and a plant with health-enhancing properties. They are rich in carotenoids, flavonoids, polyacetylenes, vitamins, and minerals, which contribute to their status as functional foods with potential anti-diabetic, cholesterol-lowering, and cardiovascular protective effects [8]. The cultivation of carrots is relatively straightforward, often characterized by a low susceptibility to pests and diseases. This enhances their viability for extensive agricultural operations and large-scale farming [9]. In terms of post-harvest handling, carrots offer several logistical advantages. They are robust, facilitating easy storage and transportation, which is critical for markets requiring long-distance distribution [10]. Carrots have a relatively short growing period and are compatible with various crop rotation strategies, thereby enhancing soil health and mitigating the risk of disease build-up in the fields. These attributes make carrots particularly valuable as a traditional crop for disaster relief efforts, where quick cultivation and easy distribution are necessary [11].

Given these characteristics, the development of mechanized harvesting technologies for carrots is particularly pertinent [12]. Such technologies aim to enhance the efficiency of the harvesting process, reduce the dependency on manual labor, and maintain the integrity and cleanliness of the harvested produce. The robot integrates advanced sensory and automation technologies to optimize the harvesting process, thereby aligning with the agricultural industry's move towards increased mechanization and sustainability in crop production [13].

2.2 Usage Scenario Analysis

For the field of agricultural consumption, the carrot harvester integrates advanced monitoring and tracking capabilities to oversee the entire lifecycle of agricultural products—from production and processing to transport and sales. Utilizing agricultural big data, this system ensures a transparent record of the food's journey from the farm to the consumer’s table. This transparency meets the growing consumer demand for traceability, allowing an assessment of food quality prior to purchase and safeguarding consumer interests. Such technological integration into agricultural practices enhances operational efficiency and reinforces consumer trust in food safety and quality [14].

The adoption of automated harvesting technology by agricultural operators can effectively address issues such as low crop yields and the suboptimal structuring of agricultural products. This technology reduces the need for manual labor and resource input, thereby enhancing the efficiency of agricultural production and increasing the income of operators. Currently, the minimal mechanization of carrot harvesting results in high labor intensity, low efficiency, and elevated planting costs for farmers, which directly diminishes their motivation to cultivate carrots [15]. As manual labor resources continue to dwindle, the mechanization of carrot production emerges as an essential strategy for the development of the carrot industry.

2.3 Hierarchical Task Model of Carrot Harvesters

The complete hierarchical task model for carrot harvesting in a field farm environment is analysed through scenarios. The overall task of using a carrot harvester in this process consists of three main tasks of preparation, harvesting and storage forming a complete task flow.

3 Prototype design of carrot harvester

3.1 Materials and Methods

Carrot harvesters operate in a variety of soil conditions, from sandy to clay-heavy soils. For the digging and cutting components, have to highly durable and wear-resistant to withstand the abrasion and mechanical stress encountered during operation. Carbide-tipped blades are used for these parts to ensure longevity and effectiveness. Aluminum alloys are favored for structural components to prevent rust and degradation, maintaining the structural integrity and reliability of the machinery over time and can lead to better energy efficiency.

Track-driven systems distribute the weight of the harvester more evenly than traditional wheels, reducing soil compaction which can adversely affect crop growth. The tracks, typically made from durable rubber with reinforced steel or composite cores, provide excellent traction in various soil conditions, from wet and muddy to dry and sandy.

After defining the functionality of the product module and the functional scheme, the next step is to carry out the specific design, which includes features such as the type of control, the way it works and the structural layout. The overall structure apperance of the robot is designed as shown in Fig 1.

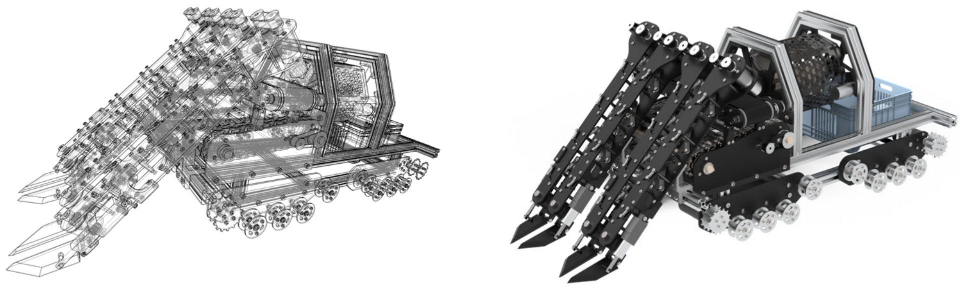

Fig. 1. Design scheme of carrot harvester.

3.2 Structure design

3.2.1 Spring-adjusted harvesting mechanism with clamp design

The main role of the clamping device is to pull out the carrot plant, with the current disclosure of other chain clamping mechanism [16] composed of pulling chain, sprocket and tensioning spring, etc., to avoid easy to clip off the carrot stems and leaves, resulting in the leakage of the pulling, and the complexity of the structure, the cost of manufacturing and so on, we use the clamping type of harvesting, in order to meet the different stems and leaves of different sparsely spaced carrots harvested, the team set up a spring adjustable design, the spring can be changed through the sparsely spaced leaves and leaves to change the spring expansion and contraction, thereby changing the friction band spacing to reduce the leakage of pulling and pulling the phenomenon of the occurrence of a fewer number of strong versatility, such as shown in Fig 2

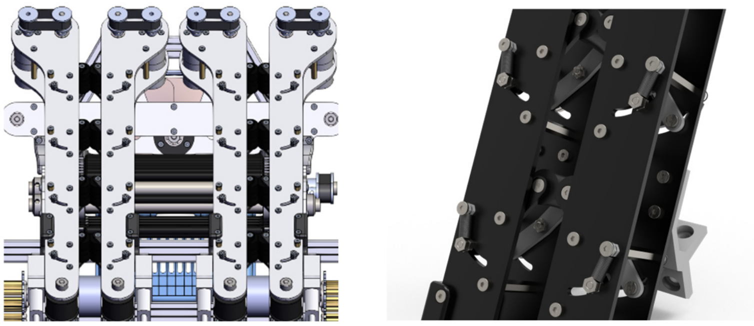

Fig. 2. Diagram of spring adjustment with clamping harvesting mechanism.

3.2.2 Multi-tilt angle adjustment groundbreaking structure design

The central element of the loosening device is the loosening shovel, which is pivotal in enhancing the effectiveness of soil-fruit separation. To develop a loosening shovel optimized for carrot harvesting, it is crucial to ensure that it effectively disturbs the soil without damaging the carrot roots, while also minimizing operational resistance. Addressing the challenge posed by varying soil physical properties, the shovel incorporates an articulated design powered by linear motors. This design allows for adjustments in the tilting angle of the breaking claw, enabling it to adapt to different soil hardness levels effectively. This functionality is illustrated in Fig 3.

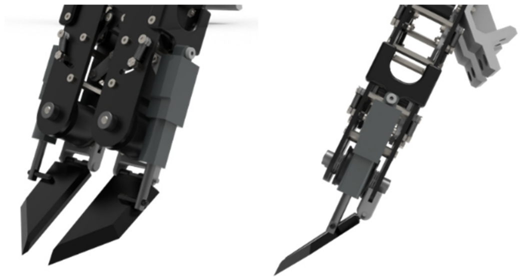

Fig. 3 Diagram of mlti-tilt angle adjustment groundbreaking structure.

3.2.3 Spiral soil separation structure design

To address the issue of soil adhesion to harvested carrots, which typically necessitates a secondary processing step to clean them. Taking inspiration from composite planters[17], we designed and developed an innovative spiral leaf shaking mechanism. This mechanism, depicted in Fig 4 mploys a motor-driven spiral leaf that rotates to effectively dislodge soil clinging to the carrots. The rotational movement of the spiral leaf creates a dynamic shaking action, ensuring that the carrots are subjected to sufficient agitation to shake off the adhering soil without causing damage to the produce.

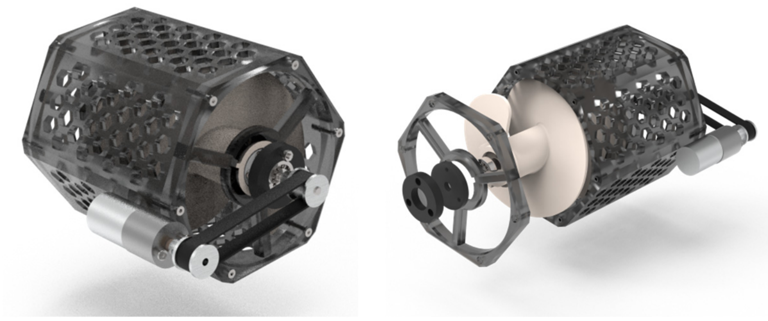

Fig. 4 Diagram of spiral soil separation structure.

3.3 Function design

The carrot harvesting robot has been designed to have 8 main functions which are: (1) angle adjustment of groundbreaking claw; (2) multi-tilting angle adjustment; (3) synchronous belt adjustment; (4) drive module operation; (5) cutting mechanism; (6) stem and leaf transport; (7) carrot transport to cleaning mechanism; (8) collection in staging box. The carrot harvester was designed to perform a "primary task", and in order to perform the "primary task", the robot needed to have the ability to perform a number of "support tasks". Information and commands are passed between the "support tasks" and between the "support tasks" and the "primary task".

Each "support task" controls one or more subsystems and devices, and one subsystem or device may serve more than one "support task". This is illustrated in Fig 5.

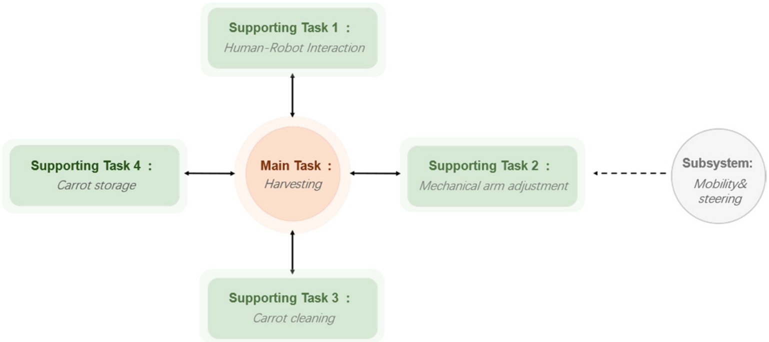

Fig. 5 Structure of task sub-systems in carrot harvester.

To initiate operation, the main switch is activated, enabling the adjustment of the groundbreaking claw's tilting angle via the linear motor based on the soil's physical characteristics. The groundbreaking structure's tilting angle is variably adjusted to accommodate the sparsity of the radish stems and leaves. Concurrently, the spacing of the synchronous belt is modified through a spring mechanism, allowing the motor within the drive module to commence operation. This initiates the forward movement of the machine, where the synchronous belt grips and lifts the stems and leaves upward.As the machine progresses, the blades execute a cutting motion to separate the stems from the carrots. The separated stems and leaves are then conveyed to the ridges on either side of the machine via a belt transmission system. Meanwhile, the carrots are transported towards the spiral leaf shaking mechanism through a rolling drive mechanism. Here, the rotating spiral blade vigorously shakes the carrots, effectively dislodging soil adhered to their surfaces. The cleaned carrots subsequently fall into a staging box, ready for further processing or packaging.

4 Conclusion

This study provides design ideas for the realisation of smart agricultural products through the above analysis and practical design of carrot harvester. For large-scale carrot producers, this equipment can improve harvesting efficiency, reduce production costs, precisely control the strength and operation mode during the harvesting process, reduce the damage rate, ensure the quality of agricultural products and maintain consistency, and improve the market competitiveness of agricultural products.

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