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 potential AM application scenarios. To this end, this paper explores a human-centric interoperability method for the greenhouse DT, in the era of the future agricultural metaverse. 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

According to the United Nations, the world population is estimated to reach around 9.6 billion by 2050. To meet the growing population's needs, agriculture will need to increase its production by approximately 50% compared to today [1]. This poses a significant challenge to the scale and technological innovation in agriculture.

Meanwhile, the continuous deterioration of the environment is impacting agricultural development. 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, the aging population leads to a lack of labor and the need for unmanned or less humanized production methods, which the Internet of Things and digital twins use to deploy large-scale networked, intelligent sensors and agricultural robots in smart greenhouses.

To cope with large-scale sensing and interoperable control, the concept of the Agricultural Metaverse（AM） has been proposed by researchers [2]. The Agricultural Metaverse enables virtual device coordination in greenhouses, leading to more intelligent management. Additionally, 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. Therefore, this paper proposes a human-centric interoperability method for greenhouse digital twins in the era of the Metaverse.

Moreover, the interoperations feature of multi-robots leads the AM production system to be more complex, 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 agricultural metaverse rarely reports on these issues.

Greenhouse production is a complex process involving multiple inputs and factors. 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, the control of agricultural machinery/robots is necessary 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 product transportation, customer customization, and 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.

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

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Direction of development | Functional features | | | | Technical Support | | |
| Remote Monitoring | Equipment  Regulation | Intelligent Prediction | Social Management | Artificial intelligence | Virtual Reality | Blockchain |
| [6]2022 | Internet of Things (IoT) | Y |  |  |  |  |  |  |
| [8]2023 | Y |  |  |  | Y |  |  |
| [7]2022 | Y | Y |  |  | Y |  |  |
| [14]2022 | Digital Twins（DT） | 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） | Y |  |  | Y | Y | Y | Y |
| This article | Y | Y | Y | Y | Y | Y | Y |

the framework is validated. Part IV summarizes the work of this paper.

# Ⅱ. Related Work

Human-centric interoperability means placing human society in a more important position, while interoperability refers to the organization and collaboration between humans and multiple robots, enabling greenhouse production to better serve 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 the field of 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.

Furthermore, the AM constructed with greenhouse is a complex system in which multiple technologies are integrated with each other. IoT and digital twin are both the basic components of the future metaverse and also the different development directions of 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 Agricultural Metaverse 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 agricultural Metaverse 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 agricultural Metaverse, users experience an unprecedented level of immersion and enhanced sensory experience. While the agricultural Metaverse has started to take shape, there is still a lack of research on using the Metaverse to build an Agricultural Metaverse (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.

# Ⅲ. Human-Centric Interoperability Framework for the agricultural Metaverse

The Agricultural Metaverse framework, as shown in Figure 1, includes a physical greenhouse with smart multi-robots, greenhouse digital twins, and human-centered interactions. The interaction between humans and the physical greenhouse and robots forms an IoT system along with dynamic social factors. The interaction between humans and greenhouse digital twins forms a socialized greenhouse.

The physical greenhouse with smart multi-robots serves as the foundation of the agricultural metaverse, encompassing the physical structures of the greenhouse and the robots and agricultural machinery inside. Physical greenhouse with smart multi-robots provide virtual representations of human knowledge models, crop models, and digital devices within the Agricultural Metaverse.

The greenhouse digital twin is an exact replica of the intelligent greenhouse in a digital space, including digital plants, digital facilities, and digital greenhouse scenes, as shown 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, together 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 Agricultural Metaverse, 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 schedule of farmers. The integration of the Internet of Things and dynamic social elements must align with the desires and patterns of human society. 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 Agricultural Metaverse.

The Agricultural Metaverse serves as the core component of this framework, coordinating the operation of the entire system. On one hand, the Agricultural Metaverse 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 Agricultural Metaverse 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 formed through the interaction between the physical greenhouse with smart multi-robots and humans. The IoT platform includes: humans as operators who control the Agricultural Metaverse 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 formed through the interaction between humans and the greenhouse digital twin, with blockchain technology at its core, and consists of multiple greenhouse producers and social consumers. Producers and consumers form different blocks based on geographical location information, allowing for direct peer-to-peer transactions between producers and consumers. 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 serves as a connecting bridge between producers and consumers, helping to reduce production costs and increase the value of agricultural products.

# Ⅳ. A case study of greenhouse environmental control

To validate the feasibility of the human-centric interoperability method framework, this paper has built a greenhouse digital twin system. The human-centric interoperability method framework in the agricultural metaverse has been successfully applied at Huazhong Agricultural University, establishing an initial agricultural metaverse system. The greenhouse digital twin model was constructed using SolidWorks and Unity software, as shown in Figure 3. Figure (a) shows the interior of the intelligent greenhouse digital twin, where greenhouse staff can remotely monitor and control the greenhouse operations, and consumers and learners can visit and learn about greenhouse management. Figure (b) shows the physical greenhouse with smart multi-robots at the National Vegetable Improvement Center of Huazhong Agricultural University. Figure (c) shows the platform for displaying greenhouse sensor data and crop growth models. Figure (d) shows the mobile platform for controlling greenhouse devices. The greenhouse digital twin system can be applied to different end devices to adapt to different situations in greenhouse production.

# Ⅴ. conclusion

In this paper, a human-centered interoperability method for digital twins in the metaverse era is proposed and validated. Firstly, a comprehensive comparison and summary of the Internet of Things, digital twinning, and agriculture metaverse are provided based on the literature review, emphasizing the necessity of a person-centered interoperability method in the metaverse era. Secondly, a framework for human-centric interoperability in the metaverse is proposed. Lastly, 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 provides a practical approach for the construction of agricultural metaverses.

# Acknowledgment

This work is supported by the Key Technologies Research and Development Program of Hubei Province [2020BBA040], and has been carried out by research group of Connected and Intelligent Laboratory (CIA lab) at the college of engineering of Huazhong Agricultural University. Moreover, thank Can Deng, DaXin Zeng, AnAn Yuan, Hua Feng and WenTao Song for the contributions on experiments.

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