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SCENARIO OF AGRICULTURE ROBOT: BACKGROUND, CHALLENGES AND POLICY

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ABSTRACT

In the realm of digital agriculture, agricultural robots assume a distinctive role, offering numerous advantages in farming production. Since the emergence of the first industrial robots in the 1950s, these machines have garnered attention from both the research community and industry. Recent strides in computer science, sensing technologies, and control methodologies have propelled agricultural robots through a swift evolution, leveraging cutting-edge technologies tailored for various application scenarios. Notably, considerable enhancements have been realized by seamlessly integrating perception, decision-making, control, and execution techniques. Despite these advancements, the majority of agricultural robots still necessitate intelligent solutions, constraining their deployment to small-scale applications due to a lack of integration with artificial intelligence. Consequently, researchers and engineers face challenges in scaling these technologies for mass production. In this comprehensive review, we delve into the current landscape of agricultural robots by examining literature categorized based on the types of agricultural robots discussed. Our aim is to provide a panoramic view of diverse research statuses and applications of agricultural robots, shedding light on both the benefits and challenges associated with their broader deployment.

***Key words*:** computer science; sensing technologies; decision-making; artificial intelligence

Introduction

Agricultural robots, encompassing machines specifically tailored for use in farming production (Reddy *et al.*, 2016), constitute a vital segment within the robot family. Typically, these robots are equipped with sophisticated perception capabilities, autonomous decision-making skills, precise control mechanisms, and adept execution abilities. Notably, they excel in attaining precise and efficient production objectives, even in intricate, adverse, and hazardous environments. Driven by the imperative for labor-saving and efficient agricultural practices, the spectrum of agricultural robots has undergone continuous expansion, leading to a more diversified array of application scenarios. Reflecting their diverse targets, agricultural robots are commonly categorized into field robots (Kayacan *et al.*, 2018), fruit and vegetable robots (Wang *et al.*, 2022), and animal husbandry robots (Skvortsov *et al.*, 2018). Additionally, through an examination of pertinent literature, research on agricultural robots predominantly centers on field robots and fruit and vegetable robots, with a particular emphasis on the harvesting domain. Despite variations in their specific application contexts, these agricultural robots share commonalities in core technologies. Essential components include a stable mobile platform, collaborative multi-sensor systems, advanced visual image processing technology, intricate algorithms, and adaptable locomotion control-elements typically indispensable for the constitution of an effective agricultural robot. Fig. 1 encapsulates various related techniques that are integral to this domain.

The development and implementation of agricultural robots have roots in addressing various challenges and opportunities within the agriculture sector. The background of agricultural robots can be understood by considering several factors: Labor Shortages: Many regions face challenges in finding an adequate labor force for agricultural tasks, especially during peak seasons. Agricultural robots offer a solution by automating repetitive and labor-intensive tasks.

Increased Efficiency: Automation in agriculture can significantly improve efficiency. Agricultural robots can work continuously without fatigue, leading to increased productivity and faster task completion. Precision Agriculture: Agricultural robots contribute to the concept of precision agriculture, where technologies such as sensors, GPS, and data analytics are used to optimize field-level management with regard to crop farming. This includes the precise application of water, fertilizers, and pesticides. Technological Advancements: Advances in robotics, artificial intelligence, and sensing technologies have paved the way for the development of sophisticated agricultural robots. These machines can perform complex tasks with precision and autonomy. Environmental Sustainability: Agricultural robots can contribute to more sustainable farming practices. By allowing for targeted application of resources and reducing waste, they can minimize the environmental impact of agriculture. Harsh and Dangerous Environments: Certain agricultural tasks, such as handling hazardous materials or working in extreme weather conditions, can pose risks to human workers. Agricultural robots can be designed to operate in such environments, enhancing safety. Data-Driven Decision Making: The integration of robotics and data analytics in agriculture enables farmers to make informed decisions based on real-time information. This data-driven approach can lead to better crop management and resource allocation. Research and Development: Academic research, as indicated by references like (Skvortsov *et al.*, 2018), contributes to the development of agricultural robots. Scientists and engineers explore new mechanisms, technologies, and solutions to enhance the capabilities of these robots in addressing specific agricultural challenges. Overall, the background of agricultural robots is characterized by a combination of technological advancements, the need for increased efficiency, and a desire to address challenges in modern agriculture. The ongoing development and adoption of these technologies continue to shape the future of farming practices.

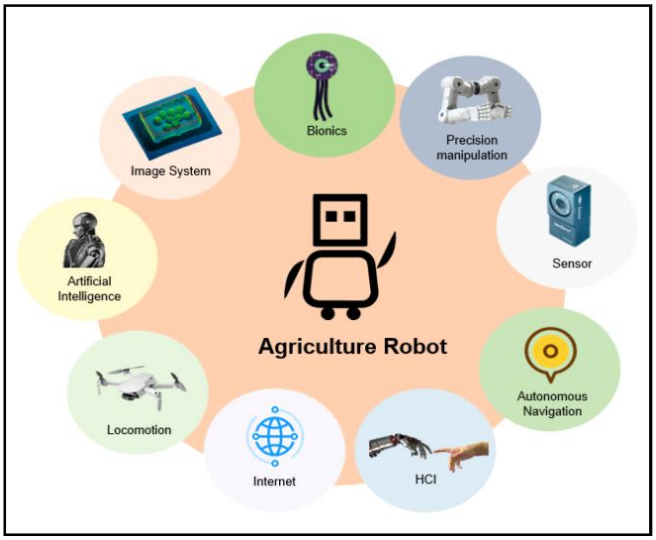

Fig. 1: Agricutural robot.

Current Status of Agricultural Robot in World

As of my last knowledge update in January 2022, the field of agricultural robotics has been advancing rapidly, but the specific developments and status may have evolved since then. Here are some general trends and aspects that were relevant at that time:

(i) Autonomous Tractors and Harvesters

Autonomous tractors and harvesters were gaining traction, with several companies working on developing and deploying these machines for various crops. These robots are designed to perform tasks such as plowing, seeding, and harvesting with minimal human intervention. In the initial stages, Tamaki *et al.*, (2013) pioneered the development of a robotic system featuring three robots tailored for large-scale paddy farming. The automated system comprised a tillage robot equipped with RTK-GNSS (Real-Time Kinematic Global Navigation Satellite System) and an inertia measurement unit (IMU) or GPS compass, facilitating navigation between the paddy fields. This innovative approach served as an early glimpse into the promising future of agricultural robots in Japan. Fast forward to 2021, Panarin and Khvorova (2021) made significant strides by enhancing existing software specifically designed for tilling robots. Part of this effort aimed at ensuring seamless adaptation between software systems and the robots manufactured, marking a noteworthy advancement in the field.

(ii) Weeding Robots

Weeding robots equipped with computer vision and machine learning algorithms were being used to identify and remove weeds selectively. These systems help reduce the reliance on herbicides and promote more sustainable farming practices. Sori and collaborators (Sori *et al.*, 2018) introduced a specialized robot designed for weeding in paddy fields. This robotic system, featuring two wheels and equipped with touch sensors and a turning azimuth sensor, demonstrates the ability to weed by agitating the soil and obstructing sunlight. The intended outcome is an enhancement in crop yield, as suggested by experimental results.

(iii) Drones for Monitoring

Unmanned aerial vehicles (UAVs) or drones were

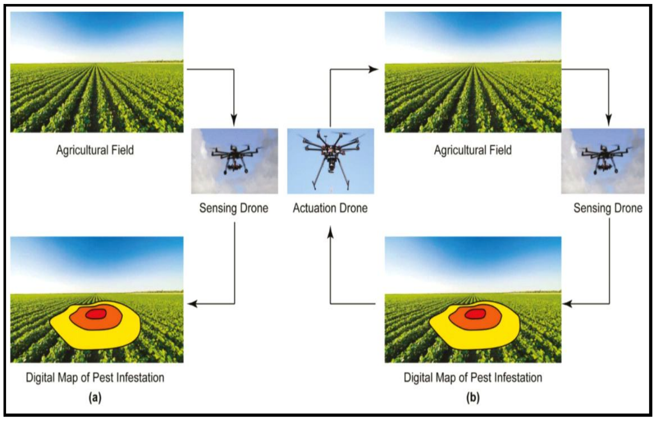

Fig. 2: UAV for crop monitoring.

being employed for crop monitoring and data collection. Drones equipped with cameras and sensors provide real-time information on crop health, allowing farmers to make informed decisions. As depicted in Fig. 2, Filho *et al.*, (2020) presented innovative technologies for small drones, encompassing both sensing and actuation capabilities. Through collaborative efforts, this intelligent system is designed to offer sustainable pest control solutions. In a related development, a new modular system for precision farming was proposed in Terra *et al.*, (2021), leveraging individual nozzles and computer vision technology. The deployment of these machines holds the dual benefit of safeguarding the environment and reducing farming expenses.

(iv) Robotic Fruit Pickers

Developments in robotic fruit picking technology were underway. Robots capable of identifying and gently picking ripe fruits were being tested and deployed in orchards, addressing labor shortages and increasing efficiency. Fruit and vegetable picking robots are automated machines specifically designed for the large-scale detection and harvesting of fruits and vegetables in modern agriculture (Vasconez *et al.*, 2020; Gené-Mola *et al.*, 2019; Gené-Mola *et al.*, 2020). These robotic harvesters are categorized into bulk and selective types (Fountas *et al.*, 2020), covering a range of applications such as kiwi-picking robots, apple-picking robots, strawberry-picking robots, tomato-picking robots, and more (Wang *et al.*, 2022). Fruit and vegetable picking robots have emerged as a prominent subject within the realm of agricultural robotics. For instance, Williams and collaborators (Williams *et al.*, 2019). developed a kiwi fruit-picking robot. This robot incorporates a machine vision system, end effectors, and four harvesting arms. Notably, the robot utilizes a convolutional neural network (CNN) for semantic segmentation on images of the canopy. However, during testing in the orchard, the novel robotic kiwifruit harvesting system achieved successful picking for only 51% of the kiwi fruits due to obstructions and losses.

(v) Data-Driven Precision Agriculture

The integration of robotics with data analytics and precision agriculture techniques was helping farmers optimize resource use. This includes precise application of water, fertilizers, and pesticides based on real-time data and analysis. Although the process of collecting information in the field can be labor-intensive and challenging, the data obtained plays a crucial role in aiding farmers in making informed decisions. Recognizing this, robots designed for collecting field information have been developed to handle this demanding task. A notable example is the work by Bayati and colleagues at the University of Saskatchewan (Bayati and Fotouhi, 2018). They developed, implemented, and validated a field-based high-throughput plant phenotyping mobile robotic platform specifically designed to monitor Canola plants. The platform is capable of automatically gathering and analyzing wide-range images of plant canopies. This innovation has demonstrated its ability to enhance farm productivity while concurrently reducing long-term costs.

(vi) Research and Innovation

Ongoing research and innovation were driving the development of new robotic technologies for agriculture. Academic institutions, startups, and established companies were actively contributing to advancements in the field.

(vii) Global Adoption

Agricultural robots were being adopted in various parts of the world, particularly in regions facing labor shortages and seeking ways to enhance agricultural productivity. Different types of robots were being customized to meet the specific needs of diverse crops and farming practices. It’s essential to note that the specific status and advancements in agricultural robotics can vary by region, depending on factors such as technological infrastructure, regulatory frameworks, and the agricultural landscape.

Development of Robot for Agricultural Robot

The development of robots for agricultural applications involves a multidisciplinary approach, integrating expertise from robotics, automation, computer vision, artificial intelligence, and agricultural sciences. The following key aspects contribute to the development of robots for agricultural use:

(i) Sensing Technologies

Computer Vision: Vision systems equipped with cameras and image processing algorithms enable robots to visually perceive the environment. This is crucial for tasks such as identifying crops, detecting weeds, and assessing crop health.

LiDAR and Radar: Light Detection and Ranging (LiDAR) and Radar sensors provide depth perception and help in mapping the terrain accurately, enabling robots to navigate autonomously.

(ii) Autonomous Navigation

Algorithms for simultaneous localization and mapping (SLAM) enable robots to navigate autonomously in dynamic and unstructured environments. GPS and other localization technologies contribute to precise positioning.

(iii) Manipulation and Actuation

Robotics arms and end-effectors designed for agricultural tasks, such as planting, harvesting, and pruning, are essential components. Actuators and grippers are chosen based on the specific requirements of the task.

(iv) Machine Learning and AI

Artificial intelligence, including machine learning, is used for decision-making and adaptive control. Machine learning models can be trained to recognize crops, pests, and diseases, allowing robots to make informed decisions in real-time.

(v) Human-Robot Interaction

User interfaces and communication systems facilitate interaction between farmers and robots. This includes interfaces for programming, monitoring, and controlling the robots, as well as feedback mechanisms.

(vi) Energy Efficiency and Power Systems

Agricultural robots need to operate efficiently over long durations. The development of energy-efficient systems, as well as reliable and sustainable power sources, is crucial for prolonged field operations.

(vii) Data Management and Analytics

Sensors on agricultural robots generate large amounts of data. Effective data management and analytics help farmers derive actionable insights, contributing to better decision-making for crop management.

(viii) Weather and Environmental Considerations

Robots designed for agriculture must withstand and operate in diverse environmental conditions. Considerations for water resistance, dust protection, and temperature tolerance are important for field deployment.

(ix) Collaborative and Swarm Robotics

Collaborative robots working together in a coordinated manner (swarm robotics) can enhance efficiency and coverage. This approach is particularly useful for tasks like crop monitoring or large-scale planting.

(x) Regulatory Compliance

Complying with local regulations and standards is crucial for the development and deployment of agricultural robots. Adhering to safety standards ensures the protection of both the robots and the farmers.

(xi) Field Trials and Feedback

Real-world testing and feedback from farmers are integral to refining and improving agricultural robots. Field trials help developers understand the practical challenges and optimize robot performance.

Challenges in Design of Robot

The design of robots, regardless of their intended application, comes with various challenges that engineers and developers must address. Designing robots for complex tasks, especially those involving intricate manipulation, decision-making, or interaction with unpredictable environments, poses a significant challenge. Ensuring that the robot can handle diverse and dynamic scenarios is crucial. Developing effective sensory systems for robots, including vision, touch, and spatial awareness, is a challenge. Achieving accurate and real-time data acquisition is essential for enabling robots to navigate and interact with their surroundings. Creating robots with a high level of autonomy requires sophisticated decision-making algorithms. Designers must address challenges related to real-time processing, learning from experience, and adapting to changing conditions. Designing robots that can interact seamlessly and safely with humans is a complex challenge. Ensuring intuitive interfaces, natural communication, and safe physical interaction are critical aspects of HRI design. Balancing power consumption and performance is a challenge, especially for robots operating in remote or resource-constrained environments. Developing efficient power sources and energy management systems is crucial. Robots often operate in challenging conditions, and their design must account for variations in terrain, weather, and other environmental factors. Ensuring the robustness and reliability of the robot under different circumstances is a persistent challenge. Creating a mechanically sound and efficient robot involves addressing challenges related to materials, weight distribution, durability, and the ability to perform tasks with precision. This is particularly important for robots with manipulators or moving parts. Designing cost-effective robots that can still meet performance requirements can be challenging. Striking a balance between functionality and affordability is crucial for the widespread adoption of robotic technologies. Designing robots that can be easily scaled for different applications or adapted to various sizes and environments is a challenge. Achieving modularity and flexibility in design contributes to scalability. Ensuring that the robot design complies with relevant safety standards and regulations is essential. Navigating the regulatory landscape can be challenging, particularly as technology evolves. Addressing ethical concerns related to the use of robots, such as privacy, security, and potential job displacement, is increasingly important. Designers must consider the broader societal impact of their creations. Incorporating cutting-edge technologies, such as artificial intelligence, machine learning, and advanced sensors, presents challenges in terms of integration, compatibility, and keeping up with rapid technological advancements.

Addressing these challenges often requires interdisciplinary collaboration, innovation, and a thorough understanding of the specific application for which the robot is designed. Continuous research and development efforts are necessary to overcome these challenges and push the boundaries of what robots can achieve.

Commercial Approach of the Robot

Robotics companies adopt various business models depending on their offerings, target markets, and the specific needs of their customers. Here are some common business models for robotics companies:

(i) Product Sales

Hardware Sales: Companies manufacture and sell robotic hardware, such as industrial robots, robotic arms, drones, or specialized robotic devices.

Software Sales: Offering robotic software solutions, including control systems, simulation software, and programming tools.

(ii) Robot as a Service (RaaS)

Providing robots on a subscription or pay-per-use basis. This model reduces the upfront costs for customers and often includes ongoing maintenance and updates.

(iii) Subscription Services

Offering subscription-based services for access to advanced features, regular updates, and customer support. This model is common for software-based robotics applications.

(iv) Platform as a Service (PaaS)

Providing a platform that allows users to build, deploy, and manage their robotic applications. This may include cloud-based services for data storage, processing, and analytics.

(v) Maintenance and Support Services

Offering maintenance, repair, and support services for robotic systems. This model can be coupled with product sales or RaaS.

(vi) Consulting and Integration Services

Providing consulting services to help clients integrate robotics into their operations. This can include customization, system integration, and training.

(vii) Data Services

Leveraging data generated by robotic systems for analytics, insights, and optimization. Companies can offer data services to help clients make informed decisions based on the collected data.

(viii) Custom Solutions

Developing customized robotic solutions tailored to specific industry needs. This model involves understanding the unique requirements of clients and delivering bespoke robotic systems.

(ix) Collaborative Partnerships

Collaborating with other companies, either through partnerships, joint ventures, or alliances, to provide end-to-end solutions that combine different technologies and expertise.

(x) Licensing and Royalties

Licensing intellectual property, patents, or proprietary technology to other companies for use in their products. This model can provide a revenue stream through royalties.

(xi) Education and Training

Providing training programs and educational materials for individuals and organizations looking to learn how to use and implement robotics.

(xii) E-commerce Platforms

Operating an online marketplace for buying and selling robotic components, parts, or accessories. This model serves the broader robotics community.

(xiii) Robotics-as-a-Platform (RaaP)

Building a platform that allows third-party developers to create applications or add-ons for existing robotic systems. This can create an ecosystem around the company’s core technology.

(xiv) Subscription Box Models

Offering a subscription box service where customers receive robotic kits, components, or educational materials regularly. This model is popular in the educational and hobbyist robotics space.

The choice of a business model often depends on factors such as the nature of the robotics technology, the target market, and the company’s strategic goals. Many robotics companies may combine multiple models to create a diversified revenue stream.

Ethics

The potential impacts of utilizing robots in agriculture can be perceived as either "bugs" or "features," depending on the perspective and interests of the critic. When deciding on policies that could lead to specific outcomes or potentially hinder them, there is a necessity to grapple with questions of value, essentially delving into ethical considerations. The choice between policies involves addressing fundamental ethical questions that shape the values and priorities guiding decisions in the realm of agricultural robotics.

Economic decisions inherently involve ethical considerations, particularly concerning the areas left to market forces, the regulation and enforcement of contracts, and the definition and distribution of externalities (Satz, 2012). In the context of agricultural robotics, a critical ethical decision emerges: choosing between robots that may further incentivize industrial farming and the consolidation of ownership in the agricultural sector versus robots that could support smaller enterprises and foster the development of more diverse forms of agriculture.

Determining the appropriate trade-offs between competing ethical concerns, such as equity versus efficiency, along with considerations of social justice and wealth distribution, becomes paramount in this context. The impact of robots on employment levels in the agricultural sector also raises ethical questions about the extent of society's obligation to provide individuals with opportunities for meaningful labor and, once again, considerations of social justice. It is noteworthy that there is a significant ethical argument "for" the elimination of jobs that are deemed "dull, dirty, and dangerous," and certain forms of agricultural labor may fall into these categories (Byard, 2017). These complex ethical considerations underscore the need for thoughtful and conscientious decision-making in the integration of agricultural robots into the farming landscape.

Policy

Certainly, given the potentially significant impacts of agricultural robotics, it is imperative, as emphasized in the "responsible innovation" literature, that the widest possible community be involved in the ongoing discussions (Eastwood *et al.*, 2019; Rose *et al.*, 2018; Fleming *et al.*, 2018). While recognizing the need for inclusivity, the following proposals are put forth in the hope that they may contribute meaningfully to this broader debate. Considering the scale of the current global environmental crisis and its impact on food security, it becomes crucial to explore every available option to enhance the sustainability of agriculture. To mitigate the risk of robots exacerbating the centralization of ownership in the agricultural sector and promoting monocultures at the expense of biodiversity, governments and researchers could prioritize the development of sophisticated robots. These robots should exhibit sufficient flexibility to accommodate usage on small properties and across a wider array of crops and livestock. Investing in research on the applications of agricultural robotics, and potentially offering subsidies for their early adoption, could help reduce the likelihood that small farms miss out on the benefits of this technology (Fleming *et al.*, 2018; Lowenberg *et al.*, 2019). By fostering adaptability and inclusivity in agricultural robotic technologies, there is an opportunity to address environmental challenges and promote sustainable practices across diverse agricultural landscapes.

To facilitate the widespread adoption of robots in agriculture, it is crucial to address the impact of automation on farmers' relationships with agricultural service providers. The contractual obligations between farmers and providers, influenced by the use of robots, are subject to modification through regulation. While such changes may be unpopular with manufacturers, one regulatory approach could involve governments mandating that all agricultural robots operate using "open source" software. Additionally, it may be more feasible for governments to stipulate that farmers retain and control the data produced by these robots (Keogh *et al.*, 2016; Jakku *et al.*, 2016). Policy makers must be mindful of the potential impacts of regulations on manufacturers' incentives to innovate and develop robotic technologies. Striking a balance between regulatory measures and encouraging continued innovation is crucial to ensuring the successful integration of robots in agriculture.

Conclusion

This study has comprehensively examined the present state and diverse applications of agricultural robots. Alongside this exploration, we have delved into the challenges that accompany the ongoing progress of agricultural robotics. It is our aspiration that this review serves as a source of inspiration for researchers, guiding them in understanding the evolving trends within the field of agricultural robots. These trends encompass, but are not limited to, critical aspects such as human–robot interaction, agronomics, sensor technologies, and the pursuit of achieving full automation. By reflecting on the current landscape and challenges, researchers can chart a course toward innovative solutions that propel the future development of agricultural robotics.

Public fears and stakeholder anxieties can significantly impede the development and adoption of new technologies. Neglecting to address public concerns and address the social and political impacts may undermine the progress and implementation of agricultural robotics, with potential repercussions on the economy, environment, and society at large. It is only by directly confronting the ethical and policy questions that researchers, government bodies, and industry players can hope to engage the public effectively and garner their support in embracing the potential benefits of robots in agriculture. Open dialogue and transparent communication are essential to building trust and fostering a shared understanding of the ethical implications and societal impacts of agricultural robotic technologies.

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