Human-centric interoperability Method for Greenhouse Digital Twins in Metaverse era

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***Abstract*—With the emerging of Digital twins (DT) and Internet of Things（IoT） technologies in the field of smart agriculture, the agricultural metaverse (AM) is becoming a research hotspot currently. Massive networked and smart sensors and agricultural robots are deployed in greenhouses, and factory greenhouses have become one of the most promising AM application scenarios. Therefore, this paper explores a human-centric interoperability method for the greenhouse DT, in the era of the future AM. First, a smart greenhouse DT model is built, including greenhouse digital twins, crop growth models, and facility control modules; Second, based on the greenhouse DT, a human-centered interoperability framework is proposed for socialized greenhouses. Finally, a prototype system of greenhouse DT is designed, to verify the feasibility of the human-centered interoperability method.**

Keywords—Smart Agriculture, Greenhouse, Agricultural Metaverse, Human-centric interoperability, Digital Twin

I. INTRODUCTION

The United Nations predicts that the global population will hit 9.6 billion by 2050. Addressing the increasing population's needs, agriculture will need to ramp up production by around 50% compared to current levels [1]. This presents a formidable challenge to the agriculture sector's scale and technological innovation. Meanwhile, the environment's continuous deterioration is adversely affecting agricultural growth. With population growth, there is an increasing need for efficient and reliable environmentally controlled agricultural production methods to sustain food and grain supply. Greenhouse production stands out as the most representative and promising method in terms of intelligence and productivity. Additionally, Moreover, the aging population has resulted in a labor shortfall, and less humanized or unmanned production methods are required. The Internet of Things and digital twins use to deploy large-scale networked, intelligent sensors and agricultural robots in smart greenhouses.

To address large-scale sensing and interoperable control, the concepts of the DT and (AM) have been proposed by researchers [2]. The AM facilitates virtual device coordination in greenhouses, leading to more intelligent management. Moreover, the Agricultural Metaverse involves processes such as social orders and logistics tracking that cannot be controlled by traditional technologies, requiring a change in greenhouse control strategies based on social factors. As a result, this paper proposes a human-centric interoperability method for greenhouse digital twins in the Metaverse era.

Furthermore, multi-robot interoperations add complexity to the AM production system, such as self-organization and autonomous collaboration of greenhouse facilities and robots. On the one hand, in unmanned or less-manned greenhouse indoor production, it is needed the agricultural machines/robots controlling to match the crop growth rhythms. On the other hand, in greenhouse outdoor production, it is preferred crop production rhythms to match the social disturbances, such as dynamic social factors of agricultural product transportation, customer customization, and agricultural order changes in socialized greenhouses etc. Such rhythms and beat consistency problems are close related to the interoperability between humans and the Internet of Things, necessitating a new theoretical framework to support human-centric interoperability of greenhouses. However, the current research of agricultural DT or AM rarely reports on these issues.

Greenhouse production is a complex process that involves multiple inputs, outputs and factors across cyber-physical mixed environments. The interoperability of multiple robots further complicates greenhouse production systems, including the self-organization and autonomous collaboration of greenhouse facilities and robots. On one hand, in unmanned or minimally manned greenhouse production, it is necessary for agricultural machinery and robots to synchronize with the growth rhythm of crops. On the other hand, in outdoor greenhouse production, it is desirable for the production rhythm of crops to align with social disruptions, such as dynamic social factors in agricultural products transportations and customization, and dynamical changes in agricultural orders in socialized greenhouses.

Therefore, there is a need to propose a human-centric interoperability method that can adapt to the pacing of human society and enable the control and interaction of multiple robots. Human-centric interoperability means placing human society in a more important position, while interoperability refers to the organizations and collaborations among humans and multiple agricultural robots, enabling greenhouse production to better serve

Table 1 Related work on greenhouse metaverse

	Greenhouse Digitalization Progresses	Functional features				Technical Support		
		Remote Monitoring	Equipment Regulation	Intelligent Prediction	Social Management	Artificial intelligence	Virtual Reality	Blockchain
[6]2022	Internet of Things (IoT) for device connection and control	Y						
[8]2023		Y				Y		
[7]2022		Y	Y			Y		
[14]2022	Digital Twins （DT） for cyber devices	Y					Y	
[9]2022		Y		Y		Y	Y	
[10]2021 [11]2023		Y	Y	Y		Y	Y	
[2]2022 [12]2022 [13]2023	Agriculture Metaverse （AM） for cyber-physical mixed	Y			Y	Y	Y	Y
This work		Y	Y	Y	Y	Y	Y	Y

society. The human-centric interoperability method has been proposed and applied in industries such as medicine [3], manufacturing [4], and urban planning [5]. However, in agriculture, there is no existing literature on the concept of human-centric interoperability. Greenhouse production needs to consider the influence of human factors and align with the operational pace of human society to address the issue of mismatch between greenhouse production and societal demands.

The remaining sections of this paper are organized as follows: Section II provides an overview of the current research status of greenhouse digital twins. Section III, the human-centric interoperability framework in the Metaverse proposed in this paper is presented, and the feasibility framework is validated. Section IV summarizes the work of this paper.

II. RELATED WORK

The AM constructed with greenhouse is a complex system in which multiple technologies are integrated with each other, some work has been explored the key technologies listed in Table 1. IoT and digital twin are both the basic components of the future metaverse and also the different digitalization progresses for greenhouse intelligent control.

Smart greenhouse agriculture has already utilized IoT technology for remote monitoring of greenhouse operations [6], enabling device control [7]. In the field of agriculture, IoT can be combined with artificial intelligence to achieve precise monitoring and control [7,8]. However, IoT alone cannot achieve virtual reality, blockchain integration, intelligent prediction, and social management capabilities, which require the implementation of digital twins and the Agriculture Metaverse.

Digital twins built upon the foundation of IoT, enable the realization of virtual reality. By simulating and deducing in virtual spaces, more accurate environmental monitoring can be achieved [14]. Based on this, certain greenhouse digital twins combined with artificial intelligence, can enable intelligent prediction [9-11] and device control [10,11]. However, the virtual reality aspect of digital twins is limited to the agricultural production process, with users primarily being greenhouse managers. It does not encompass the entire industry chain and lacks the integration with blockchain for achieving social management.

The AM based with smart greenhouse is a real-time virtual world constructed based on actual agricultural environments, encompassing the entire process of agricultural production [15]. The AM goes beyond the scope of agricultural production alone; it combines blockchain technology to encompass the complete agricultural industry chain, including greenhouse management, agricultural product transportation, agricultural product trading, agricultural education, and inheritance processes [13,14,15]. In the AM, users experience an unprecedented level of immersion and enhanced sensory experience. While the AM has started to take shape, there is still a lack of research on using the Metaverse to build an AM with greenhouse production as its core, specifically exploring the application of AM in greenhouse equipment control.

In summary, the Metaverse, as a new concept in the field of agriculture, holds great potential for development. The Agriculture Metaverse encompasses social development and human activities, necessitating a human-centric method to interoperability. Furthermore, there is a lack of research on constructing the Metaverse with greenhouses as the core focus. Therefore, the proposed human-centric interoperability method for greenhouse digital twins in the Metaverse era proposed in this paper is innovative.

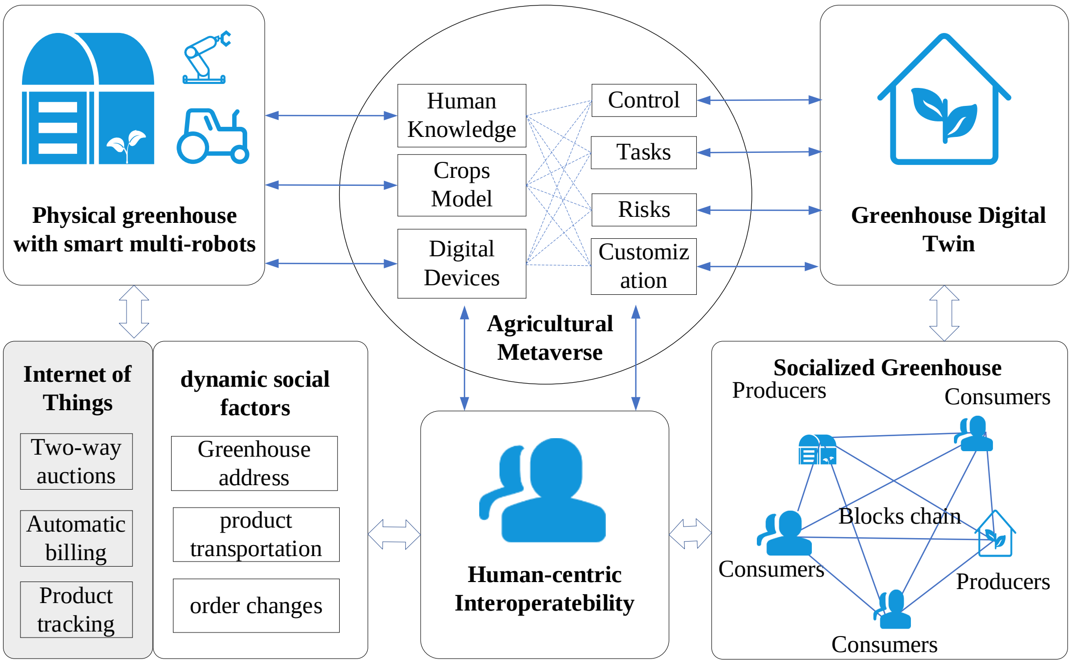

Figure 1 A human-centric interoperability framework for greenhouse metaverse

III. Human-Centric Interoperability Framework for the Agricultural Metaverse

As presented in Figure 1, the AM framework encompasses a physical greenhouse with smart multi-robots, greenhouse digital twins, and human-centered interactions. The interaction between humans and the physical greenhouse and robots generates an IoT system along with dynamic social factors. The interaction between humans and greenhouse digital twins establishes a socialized greenhouse.

The physical greenhouse with smart multi-robots acts as the basis of the AM, encompassing the physical structures of the greenhouse and the robots and agricultural machinery inside. Physical greenhouse with smart multi-robots provides virtual representations of human knowledge models, crop models, and digital devices inside the AM.

The greenhouse digital twin is an exact digital replica of the intelligent greenhouse. It comprises digital plants, digital facilities, and digital greenhouse scenes, as depicted in Figure 2. The digital plants are digitally modeled based on crop growth models, containing growth information and visual representation of the crops. The digital devices are digital twins of greenhouse robots or equipment, used to monitor the real-time operational status of the devices and generate control commands based on the environmental parameters of the digital greenhouse. The digital greenhouse model is a digital replica of the physical greenhouse, encompassing various environmental parameters of the greenhouse. The digital greenhouse, coupled with the digital crops and digital devices, simulates the operation of the intelligent greenhouse, enabling comprehensive greenhouse monitoring and identification of potential risks.

The concept of human-centric interoperability method is the core idea of the AM, permeating throughout the framework. In the Agriculture Metaverse, the interactive control of the digital and physical components of the greenhouse requires coordination with the working

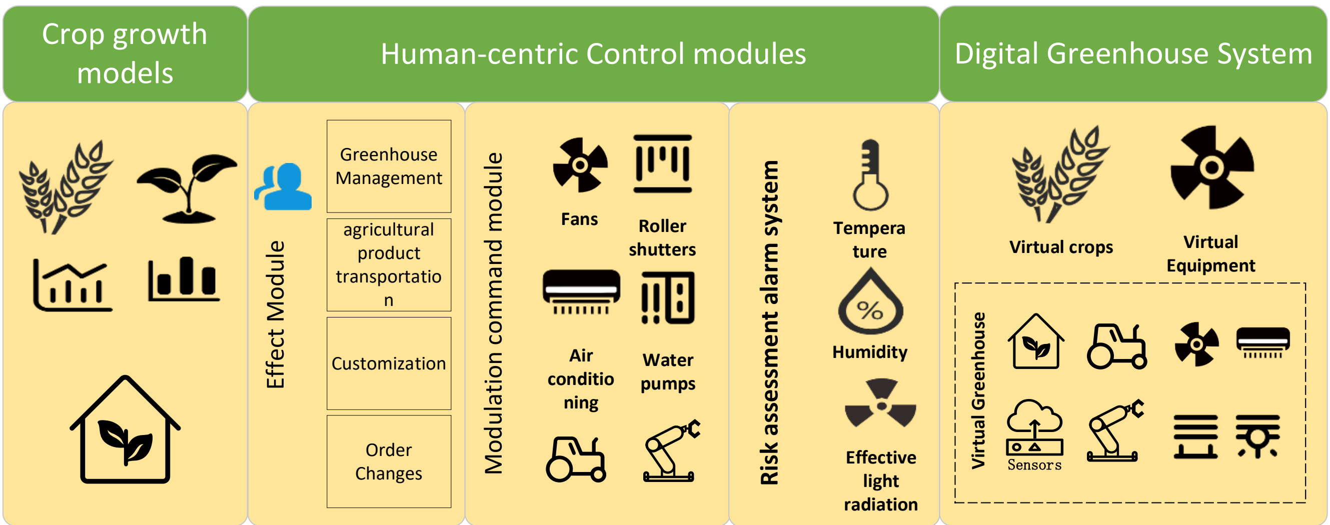

Figure 2 Greenhouse digital twin

schedule of farmers. The integration of the Internet of Things and dynamic social elements must be in sync with human society's needs and patterns. The socialized greenhouse needs to consider consumer preferences and producer transportation conditions. Human- centric interoperability method serves as a guiding principle for these processes, providing guidance for the overall operation of the AM.

The AM serves as the central component of this framework, overseeing the operation of the entire system. On one hand, it receives inputs from the physical greenhouse with smart multi-robots, including Human Knowledge, crop models, and digital devices. Utilizing the human- centric interoperability method, it leverages the greenhouse's digital twin to control, tasks, risk assessment, and customization these inputs. On the other hand, the proposed Human Knowledge, crop models, and digital devices can also be evaluated and assessed through the control, tasks, risk assessment, and customization provided by the greenhouse's digital twin, forming a two-way control process. The AM collects data during the interaction between the digital and physical components, enabling real-time monitoring, intelligent prediction, and smart control of the intelligent greenhouse.

The Internet of Things (IoT) and dynamic social factors are created through the interaction between the physical greenhouse with smart multi-robots and humans. The IoT platform comprises: humans as operators who control the AM system while also being influenced by its control, resulting in a two-way auction within the IoT system; humans as consumers who generate automatic billings to purchase agricultural products; and product tracking information that encompasses the entire process from production to sales of agricultural products. Dynamic social factors include: greenhouse address, product transportation, and order changes. The IoT and dynamic social factors provide data support for human-centric interoperability method, ensuring the collaborative control of the greenhouse and the implementation of a traceability system for agricultural products.

The socialized greenhouse is created through the interaction between humans and the greenhouse digital twin, which relies on blockchain technology. It comprises multiple greenhouse producers and social consumers, who form blocks based on their geographical location, allowing for direct peer-to-peer transactions. Consumers can visit designated virtual greenhouses and purchase agricultural products, gaining access to real and transparent information about the products and enjoying a highly immersive purchasing experience. Greenhouse producers can deliver products directly to consumers' doorsteps, reducing storage and logistics costs. The order information serves two purposes: personalized product offerings that cater to consumers' preferences and as a demand guide for the greenhouse's production activities, thereby improving the greenhouse's economic efficiency. The socialized greenhouse acts as a bridge between producers and consumers, reducing production costs and enhancing the value of agricultural products.

IV. A CASE STUDY OF GREENHOUSE ENVIRONMENTAL CONTROL

To validate the feasibility of the human-centric interoperability method framework, a greenhouse digital twin system was built in this study. This framework was applied at Huazhong Agricultural University to establish an AM prototype system. The digital twin was constructed using the software tools of SolidWorks and Unity3D, as

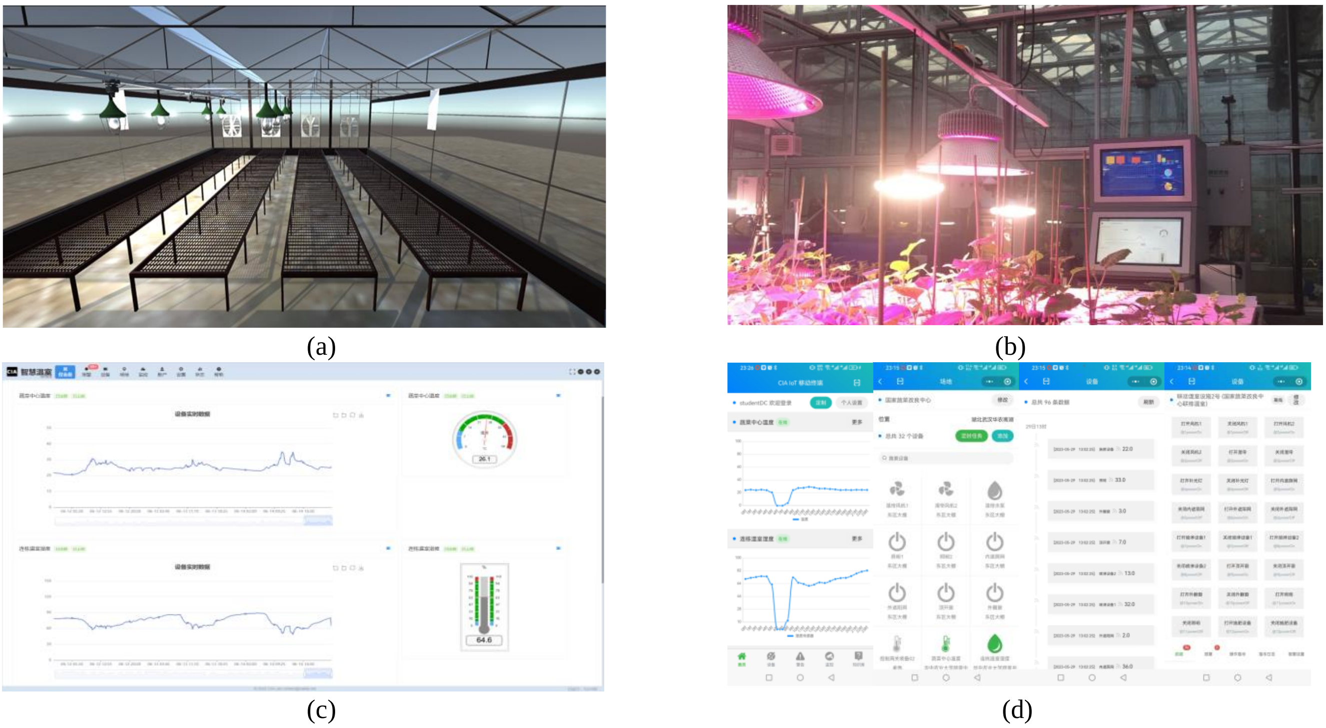

Figure 3 A case study of greenhouse environmental control. (a) Interior view of the intelligent greenhouse digital twin model. (b) Greenhouse scene in real physical world. (c) Crop growth models. (d) Greenhouse equipment control.

shown in Figure 3. Figure 3(a) depicts the intelligent greenhouse digital twin's interior, which allows greenhouse staff to remotely observe and manage the greenhouse operations, while consumers and learners can visit and learn about greenhouse management. Figure 3(b) shows the physical greenhouse equipped with smart multi-robots at the National Vegetable Improvement Center of Huazhong Agricultural University. Figure 3(c) represents the platform for displaying greenhouse sensor data and crop growth models, while Figure 3(d) displays the mobile platform for controlling greenhouse devices. The greenhouse digital twin system can be adapted to different end devices to suit various situations in greenhouse production.

V. CONCLUSION

This paper proposes and validates a method for human-centered interoperability of digital twins in the metaverse era. Firstly, based on a literature review, the paper offers a comprehensive comparison and summary of the Internet of Things, digital twinning, and agriculture metaverse, emphasizing the need for a human-centered approach to interoperability in the metaverse. Secondly, the paper proposes a framework for achieving human-centric interoperability in the metaverse. Finally, a prototype system of a digital twin for a greenhouse is designed and implemented to validate the feasibility of the human-centered interoperability method. This research offers a practical approach to the construction of AM.

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ACKNOWLEDGMENT

This work is supported by the Key Technologies Research and Development Programs of Hubei Province [2021BBA239] and Shannan [SNSBJKJJHXM2023004]. It has been carried out by the research group of the Connected and Intelligent Laboratory (CIA Lab) at the College of Engineering, Huazhong Agricultural University. Additionally, we would like to express our gratitude to Zhilong Bie, Yuan Huang, Wentao Song, and Can Deng for their valuable contributions to the experiments and their solid advice.

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