Autonomous Robotic Hyperspectral Monitoring for Whole-Farm Crop Health Assessment in Multi-Tier Vertical Hydroponic Systems

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INTRODUCTION

Urbanization and climate change are driving the need for sustainable, technology-enabled food production. Vertical farming, empowered by Agri 4.0 technologies, offers a solution for efficient urban agriculture as shown in Fig. 1.

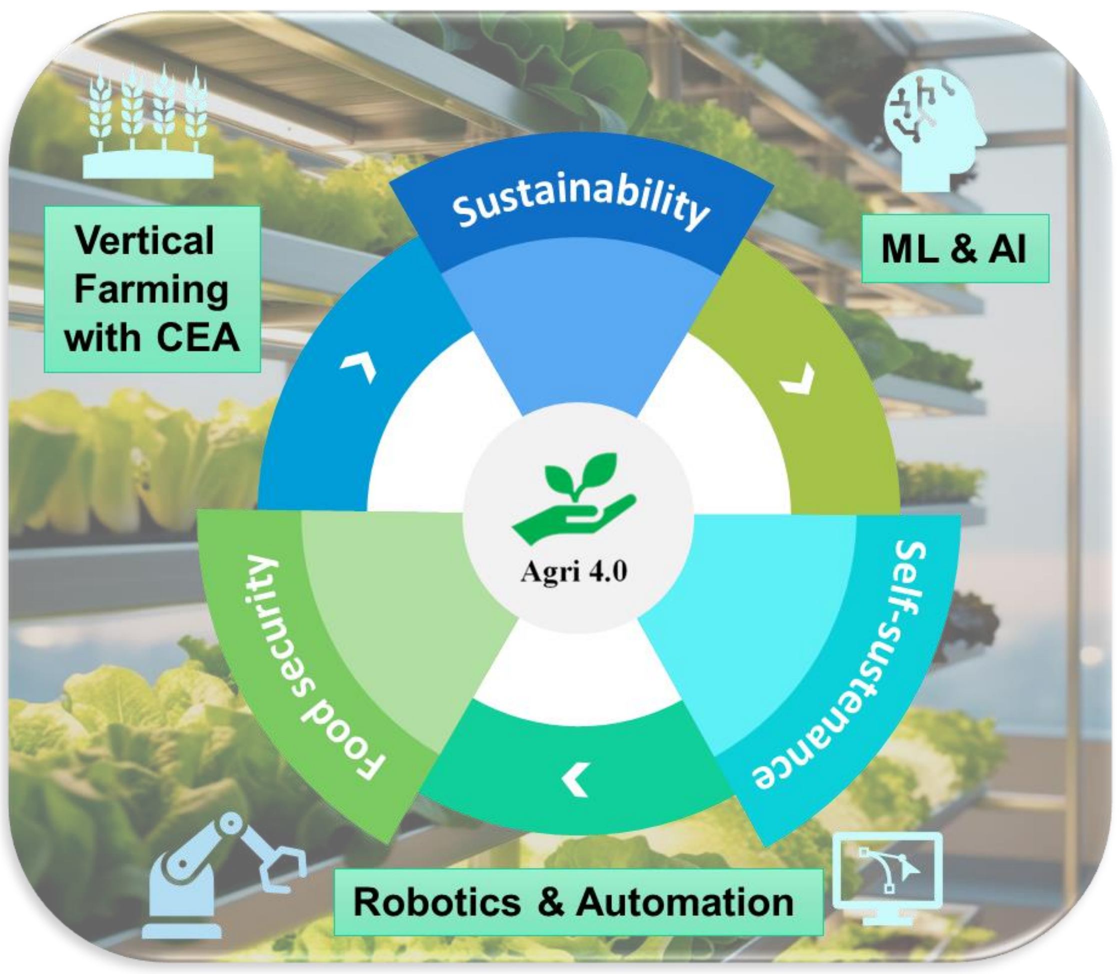

Fig. 1. Overview of the Agri 4.0 framework linking advanced technologies with sustainability, food security, and self-sufficiency.

Limitations of the Current Art: Multi-tier farms are difficult to monitor manually. Delayed detection of crop stress and nutrient deficiencies.

Proposed solution:

- **Autonomous robotic platform for whole-farm crop monitoring using hyperspectral imaging (HSI).**
- **Integrates hyperspectral imaging and AI for early stress detection and precision crop management.**

METHODS

- **Automated plant detection and hyperspectral scanning for high-throughput spectral phenotyping (Fig. 2).**
- **A push-broom HSI system (Resonon Pika XC2, 400–1000 nm, 1.3 nm resolution) was used. The camera was mounted on a synchronized rotational stage for precise scanning, with a broadband light source providing uniform illumination.**

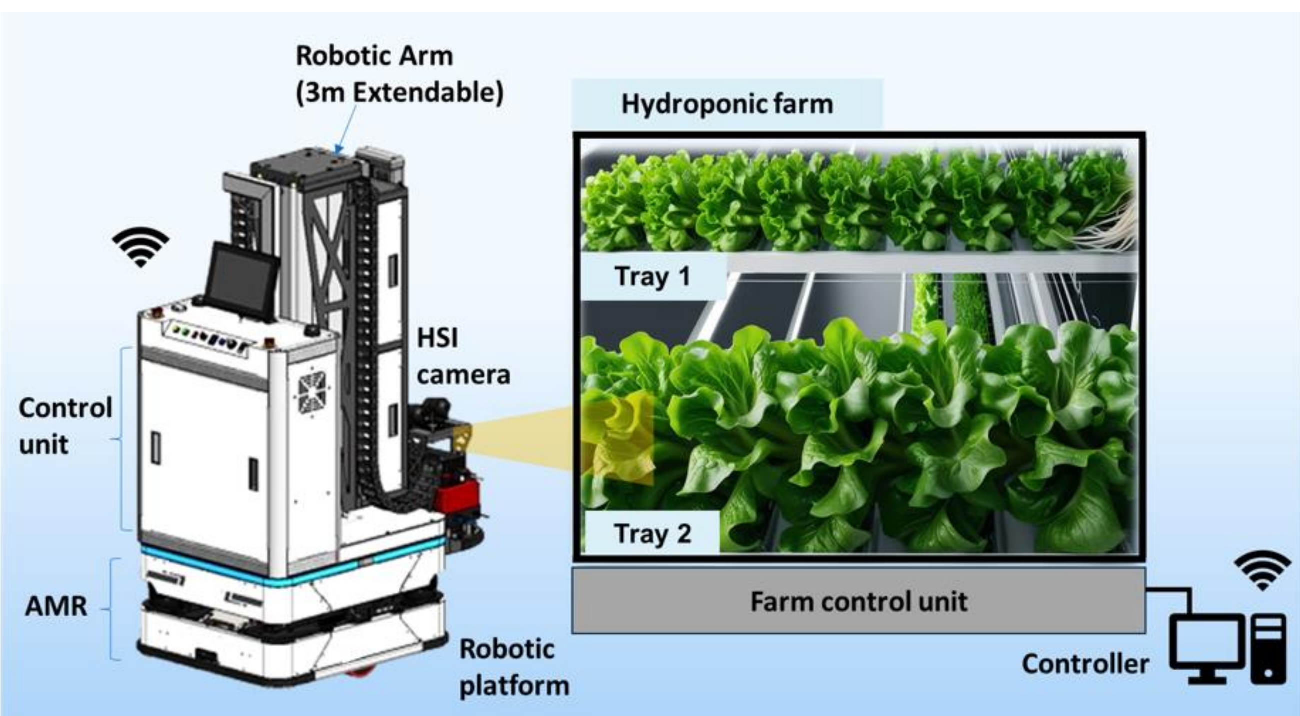

Fig. 2. Schematic diagram of the developed system

- **Laser-guided autonomous navigation for obstacle avoidance and full coverage of a 3-meter high hydroponic vertical farm.**
- **The robotic arm deployment provides access to upper and lower cultivation tiers for standardized data acquisition.**
- **The acquired data is processed using Machine Learning models based on Random Forest as the based model.**

RESULTS AND DISCUSSION

- **The developed framework was deployed and evaluated within a commercial vertical farming environment, to assess its operational feasibility under realistic farming conditions.**
- **The deployment demonstrated that the robotic monitoring platform could function within the constraints imposed by cultivation racks, multiple growing layers, and narrow navigation corridors (Fig. 3).**
- **Data acquired were trained using ensemble learning models and crop health maps were generated.**

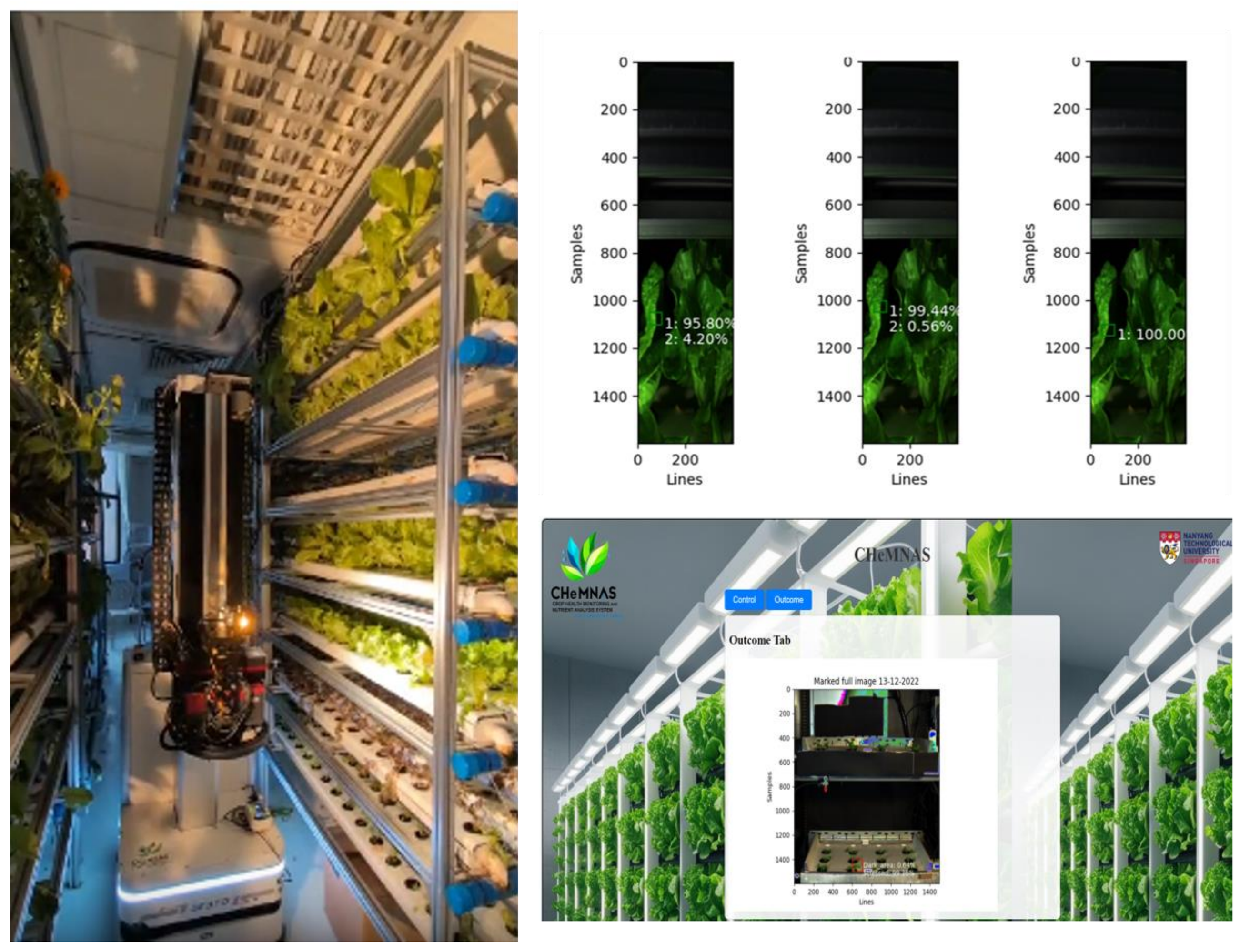

Fig. 3. Photograph of deployment in a commercial vertical farm and representative crop-health assessment results

Table 1. Operational performance during autonomous deployment

Metric	Value
Number of monitored tiers	Customisable and can be programmed to any number
Number of monitoring locations	Can be programmed
Average scan time per sq. m	~ 2 min
Navigation success rate	Depends on mapping accuracy
Localization repeatability	• Positioning accuracy of ±50 mm • Docking accuracy of ±20 mm (2 cm) when using feature-based docking markers • Docking accuracy of ±10 mm (1 cm) when using magnetic tape docking markers • Angular accuracy of ± 5° of position

Key features of robotic platform
The developed robotic platform successfully integrated autonomous navigation, vertical positioning, hyperspectral sensing, and crop-health analytics into a unified monitoring framework (Table 1). During operation, the autonomous mobile robot navigated between cultivation racks using onboard localization and obstacle-detection systems while carrying the hyperspectral imaging payload.

Table 2. Performance summary of previously validated ensemble learning models for nutrient stress detection in hydroponically grown lettuce using hyperspectral imaging. Data from Ref [2]

Model	Test Accuracy (%)	Precision (%)
RF1000	98.61	95.13
Bagging-RF100	98.38	94.98
AdaBoost-RF100	98.55	94.97
XGB1000	99.52	96.76

Key observations
Random Forest (RF), Bagging-RF, AdaBoost-RF, and eXtreme Gradient Boosting (XGB) models were evaluated (Table 2), demonstrating high classification accuracy for nutrient stress detection. Among these models, XGB1000 achieved the highest test accuracy of 99.52% and precision of 96.76%.

CONCLUSION AND FUTURE WORK DIRECTIONS

- **Developed an autonomous robotic hyperspectral monitoring platform for multi-tier hydroponic vertical farms.**
- **Enabled non-invasive, whole-farm crop health assessment through integrated robotics, hyperspectral imaging, and AI analytics.**
- **Achieved 96.71% precision in nutrient stress classification, demonstrating reliable automated crop monitoring.**
- **Provides a scalable Agri 4.0 solution for precision crop management and sustainable controlled-environment agriculture.**

REFERENCES

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