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## MULTI-SYSTEM ENHANCEMENT OF AUTONOMOUS FIELD VEHICLES FOR CROP MONITORING APPLICATIONS

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### ABSTRACT

Autonomous field vehicles face operational challenges in agricultural environments, including terrain-induced instability, image quality degradation during motion, and limited operational endurance that compromise the reliability of data collection for precision agriculture applications. This study presents systematic improvements in three critical subsystems of autonomous vehicles for field-based crop monitoring: mobility optimization, visual stabilization, and power management. The study addresses fundamental engineering challenges limiting the deployment of autonomous monitoring platforms in agricultural terrains. Mobility performance was assessed through comparative analysis of foam versus pneumatic tire configurations using slip ratio. Slip ratio analysis showed reductions from 14.81% to 18.56% for foam tires to 8.35% to 9.67% for pneumatic tires. For visual stabilization, a gimbal-based system reduced the vertical deviation standard deviations 4.255 cm to 2.090 cm and the tilt angle from 4.293° to 0.999°, indicating substantial gains in image stability during vehicle movement. For power management power system testing on grassy terrain showed approximately 3 hours of continuous operation. These integrated improvements enhance the performance and reliability of autonomous vehicles in agricultural monitoring, providing a stable platform for precision data collection. This comprehensive approach addresses the key technical barriers that limit the adoption of autonomous monitoring systems in modern agriculture.

**Keywords:** Autonomous vehicles, Power management, Terrain adaptation, Vehicle dynamics, Smart farming.

### INTRODUCTION

Modern agriculture faces growing challenges from labor shortages and aging workforces. Tasks such as crop monitoring demand long hours of repetitive work. Unmanned Ground Vehicles (UGVs) offer a solution by operating without human intervention, enabling autonomous navigation through crop rows while capturing images for crop monitoring, thereby reducing reliance on manual labor (Mueller-Sim et al., 2017). Different types of vehicles inevitably rely on sensing and power supply. This study presents the development of an agricultural vehicle integrating mobility optimization, visual stabilization, and power management subsystems, aiming to provide a reliable platform for precision agriculture.

## MATERIALS AND METHODS

### VEHICLE CONFIGURATION

In this study, a vehicle was developed to navigate orchard plant rows while recording crop conditions. The system is powered by dual 24 V 12 Ah lithium-ion batteries and controlled by an embedded computing unit (Nvidia Jetson Orin NX 16 GB) capable of real-time sensor data processing and motion control. The vehicle integrates a front-view camera and a 2D LiDAR for plant row detection and path alignment, as well as dual plant-view cameras mounted on two-axis gimbals to stabilize images on uneven terrain (Lin et al., 2024). The drive system utilizes four wheel-mounted motors with two motor drivers (Fig. 1a).

### MOBILITY STABILITY: SLIP RATIO EVALUATION OF FOAM AND PNEUMATIC TIRES

Vehicle mobility tests were conducted on a grass to compare the performance of foam and pneumatic tires. The vehicle traveled at a constant speed of 0.17 m/s over a 10 m straight path. For each test, the number of wheel rotations was determined by counting wheel marks. The theoretical travel distance without slip was calculated by multiplying the number of wheel rotations by the tire circumference, where the foam tire had a circumference of 40.5 cm and the pneumatic tire had a circumference of 44 cm. This was then compared with the actual travel distance to determine the slip ratio (Almoosa et al., 2025):

$$\text{Slip Ratio} = \frac{D_{\text{theoretical}} - D_{\text{actual}}}{D_{\text{actual}}} \quad (1)$$

where:

$D_{\text{theoretical}}$  = the calculated distance assuming no slip (m)

$D_{\text{actual}}$  = the actual travel distance (m), corresponding to the fixed 10 m test path

### VISUAL STABILIZATION: LINE-BASED ASSESSMENT OF GIMBAL EFFECT

Visual stabilization was evaluated in an outdoor tomato orchard by comparing image stability with and without a two-axis gimbal. A blue line was positioned 150 cm above ground, and a Raspberry Pi Camera Module V2 was mounted at the same height (Fig. 1b). The vehicle traveled along a 5 m straight path at 0.17 m/s while recording the line at 3280 × 2464@21 fps. Both with and without the gimbal were tested three times.

The recorded videos were then analyzed frame-by-frame: the blue line was segmented using an HSV color filter, and two features were extracted— (1) vertical deviation of the line midpoint and (2) tilt angle (Fig. 1c). For each test, the standard deviations (STDs) of these features quantified stability and were compared between with gimbal and without gimbal runs.

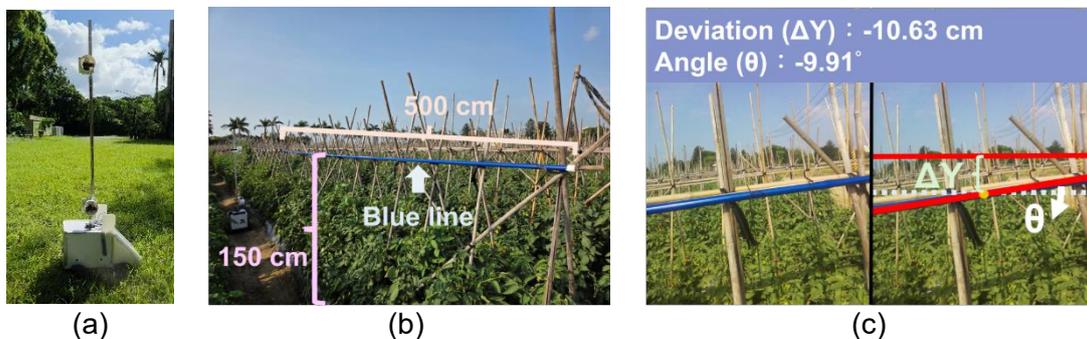


Fig. 1 Experimental setup and image-based stability evaluation.  
(a) Vehicle; (b) orchard setup with blue line;  
(c) frame with measured vertical deviation ( $\Delta Y$ ) and tilt angle ( $\theta$ ).

## POWER MANAGEMENT: EVALUATION OF VEHICLE OPERATION TIME

Power endurance tests were conducted to evaluate the operational runtime of the vehicle under continuous field operation. The vehicle was powered by two 24 V 12 Ah lithium-ion batteries. The test was performed on grass, with the vehicle traveling at a constant speed of 0.17 m/s. During operation, the vehicle was programmed to capture an image every three seconds to simulate the plant spacing of outdoor tomato crops, which is approximately 50 cm between plants. The front-view camera and 2D LiDAR were activated to provide self-guided control by detecting the lane. Battery voltage and current was monitored in real time, and the total operation time were recorded. Two replicate tests were conducted.

## RESULTS AND DISCUSSION

### MOBILITY STABILITY: SLIP RATIO PERFORMANCE OF FOAM AND PNEUMATIC TIRES

Foam tires exhibited slip ratios ranging from 14.81% to 18.56%, whereas pneumatic tires ranged from 8.35% to 9.67%, showing that pneumatic tires achieve higher traction efficiency and reduced energy loss during motion (Fig. 2, Table 1).

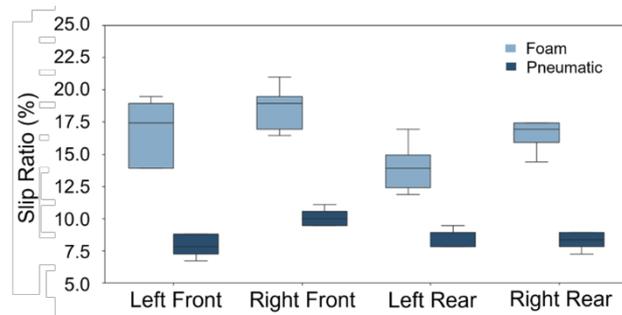


Fig. 2 Slip ratio comparison between foam and pneumatic tires.

Table 1 Slip ratio for each wheel under different tire types.

Tire Type	Left Front (%)	Left Rear (%)	Right Front (%)	Right Rear (%)	Average (%)
Foam	16.74	14.81	18.56	16.94	16.76
Pneumatic	8.66	8.35	9.67	9.01	8.92

### VISUAL STABILIZATION: COMPARISON OF STABILITY WITH AND WITHOUT GIMBAL

With gimbal stabilization, the STD of vertical deviation decreased from 4.255 cm to 2.090 cm. Similarly, the STD of tilt angle decreased from 4.293° to 0.999°. These results indicate that the addition of a two-axis gimbal effectively mitigates motion-induced image instability during field operation (Fig. 3, Table 2).

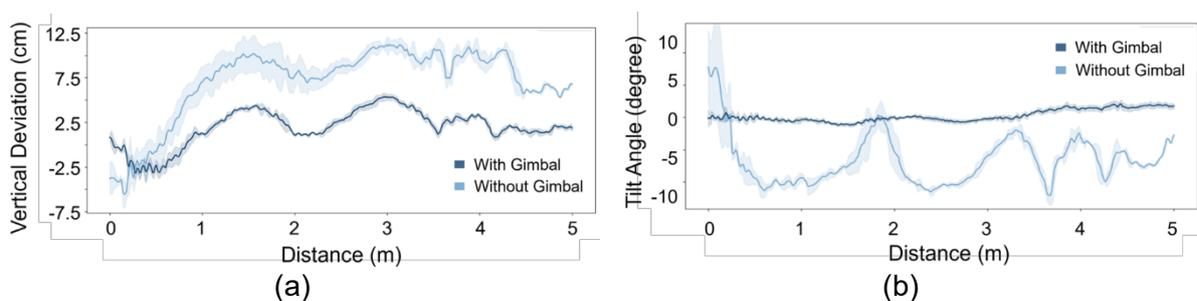


Fig. 3 STD analysis of vertical deviation and tilt angle with gimbal and without gimbal.

(a) Vertical deviation; (b) tilt angle.

Table 2 STDs of vertical deviation and tilt angle under non-gimbal and gimbal.

Condition	Vertical Deviation STD (cm)	Tilt Angle STD (degree)
Without Gimbal	4.255	4.293
With Gimbal	2.090	0.999

### POWER MANAGEMENT: CONTINUOUS OPERATING TIME OF THE VEHICLE

Dual tests conducted on grass terrain yielded operating times of 167 minutes and 181 minutes, with an average runtime of 174 minutes (Fig. 4). This endurance, corresponding to nearly 3 hours, is sufficient to support a full morning or afternoon field operation.

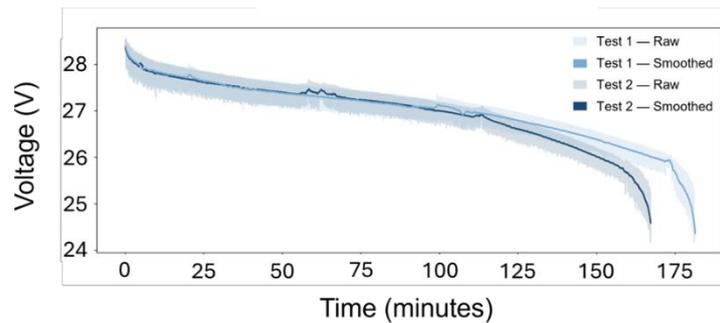


Fig. 4 Voltage–time profiles from dual endurance tests.

### CONCLUSIONS

This study shows that improvements to mobility, visual stabilization, and power management materially enhance autonomous field performance. Pneumatic tires cut slip by 46.8% compared with foam tires. A two-axis gimbal improved image stability, lowering vertical deviation by 50.9% percent and tilt angle by 76.7%. The power system sustained nearly 3 hours of continuous operation. Overall, the results support equipping the vehicle with pneumatic tires and a two-axis gimbal to achieve a more stable and reliable platform for field operations. This configuration enhances operational stability in the field and provides a stable platform for autonomous monitoring in modern agriculture.

### REFERENCES

- Almoosa, M. F., Almaliki, S. A., & Al-Atab, S. M. (2025). Prediction of traction requirements and slippage percentage for three plow types under various operational conditions. *Basrah Journal of Agricultural Sciences*, 38(1), 288-311.
- Lin, H. S., Ma, M. Y., Wu, Y. T., Lin, W. C., Shen, S. E., & Huang, Y. C. (2024). Remote surveillance object detection based on YOLO with gimbal camera tracking control. *2024 International Conference on System Science and Engineering* (pp. 1-6).
- Mueller-Sim, T., Jenkins, M., Abel, J., & Kantor, G. (2017). The Robotanist: A ground-based agricultural robot for high-throughput crop phenotyping. *2017 IEEE International Conference on Robotics and Automation* (pp. 3634-3639).