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An Intelligent Blade Balancing Control System for Steep-Terrain Tea Cutting Applications

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ABSTRACT

Tea is a famous and valuable beverage in Taiwan. Tea is mainly grown in steep or mountainous areas. The terrain is a challenge for harvesting automation. Manual labor in harvesting tea in complex terrain is time-consuming and affects the economic efficiency of the product. This study proposes a tea-cutting blade balancing control system integrating image processing and fuzzy logic control. A unique mechanism is developed to adapt to the slope of the terrain. The limiting angle is 12 degrees relative to the horizontal plane. A prototype is fabricated and evaluated in the field. Experiments are conducted on an automated tea harvesting vehicle with moving speeds of 1 m/s and 0.36 m/s for leafless cutting and leaf cutting, respectively. The system achieved a response time of 257 milliseconds, with a corresponding angular resolution of approximately 2.1 degrees per second. The results demonstrate the field performance of the system and its potential for commercial deployment.
Keywords: Tea leaf harvesting, Tea leaf detection, Fuzzy logic control, Fuzzy controller.

INTRODUCTION

Planting, tending, and harvesting crops require a large amount of labor. This increases labor costs and yields are not guaranteed. (Yang, Du et al. 2023) Summary of the core of agricultural cultivation technology. (Li, Zhu et al. 2024) proposed high-tech integrated tea harvesting systems. (Lai, Chen et al. 2020) proposed a robot that cooperates with farmers during harvesting to reduce the burden on farmers. This study focuses on the solution of cutting the entire surface of the tea bed. The height of the tea branches affects the quality and economic value in the market. Tea plantations are often located in hilly and steep terrain. The terrain has always been a challenge for automation in agriculture. (Yi, Wang et al. 2024) proposed a method to solve the complexity of the terrain. Intelligent control is increasingly proving its effectiveness in the field of agricultural machinery. (Sain, Mohan et al. 2025) A Fuzzy controller is proposed to control the active suspension system of a tractor. This study proposes a solution to control the balance of the tea-cutting blade regardless of the terrain changes.

MATERIALS AND METHODS

The tea-cutting system communicates with the autonomous platform via CAN bus communication. The tea height is extracted from the depth camera. The flowchart is shown in

Fig. 1. The controller adjusts the blade position and applies fuzzy control for terrain adaptation. It also activates the blowing–sweeping unit for leaf collection. This enables a continuous harvesting cycle. The cutting blade position must be controlled during operation. As shown in Fig. 2, the mechanical design accommodates up to a 12° terrain slope by combining rotary and linear motions, which adjust the frame length. The system operates on tea beds 1800 mm wide and 600–900 mm high. An IMU measures blade deviation from the horizontal, while a depth camera, mounted at 60° from vertical, provides terrain data.

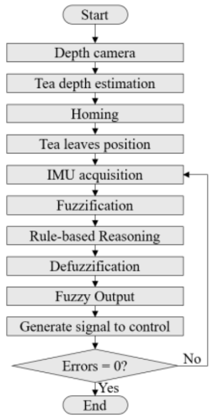

Fig. 1 Flowchart of tea cutter system.

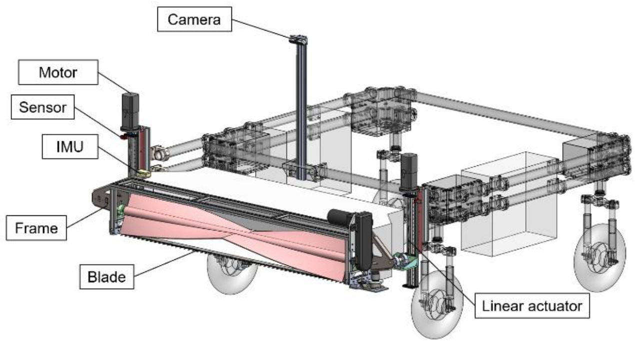

Fig. 2 Mechanism design.

Tea leaf depth estimation uses RGB and depth data from an Intel RealSense D435i. RGB images are converted to HSV, segmented by multi-thresholding, and noise-filtered to generate a leaf mask. The filtered depth image is fused with this mask to create a fusion map, combining spatial and depth information for accurate leaf–camera distance estimation. Intelligent control has shown effectiveness in agricultural machinery, where environmental factors strongly affect accuracy. In this study, terrain variations are handled by a fuzzy controller to maintain blade balance during harvesting. The IMU on the blade provides deflection angles as input, and motor speeds are the outputs. Membership functions are shown in Fig. 3. Real-time operation remains challenging, requiring a trade-off between computation and execution time.

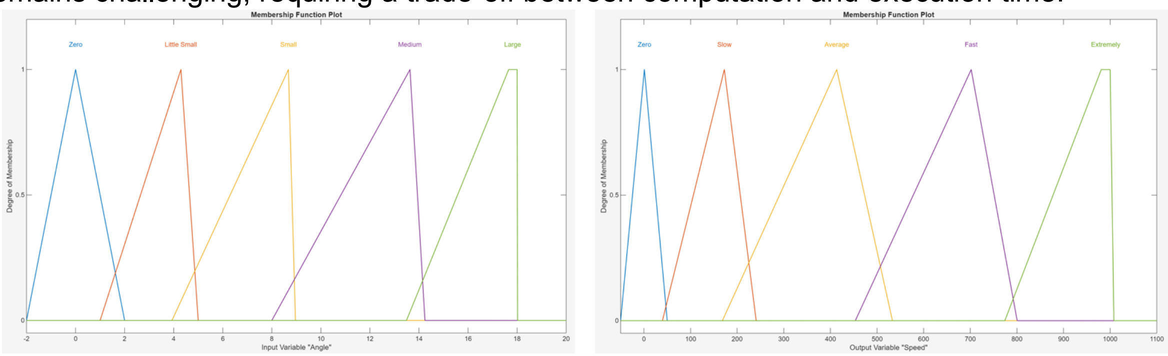

Fig. 3. The membership function.

RESULTS & DISCUSSION

To evaluate the system adaptation, field experiments were conducted with the IMU interfaced to the microcontroller at a sampling frequency of 10 kHz. The IMU was mounted on the system frame to collect data. However, significant vibrations during operation affected its measurement accuracy. An anti-vibration mechanism was implemented to reduce sensor fluctuations. A static experiment was then performed to assess the system settling time, with the results presented in Fig. 4 and Fig. 5. The experimental results confirm that the controller effectively regulates both the angle and the velocity of the system. For the angle response, the system was driven from an initial state of approximately –7.7° to the equilibrium position at 0°. The angle was rapidly corrected within the first 4–5 s and continued to converge smoothly, reaching steady state after about 20 s, with negligible overshoot and an almost zero steady-state error. Simultaneously, the velocities of both motors were thoroughly regulated, converging to zero within 14–15 s and remaining stable thereafter. The results demonstrate the stability of the control system.

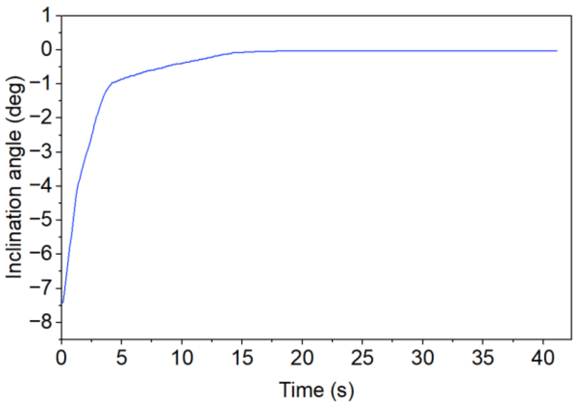

Fig. 4 Settling Time of the Controlled System.

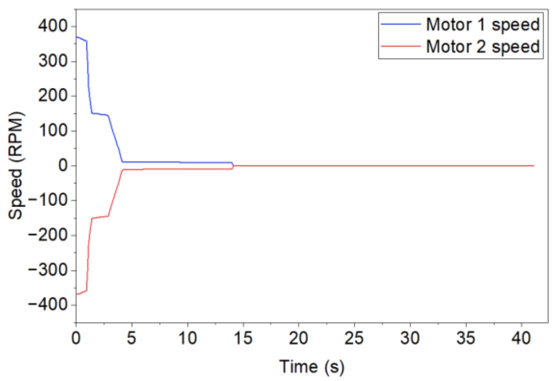

Fig. 5 Adaptive motor speed.

Fig. 6 illustrates the repeatability error at inclination angles ranging from 1° to 7°. The results show that the error varies between 0.4° and 1.0°, with most values concentrated around 0.6°–0.8°. At inclination angles of 1°–4°, the error remains relatively stable with little variation between repetitions, whereas at 5° a noticeable fluctuation occurs, with one repetition reaching 1°, the highest error across all tested angles. At 6° and 7°, the error tends to be more consistent, falling within 0.6°– 0.7°. Overall, the system demonstrates reliable and stable measurement performance at most inclination angles, except for 5°, where an abnormal increase in error was observed and requires further investigation.

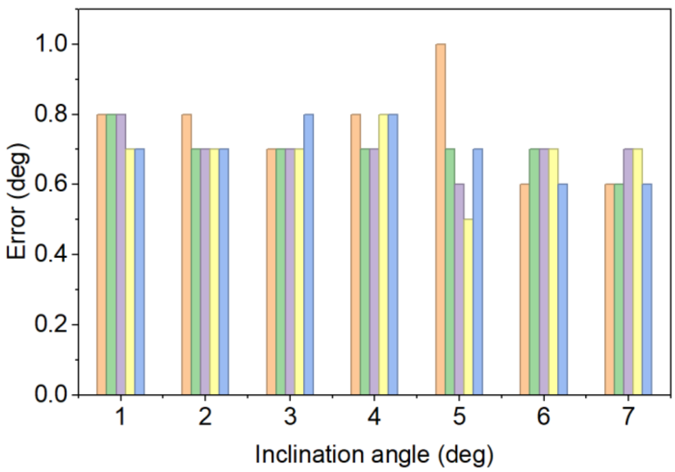

Fig. 6 System repeatability error at different inclination angles.

CONCLUSIONS

The study proposed a tea-cutting balance control system. Field experiments have demonstrated the potential of the system. Depth camera and intelligent control are the foundation of this research. However, implementing this system in practice still presents many challenges. Environmental factors will affect the accuracy and response of the system. During the experiments, the vibration of the cutting blade during operation also interferes with the control system. Improving stability and accuracy is the direction of research development.

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