

# An FPGA-based Intelligent Robotic Vehicle System for Agricultural Cyber Physical Systems

Chun-Hsian Huang\*, Pin-Lun Lin, Ting-You Chang, Zong-Wei Li, Bo-Zhi Ye, Yun-Chien Chiu, and Quan-Yu Lin

Department of Computer Science and Information Engineering  
National Taitung University

Taitung, Taiwan

\*huangch@nttu.edu.tw

## ABSTRACT

The technique of agricultural Internet-of-Thing (IoT), currently, is gradually applied to the management of crops in a greenhouse. However, for some crops such as annona squamosa, the growth environment is open and the environmental conditions are varying. Further, to support the research of prevention technology of crops, a large amount of growth information usually needs to be collected. This would take a lot of manpower and is very time-consuming. To solve the above issue, the concept of agriculture 4.0 is introduced into this work, and thus we propose an FPGA-based intelligent robotic vehicle (IRV) system for agricultural cyber physical system (CPS). An intelligent robotic vehicle is responsible for collecting the information of sensors, and then automatically deciding whether the corresponding actuators will be invoked. Compared to the most existing robotic vehicle designs, the FPGA device is adopted as the main control chip of this intelligent robotic vehicle, so that the sensor data collected can be processed in parallel and in real-time through hardware acceleration. The hardware virtualization technique is also integrated into the system design to enhance system adaptivity to changing environments. According to our experiments, the IRV system has been demonstrated it can support the agricultural CPS efficiently.

**Keywords:** agricultural cyber-physical system, intelligent robotic vehicle, reconfigurable computing

## I. INTRODUCTION

In recent years, the technique of agricultural Internet-of-Thing (IoT) is gradually applied to the management of precision agriculture. Through data collection and analysis, the development of precision agriculture can be further promoted. However, not all crops are planted in a greenhouse. The growth environment of some crops such as annona squamosa is open and changing. Thus, data collection and the control of growth environment also become more difficult. Further, in the most existing agricultural IoT systems, crop growth images are usually collected by the cameras located in the specific positions. Such an image capture method, however, also restricts the completeness of image records of crop growth. As a result, a new automatic system that can collect the growth information and perform the corresponding actions to achieve an ideal growth environment is necessary.

The main goal of this work is to design an agricultural cyber-physical system (CPS). The research issues that we would like to address in this work are introduced in the following.



Figure 1. FPGA-based intelligent robotic vehicle system for agricultural cyber physical systems.

1. In such a dynamic and changing environment, what is the system design that we should realize, so that the physical world can be integrated with the cyber system efficiently?
2. What capabilities should be included in this system, so that the data collection and the control of actuators can be performed in real-time, while the system can be reconfigured according to varying environmental conditions?
3. What is the decision model that can make this system autonomous, due to the continuous interaction between the physical world and the cyber system?

To solve the above issues, we propose an FPGA-based intelligent robotic vehicle (IRV) system for agricultural cyber physical systems, as shown in Figure 1. The IRV is equipped with a camera to capture the growth images of crops, while it acts as a data mule [1] on the farm to receive sensor data. By taking advantage of the mobility of IRV, the collection of crop growth information can become more complete. Further, to maintain the ideal growth environment, the IRV system contains an intelligent management mechanism [2] that can determine whether the actuators such as sprinklers should be invoked. To support real-time information processing and decision-making, the IRV system is implemented in an FPGA device, instead of using a microchip usually used in a smart robot car. To not only support the real-time processing of sensor data but also adapt to changing environmental conditions, the hardware virtualization technique [3] is also introduced in the IRV system. The functionalities of the IRV system can thus be dynamically adapted to different requirements of sensor data processing. This

enhances not only system adaptivity but also logic resource utilization.

The rest of this paper is organized as follows. Section II introduces the related work, while Section III presents the layered agricultural CPS design. Section IV introduces the proposed FPGA-based IRV system architecture, while system prototyping and experiments are given in Section V. Finally, Section VI concludes this work.

## II. RELATED WORK

In the early 1980s, computer science had been applied to agricultural management strategies and technologies [4]. For potato crops, Rad et al. [5] proposed a CPS model that contained the physical layer, the network layer, the decision layer, and the application layer. Sensors were used to collect information such as human work and environmental conditions in the physical layer, while a complex hardware and software integration design in the network layer was used to transfer the sensor data. An innovative technology for multispectral monitoring of the vegetation status of crops in the decision layer integrates the geographic information system elements, on which agricultural information was provided by a friendly user graphical interface. The application layer provided solutions to incoming problems such that farmers could take the appropriate decisions to increase agricultural productivity. Dong et al. [6] proposed a wireless underground sensor-aided center pivot irrigation system, in which the soil conditions could be monitored in real time using wireless underground sensors to achieve autonomous irrigation management capabilities.

With the rapid progress of robotic industry, by using the robots to interact with sensors becomes another research direction of data collection [7]. Instead of adopting a large amount of network devices, Bhadauria et al. [8] presented a robotic system that collected sensor data in a large field. In their work, they focused on the path planning of robotic motion and thus proposed the corresponding algorithm. Tekdas et al. [9] adopted multiple autonomous robots as data mules to collect sensor data within a specific communication range. The collected data were transferred to a remote data center for further data processing. They also used a low power probing method and discussed the motion path of robots. Their experiments showed that the power consumption could be reduced so as to prolong the lifetime of system. However, the above researches [8, 9] focused on data collection and were only applied to sensor network environments.

For CPS, its development still faces many challenges, including real-time processing, adaptability, hardware-software co-design, and scalability. The reconfigurable devices such as FPGAs are very suited to solve the above issues [10]. For the sensor network systems, the development of using reconfigurable devices, recently, also becomes a new trend [11]. This is because the sensors do not act all the time, and thus the system can dynamically load the required processing units by using the partial reconfiguration technique of FPGAs. Becker et al. [12] presented an automotive control system, in which all the functional units were implemented as bitstreams and stored

in the flash memory. When a functional unit was required, the corresponding bitstream was thus configured in the FPGA. This also increased the utilization of logic resources. Vipin et al. [13] presented a hybrid FPGA system to realize a collision avoidance system, in which the processing functions of sensor data were implemented as reconfigurable modules. The microprocessor was responsible for monitoring the operations of data input/output and performed an observe-decide-act loop to achieve a complete hardware/software integration, according to the processing information of reconfigurable modules. Based on the reconfiguration feature of FPGA, Vyas et al. [14] also proposed a development platform for the analysis of CPS design.

In the proposed agricultural CPS, the robotic vehicle not only acts as a data mule to collect sensor data, but also plays a key role that can perform the corresponding actions to achieve the objective of autonomous system, according to varying environmental conditions. Further, the FPGA is adopted as the main control device of robotic vehicle to provide real-time information processing and system adaptivity. The details of the proposed system will be introduced in Section IV.

## III. LAYERED AGRICULTURAL CPS

For the agricultural CPS, a layered design method is introduced in the IRV system, as shown in Figure 2. The layered agricultural CPS consists of four layers, namely physical layer, interaction layer, control layer, and application layer. The interaction layer, the control layer, and the application layer are mainly implemented in the IRV, where the physical layer is responsible for interacting with the real world.

### A. Physical Layer

Different sensors such as crop image sensors, soil sensors, and weather sensors are used to collect the growth information of crops in the farm. To maintain the ideal growth environment of crops, actuators such as sprinklers are controlled by the control layer. Based on the environmental condition between the applicable environment and the cyber system, wireless techniques such as wifi, zigbee, and Lora are used to construct the connection between the physical world and the cyber system.

### B. Interaction Layer

This layer and its upper layers belong to the cyber system. In this layer, we focus on the development of the main control chip in the IRV system, which interacts with sensors and actuators in the physical layer through the wireless communication. According to the functionalities of sensors and actuators, the corresponding hardware functions are implemented as hardware functions in the system to support real-time information processing and control.

### C. Control Layer

This layer is the key part of the layered agricultural CPS. According to the collected sensor data and the experiences of agricultural science (domain knowledge), this layer contains the decision-making mechanism of the cyber-physical interaction to maintain the ideal growth environment of crops, as shown in Figure 3. For example, an intelligent control method such as model predictive control is integrated into our current system.

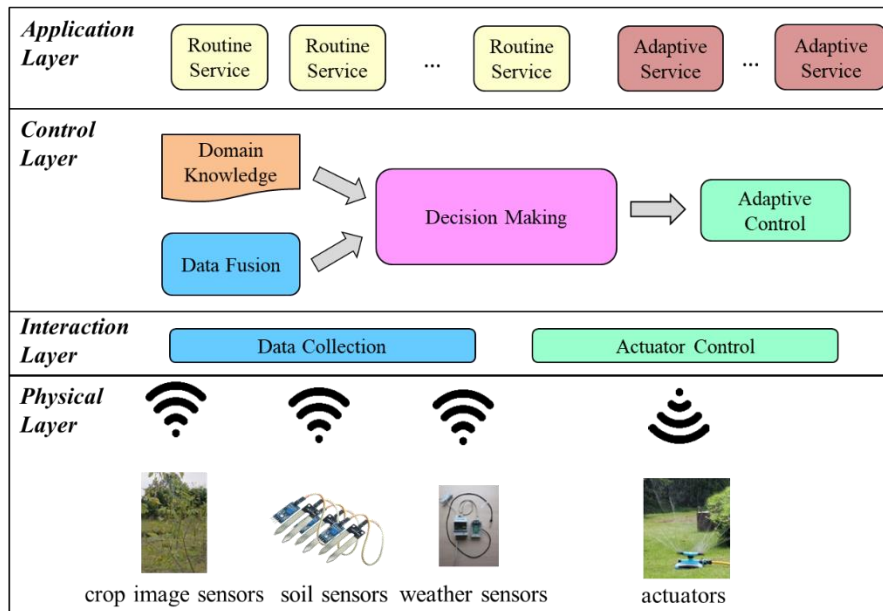


Figure 2. Layered Agricultural CPS design.

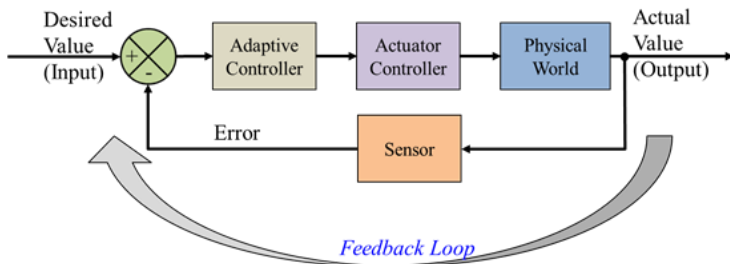


Figure 3. Closed-loop model.

One of our objectives is to minimize the root zone soil moisture deficit (RZSMD) [2]. Given  $D$  as RZSMD at the current time step, RZSMD at the next time step is  $D^+$  as depicted in Equation (1).

$$D^+ = D + E^* - P^e - I^e \quad (1)$$

where  $E^*$  is the crop evapotranspiration,  $P^e$  is the effective rainfall, and  $I^e$  is the effective irrigation amount.  $E^*$  can be obtained by the fusion of heterogeneous sensor data, while  $P^e$  can be obtained from the central weather bureau.  $I^e$  is controlled through the actuators. Based on the Equation (1), the objective of the intelligent management mechanism is to maintain RZSMD close to zero and to minimize the amount of irrigation water use.

Another objective is to apply pesticides efficiently by monitoring the effects of pests and diseases from real-time images of crops. In our current implementation, we integrate the OpenCV library and the AdaBoost method [15] of machine learning to detect the target crop. As shown in Figure 4, in the preprocessing phase, the positive samples and the negative samples are extracted their Haar features, which are then transferred to a classifier for training. The training results are exported as an XML file. The XML file is thus used in the IRV

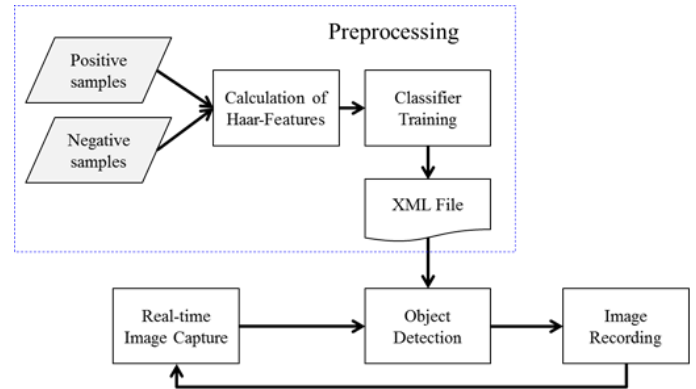


Figure 4. Detection of the Target Crop.

system to detect the target crop in real-time. Next, the growth images are recorded.

#### D. Application Layer

All application services are included in this layer. In this layer, the concept of service-oriented architecture [16] is integrated into the IRV system. The collection of sensor data is categorized into the routine services, while the control of actuators is categorized into the adaptive services. According to the domain knowledge of crops, different adaptive services are also set different priorities, which makes the emergency services can be performed earlier.

#### IV. FPGA-BASED INTELLIGENT ROBOTIC VEHICLE SYSTEM

To realize the layered agricultural CPS, we adopt a zynq-based system-on-programmable-chip as the main control chip of IRV system. As shown in Figure 5, a Linux OS runs on the microprocessor, while the OpenCV library [17] is ported in the OS for image processing. A USB controller is used to connect a USB hub that interfaces a camera and a wireless card. Sensor

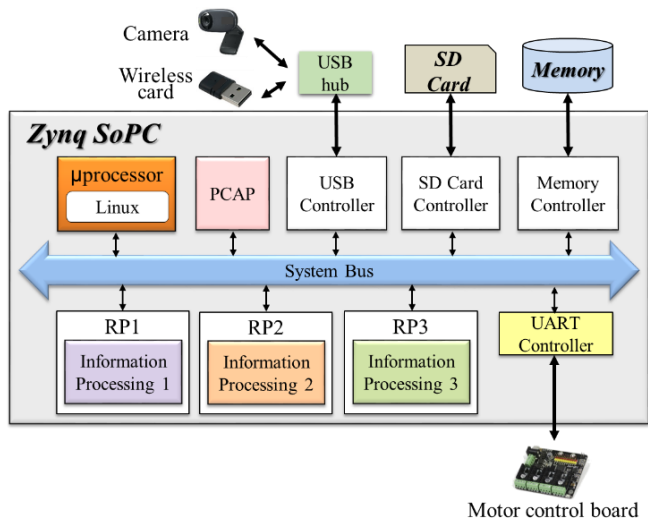


Figure 5. System Architecture.

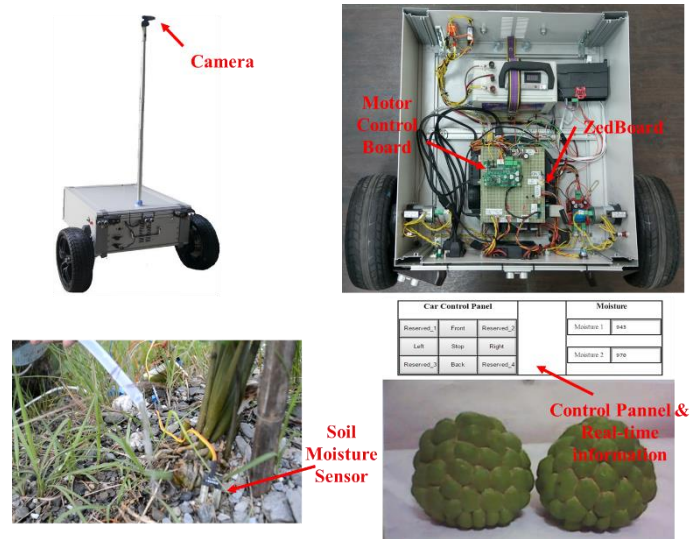


Figure 7. System Prototyping.

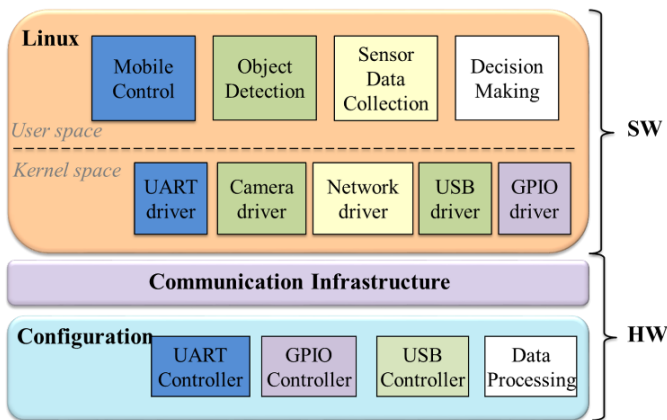


Figure 6. Hierarchical System Design.

data are received via the wireless card, while real-time images of crops are captured by a camera. Further, a UART controller is used to connect to the motor control board.

The received data are transferred to the corresponding information processing circuits for acceleration. In our current implementation, the information processing circuits include the data processing of measurement results of soil moisture based on the spatial and temporal conditions, that of microclimate, and the detection of target crops. To adapt to varying environments, the virtualization technique [3] is integrated into the IRV system. Several reconfigurable partitions (RPs) are implemented in the FPGA device. All the partial bitstreams corresponding to the RPs are stored in a SD card, which are configured in the FPGA by using the processor configuration access port (PCAP).

As shown in Figure 6, a hierarchical system design method is also introduced in the IRV system. All the hardware control circuits such as the UART controller, the GPIO controller, the USB controller, and the data processing circuits are classified in the configuration layer. The corresponding device drivers are implemented in the kernel space of the OS. All the application services, including the motor control, the object detection, the sensor data collection, and the decision making, are realized as

software programs in the user space of the OS. Further, the IRV system also has the capability of system adaptation. When the environmental conditions or the intelligent management policies change, the corresponding information processing circuits can be configured in the RPs on-demand, as shown in Figure 5.

#### V. SYSTEM PROTOTYPING AND EXPERIMENTS

To demonstrate the applicability of the proposed method, we implemented the IRV system on the Digilent Zedboard [18] with a Zynq-7000 SoC XC7Z020 chip. A linux OS was executed on an ARM cortex A9 processor, while a motor control board was connected to the Zedboard through the Pmod interface configured as the UART function. The arduino WeMos D1 boards were used to connect to sensors and actuators, while the communications with the IRV were through the wifi network. A user can also use his/her mobile phone to connect to a specific website for the motion control of the IRV system and the real-time monitoring of the crop growth. Further, to support the real-time processing of sensor data and to adapt to different environmental conditions, the corresponding information processing circuits were implemented as reconfigurable modules. To support the feature extraction of growth images of crops, a sobel edge detection function was also implemented as a reconfigurable module in the IRV system. The prototype of the IRV system is shown in Figure 7.

The implementation results, including the maximum frequency, the number of slice LUTs, that of slice registers, and the power consumption in terms of the Xilinx Zynq-7000 SoC XC7Z020 chip are given in Table I. According to our experiments, the IRV system can operate up to 160 MHz.

TABLE I. IMPLEMENTATION RESULTS

Max Clock	Slice LUTs		Slice Registers		Power (W)		
	#	%	#	%	Dynamic	Static	Total
160MHz	6,065	11.40	6,574	6.18	1.673	0.170	1.842

## VI. CONCLUSION

This work proposes an FPGA-based intelligent robotic vehicle (IRV) system for agricultural cyber physical systems. By using the mobility of IRV, the collection of crop growth information can become more complete. The IRV system also contains an intelligent management mechanism that can determine whether the actuators such as sprinklers should be invoked to maintain the ideal growth environment. Instead of using a microchip, the information processing functions are implemented as reconfigurable modules in the FPGA to meet the requirement of real-time processing of large amount of information and system adaptation. According to our preliminary experiments, the IRV system has been demonstrated it can support the agricultural CPS efficiently.

## VII. ACKNOWLEDGEMENTS

This work was partially supported by the Ministry of Science and Technology, Taiwan, under project grant MOST 106-2221-E-143-001.

## REFERENCES

- [1] M. D. Francesco, S. K. Das, and G. Anastasi, "Data collection in wireless sensor networks with mobile elements: A survey," *ACM Transactions on Sensor Network*, vol. 8, no. 1, Article 7, August 2011.
- [2] D. Delgoda, H. Malano, S. K. Saleem, and M. N. Halgamuge, "Irrigation control based on model predictive control (MPC): Formulation of theory and validation using weather forecast data and AQUACROP model," *Environmental Modelling & Software*, vol. 78, pp.40-53, 2016.
- [3] C.-H. Huang and P.-A. Hsiung, "Virtualizable hardware/software design infrastructure for dynamically partially reconfigurable systems," *ACM Transactions on Reconfigure Technology and Systems*, vol. 6, issue 2, Article 11, August, 2013.
- [4] M. Zhijun, Z. Chunjiang, W. Xiu, C. Liping, and X. Xuzhang, "Field multi-source information collection system based on GPS for precision agriculture," *Transaction of the CSAE*, vol. 19, no. 4, pp. 13-18, July 2003.
- [5] C.-R. Rad, O. Hancu, I.-A. Takacs, and G. Olteanu, "Smart Monitoring of Potato Crop: A Cyber-Physical System Architecture Model in the Field of Precision Agriculture," *Agriculture and Agricultural Science Procedia*, vol. 6, pp. 73-79, 2015.
- [6] X. Dong, M. C. Vuran, S. Irmak, "Autonomous precision agriculture through integration of wireless underground sensor networks with center pivot irrigation systems," *Ad Hoc Networks*, vol. 11, pp.1975-1987, 2013.
- [7] M. Dunbabin and L. Marques, "Robots for Environmental Monitoring: Significant Advancements and Applications," *Robotics & Automation Magazine*, IEEE, vol. 19, no. 1, pp.24-39, March 2012.
- [8] D. Bhadauria, O. Tekdas, and V. Isler, "Robotic data mules for collecting data over sparse sensor fields," *Journal of Field Robot*, vol. 28, no. 3, pp. 388-404, 2011.
- [9] O. Tekdas, V. Isler, J. H. Lim and A. Terzis, "Using mobile robots to harvest data from sensor fields," *Wireless Communications*, IEEE, vol.16, no.1, pp.22-28, February 2009.
- [10] T. Grimm, B. Janßen, O. Navarro and M. Hübner, "The value of FPGAs as reconfigurable hardware enabling Cyber-Physical Systems." *Proc. 20th IEEE Conference on Emerging Technologies & Factory Automation (ETFA)*, pp.1-8, 2015.
- [11] G. J. Garcia, C. A. Jara, J. Pomares, A. Alabdo, L. M. Poggi and F. Torres, "A survey on FPGA based sensor systems: Towards intelligent and reconfigurable low power sensors for computer vision, control and signal processing," *Sensors*, vol. 14, no. 4, pp. 6247-6278, 2014.
- [12] J. Becker, M. Hubner, G. Hettich, R. Constapel, J. Eisenmann, and J. Luka, "Dynamic and partial FPGA exploitation," *Proc. the IEEE*, vol. 95, no. 2, pp. 438-452, 2007.
- [13] K. Vipin, S. Shreejith, S. A. Fahmy, and A. Easwaran, "Mapping time-critical safety-critical systems to hybrid FPGAs," *Proc. the IEEE International Conference on Cyber-Physical Systems, Networks, and Applications (CPSNA)*, pp. 31-36, 2014.
- [14] S. Vyas, C. Kumar, J. Zambreno, C. Gill, R. Cytron, and P. Jones, "An FPGA-based plant-on-chip platform for cyber-physical system analysis," *IEEE Embedded Systems Letters*, vol. 6, no. 1 March 2014.
- [15] P. Viola and M. Jones, "Rapid object detection using a boosted cascade of simple features," *Proc. IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, vol. 1, pp. 511-518, 2001.
- [16] R. Perrey, M. Lycett, "Service-oriented Architecture," *Proc. symposium on Applications and the Internet Workshops (SAINT03)*, pp 116-119, January 2003.
- [17] OpenCV, <http://opencv.org/>
- [18] Xilinx, "ZedBoard - Version 1.1," August, 2012.