An Edge AI and Adaptive Embedded System Design for Agricultural Robotics Applications

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Outline

- Introduction
- Proposed method
  - Data collection for AI models
  - Recognition of target crops and their pest and disease severity (PDS) estimation using binarized neural networks (BNNs)
  - PDS prediction using multimodal learning
- AgrBot design
- Agricultural cyber-physical system (CPS)
- System implementation and evaluations
- Conclusion

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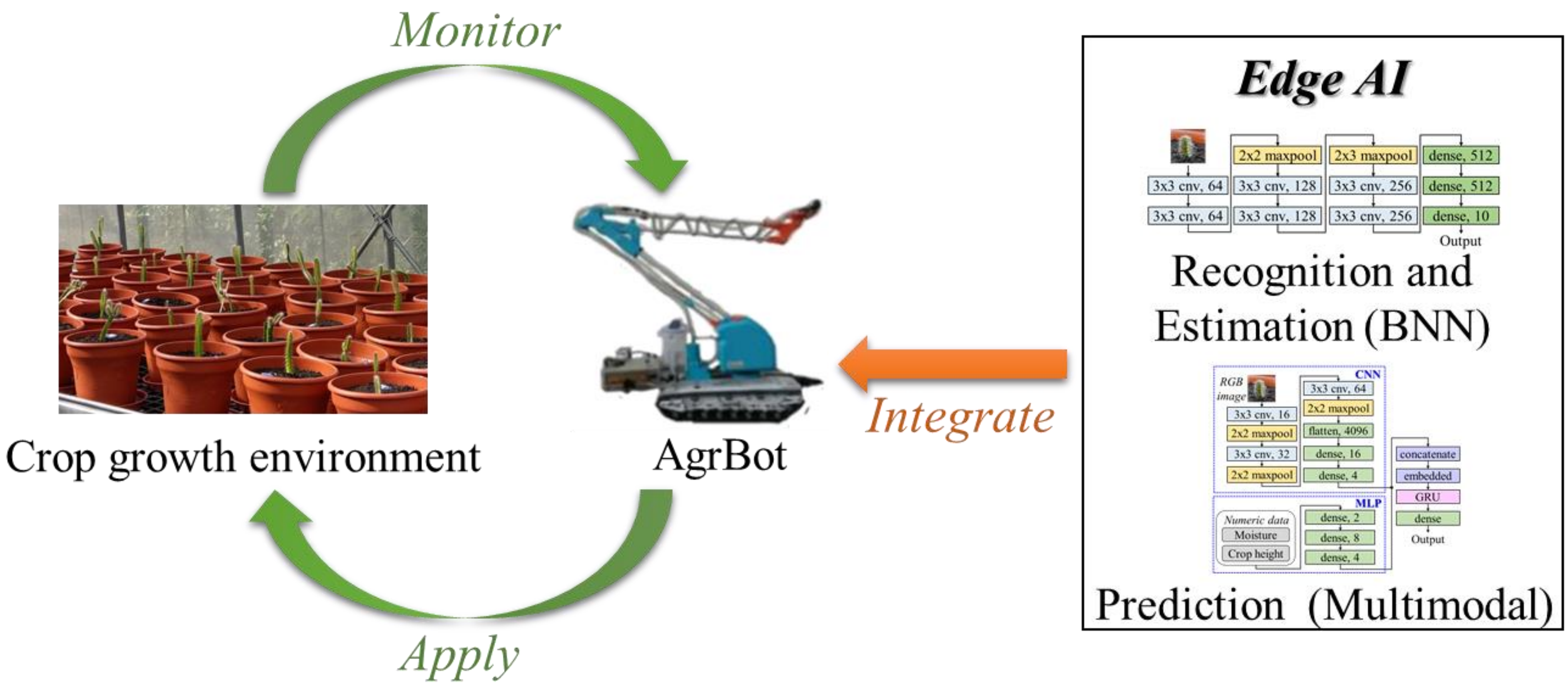
Introduction

- Monitoring crop pest and disease severity (PDS) is crucial to ensure the healthy growth of crops

- The motivation of this work is to enable an agricultural robot to directly estimate and predict the crop PDS in the growth environment.
  - Based on the PDS estimation and prediction, the agricultural robot can apply biological agents to protect the crops from pests and diseases.

Agricultural Cyber-Physical System (CPS)



- Adaptive binarized neural network (BNN) hardware module
- Prediction of PDS based on heterogeneous data

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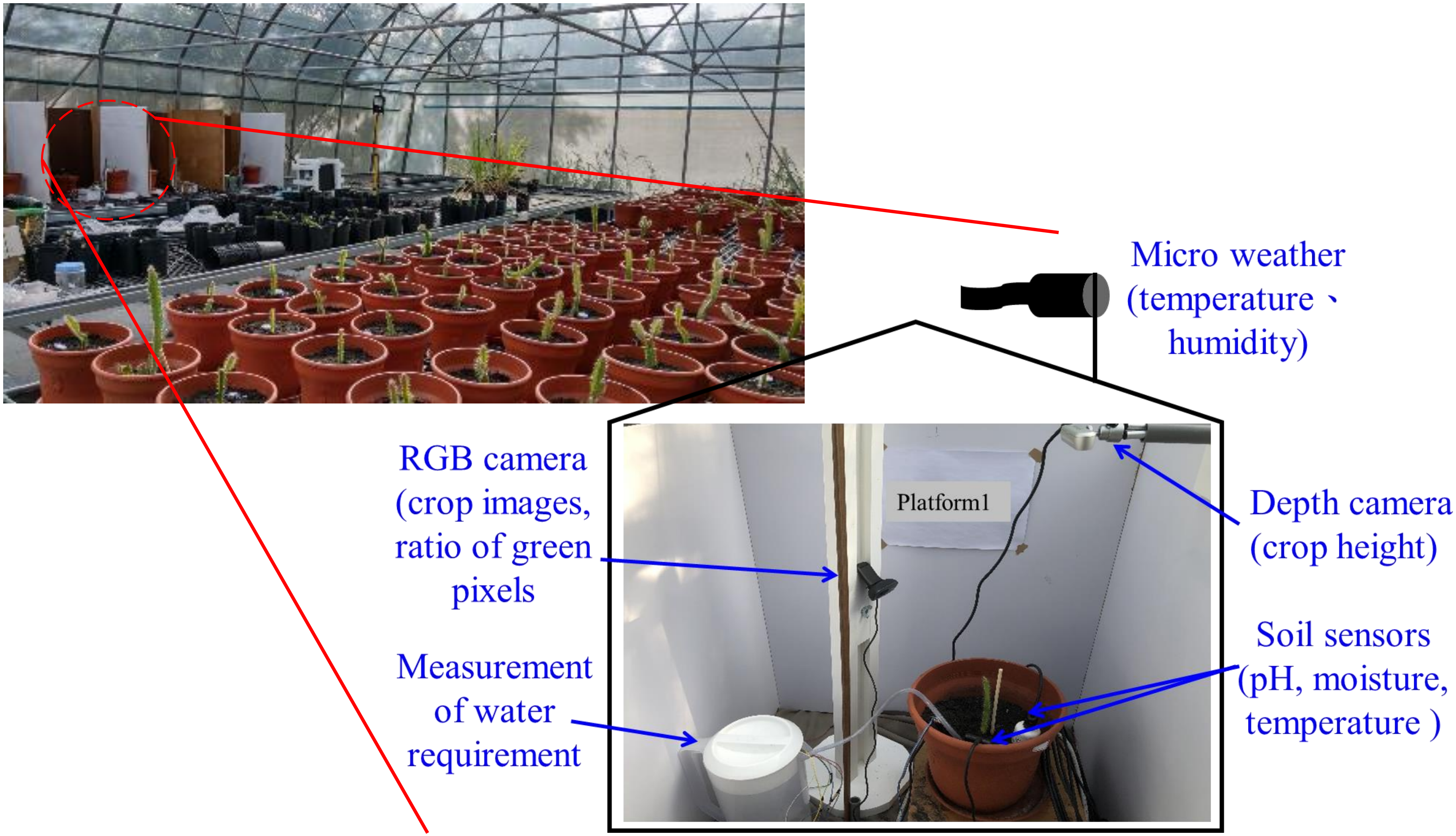
Data Collection for AI Models



Three Levels of PDS for Dragon Fruits


Level 0


Level 1


Level 2

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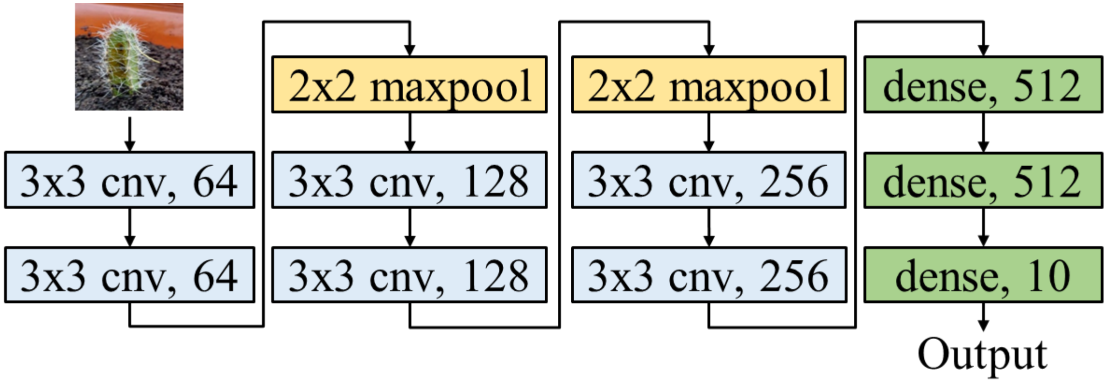
Recognition of Target Crops and Their PDS Estimation using BNNs

- The VGG16 architecture was adopted to support the recognition of target crops and their PDS estimation.
  - Was refined through binary weight regularization as the BNN to support edge AI

$$Sign(x) = \begin{cases} +1 & ,x \geq 0 \\ -1 & ,x < 0 \end{cases}$$



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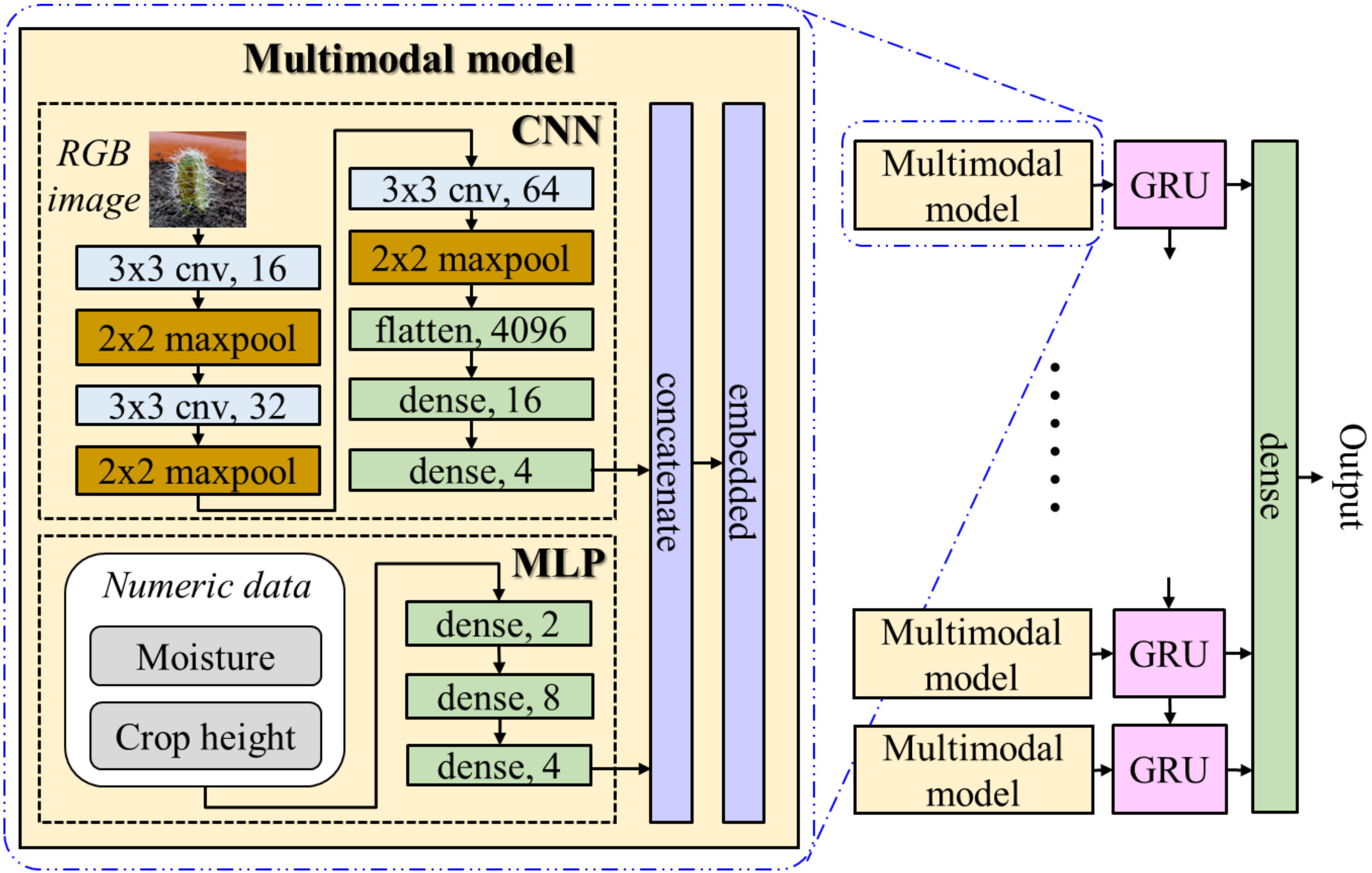
Data Preprocessing

- Fuzzy-Rough Set (FRS)
  - Reduce the input size of the proposed prediction model and retain only more relevant information to enhance prediction accuracy

$$Dep_{PDS}(A, B) = \frac{\sum_{x \in U} \mu_A(x) \cdot \mu_B(x)}{\sum_{x \in U} \mu_A(x)}$$

  - A fuzzy set A represents each data category's degree of association with the PDS. B represents a specific data category.

Multimodal Learning



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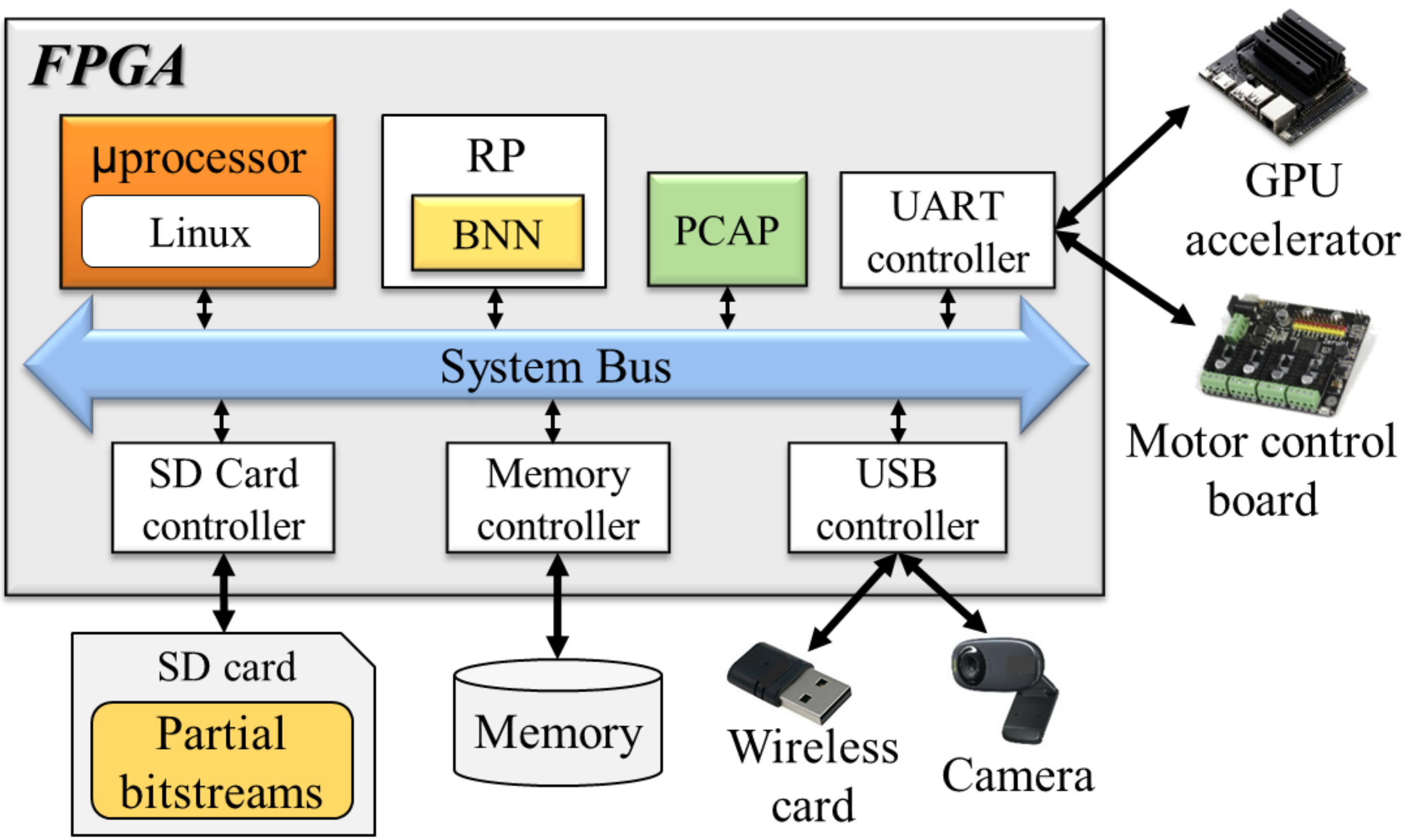
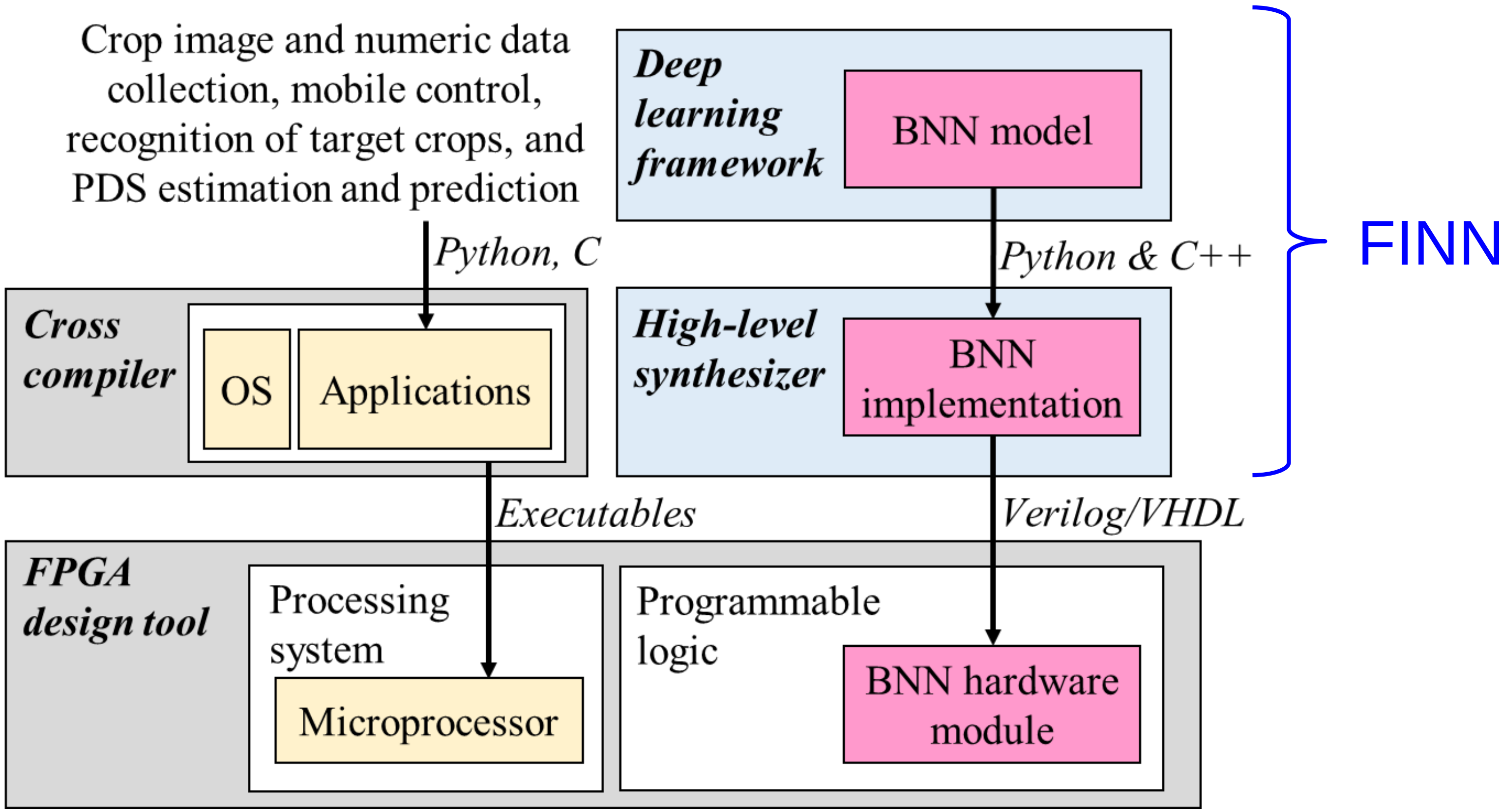
System Architecture Design



RP: Reconfigurable Partition

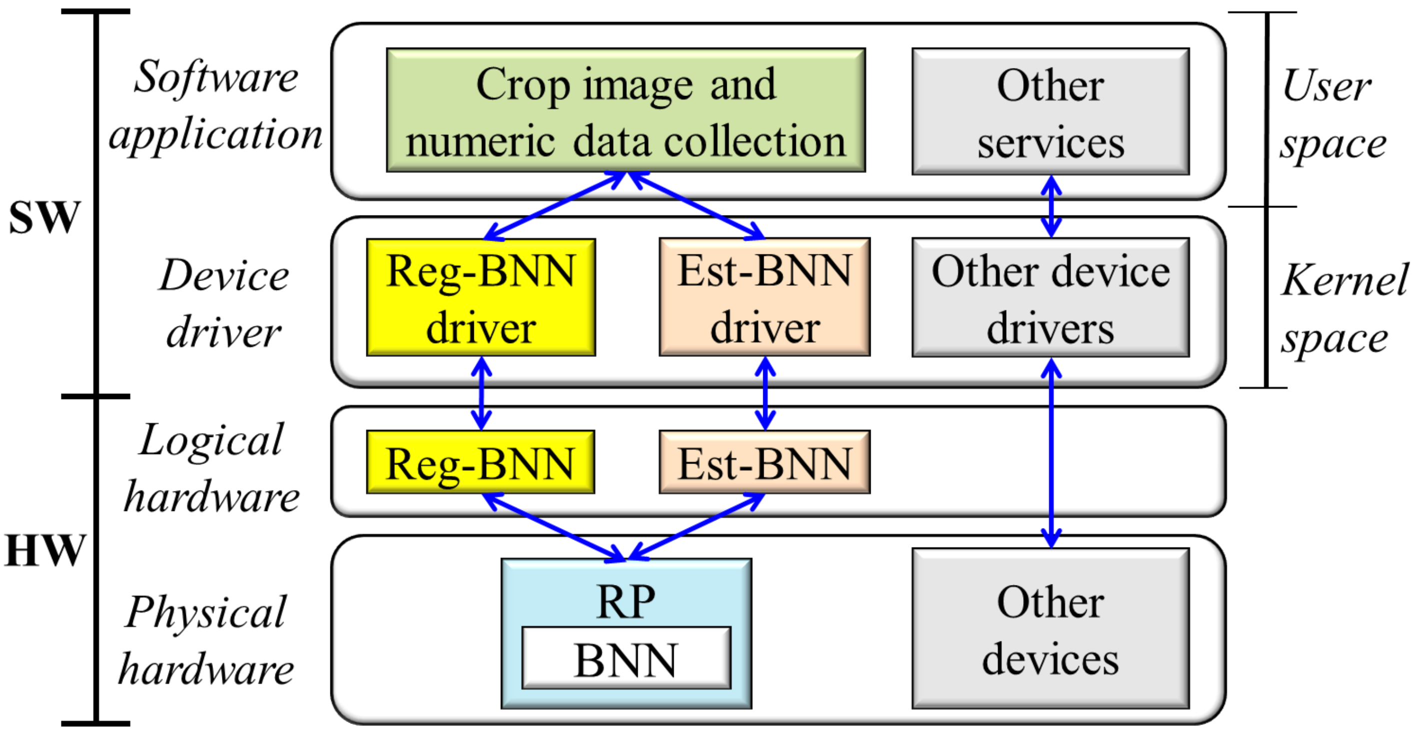
FPGA-based System Design Flow



Y. Umuroglu, N. J. Fraser, G. Gambardella, M. Blott, P. Leong, M. Jahre, and K. Vissers. FINN: A framework for fast, scalable binarized neural network inference. In Proceedings of the ACM/SIGDA International Symposium on Field-Programmable Gate Arrays, pages 65–74. ACM, Feb. 2017.

Layered and Virtualizable System Design

- The Reg-BNN and Est-BNN hardware modules are sequentially used to estimate the PDS of target crops. This means that each BNN hardware module is not active all the time.



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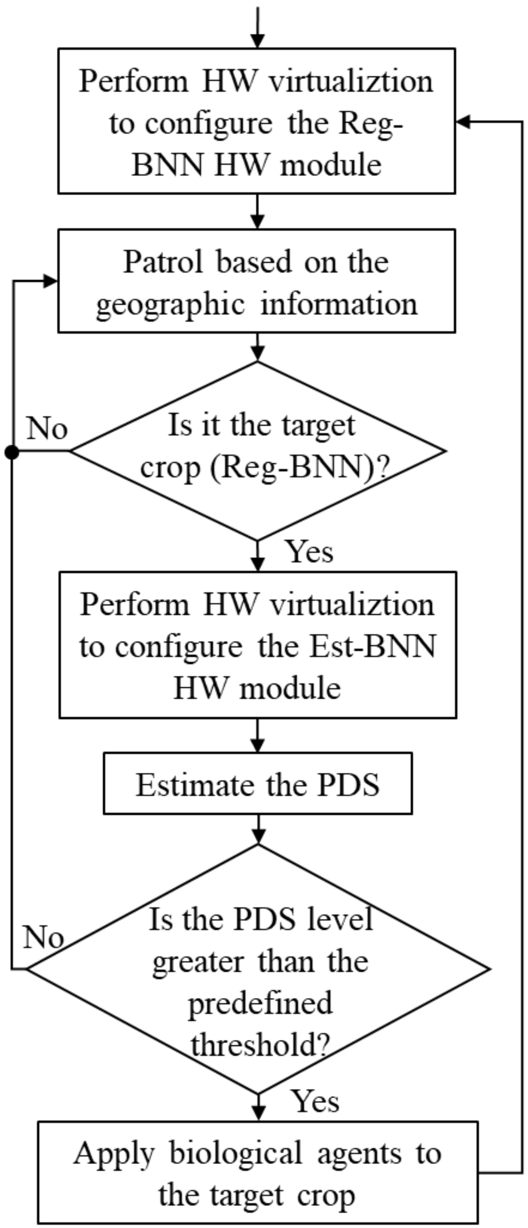
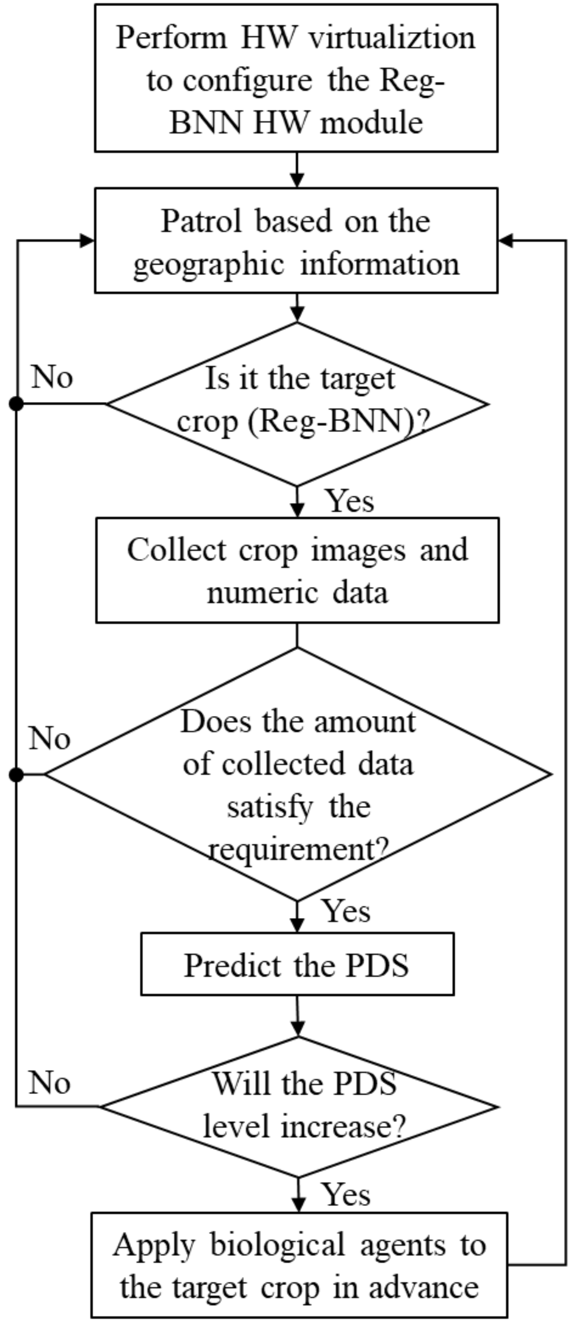
PDS Estimation Flow



PDS Prediction Flow



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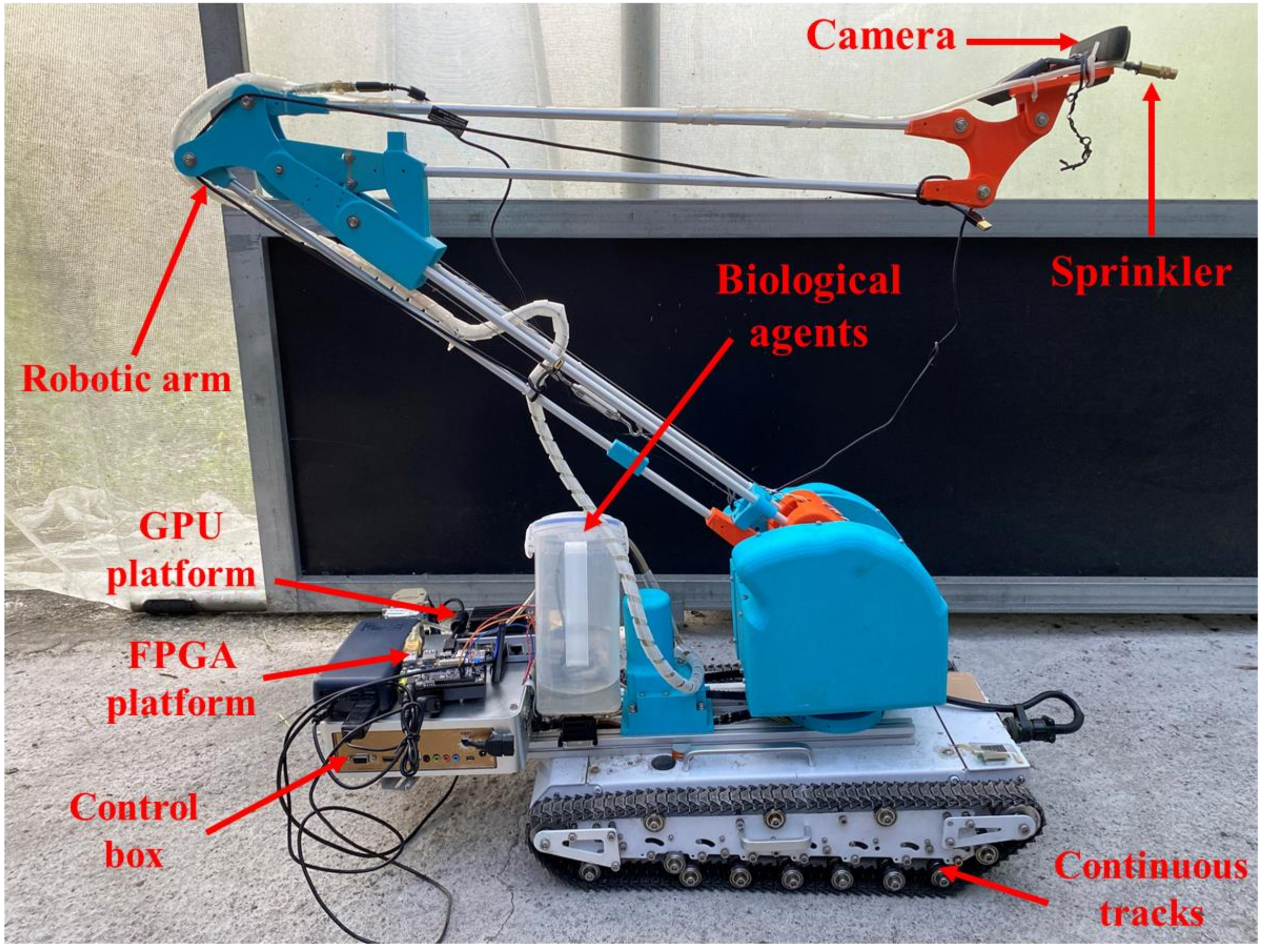
AgrBot Prototype



- AVNET Ultra96-V2 (FPGA): Reg-BNN & Est-BNN
- Nvidia Jetson Nano (GPU): Multimodal model

Classification Accuracy and Performance Evaluation for Reg-BNN and Est-BNN

Edge AI model	Classification accuracy	μProcessor -based FPS [13]	AgrBot	
			FPS	Config.
Reg-BNN	76.3%	2.4	1,896	210 ms
Ets-BNN	65.3%	2.4	1,895	210 ms

- AgrBot significantly accelerate frames per second (FPS) achieving a speedup of 790x compared to the microprocessor-based method [13]
- Incorporates the configuration prefetch approach [21], eliminating the hardware reconfiguration time overhead

[13] S. Supriya and H. L. Aravinda. Green leaf disease detection and identification using Raspberry Pi. International Research Journal of Engineering and Technology, 9(8), Aug. 2022.

[21] S. Banerjee, E. Bozorgzadeh, and N. Dutt. Physically-aware HW-SW partitioning for reconfigurable architectures with partial dynamic reconfiguration. In Proc. 42nd ACM/IEEE Design Automation Conference, pages 335–340, Jun. 2005.

Resource Usages

Design method	Slice LUTs		Slice registers	
	Count	Utilization	Count	Utilization
Huang et al. [7]	47,364	67.13%	76,648	54.31%
AgrBot	23,682	33.56%	38,324	27.16%

Traditional: without supporting hardware virtualization [7]

Reduce 33.57% Reduce 27.15%

- AgrBot: The Reg-BNN and Est-BNN hardware modules can be configured in RP on-demand at runtime

Prediction Accuracy and Performance Evaluation for the Multimodal Model

#Sequential data	Prediction accuracy	Processing time (ms)	
		μP-based [13]	AgrBot
75	41%	730	450
200	51%	1,710	840
300	58%	2,360	1,170
500	67%	3,250	2,100

μP-based: μProcessor-based method [13]

$$Prediction\ accuracy = \frac{Correct\ predictions}{All\ predictions}$$

Applicability and Scalability of ArgBot

- Based on the layered and virtualizable system design, more reconfigurable BNN hardware modules for various crops can be incorporated into the AgrBot design.
- The AgrBot addresses the concern by executing the BNN and multimodal models directly on the device.
  - Not only eliminates concerns about potential leakage of unique planting methods but also enhances the AgrBot’s applicability.

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Conclusion

- AgrBot
  - Integrates adaptive BNN hardware modules for target crop recognition and PDS estimation.
  - Includes a multimodal model for predicting PDS and determining the necessity of applying biological agents to safeguard crops.
  - Forms an intelligent and autonomous agricultural CPS.
- Experimental results showcase AgrBot’s high performance, resource efficiency, and scalability across diverse agricultural applications.

Thanks!

AgrBot’s demo

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