Global Agricultural Robotics Research and Development: Trend Forecasts

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Abstract. Agricultural robots have been recognized as one of the emerging technologies with the highest potential in agriculture. Through grasping the research and development trend of international agricultural robots and analyzing the technical hot spots, the strategy or plan of agricultural robots in China can be formulated with a decision-making support. This paper applies the methods of expert consultation, qualitative investigation and quantitative analysis to analyze and summarize the hot spots and frontier of agricultural robot research and the future development trend by tracing the development course of agricultural robots at home and abroad. Based on the analysis of China's strategic needs and key development directions for the next few years, this paper provides references and suggestions for China's forefront planning on basic research, technological R&D and industrial layout of agricultural robots in the future.

1. Introduction
Agricultural robotics has developed rapidly in recent years. It has shown great advantages in improving agricultural productivity, changing agricultural production models, solving labor shortages, and achieving scale, diversification, and precision in agriculture. Agricultural robotics has gradually become one of the important directions in agricultural engineering.

Recent years have seen many researches on the development and trends of agricultural robots. Chen Kai et al. (2016) drew patent maps for agricultural robots, showing development trends, key technical fields, geographical distribution, competing agencies, and highly cited patents[2]. Ying Xing et al. (2018) analyzed the research frontiers of international agricultural machinery based on SCI highly cited papers through bibliometrics[3]. Yuan Jianxia et al. (2019) took SCI papers as the research object and comprehensively adopted methods such as bibliometrics, content analysis and expert consultation to analyze the output trends, popular research topics, national competition trends and research frontiers of papers on agricultural robotics[4]. Based on the comprehensive analysis of patents and papers, this article investigates the strategic planning of agricultural robot development in key countries, combines quantitative and qualitative approaches, and reviews the much-talked-about research topics, frontiers, and future trends by tracing the history of agricultural robotics at home and abroad. This research also takes into account China’s strategic needs and key development directions in the next few years and provides references and suggestions for China’s future planning in cutting-edge basic research, technology development, and industrial layout of agricultural robots.
2. Data sources and analysis methods
This study comprehensively applies qualitative analysis, quantitative analysis and expert consultation to carry out trend forecast of international agricultural robot research and development.

Qualitative analysis of the strategic planning and funding projects issued by the European Union, the United States, Japan, South Korea, Australia and other countries, and information and reports by trade media and consulting companies such as PrecisionAg, CropLife, Farm Industry News and Agfunder.

Quantitative analysis of literature data from databases such as Web of Science and EI Compendex; patent data from Derwent Innovation database. The analysis covers focuses of basic research and technology R&D, and core research outcomes analysis.

Expert consultation: the study consults field experts on sorting out classes of technologies, creating search queries, filtering query results, evaluating analysis outcomes, and interpreting technology frontiers, etc. Their technical know-how and professional verdicts underpin the review of popular research topics, trend forecasts and relevant strategy proposal.

3. Research progress of global agricultural robotics

3.1. Stages of research
Agricultural robotics has generally gone through four stages (Figure 1):

(1) Early stage (1951 ~ 1980): Before 1980, the number of patents applied globally in the field of agricultural robotics was relatively small, under 30 per year, when agricultural robotics was in its infancy. The early agricultural robotics mainly came from the United States, and mainly concerned the research of robotic machinery. Compared with technology patents, papers on agricultural robotics appeared late, and the publication of relevant studies could be traced back to 1968. Annual patent applications outnumbered annual paper publications.

(2) Slow development (1981-1990): The number of patent applications in the field of agricultural robotics had gradually increased, but the total number of patents was still small. This area of research was in slow development, with the annual number of patent applications under 70. During this period, continuous development and extensive application of industrial technology and automatic positioning and navigation technology gave rise to different types of agricultural robots for picking, harvesting, milking, etc. At this stage, a small number of research papers were published in the field of agricultural robotics, and these studies mainly involved the use of industrial robotic technologies in agricultural robots, covering activities such as harvesting, grafting, transplantation, grain picking, and spraying. In 1984, Professor Naoshi Kondo of Kyoto University successfully introduced robotics into the field of agricultural engineering for the first time. Later in this period, Australia and the United Kingdom released papers on robotic shearing and milking.

(3) Stable development (1991-2005): Agricultural robotics has further developed. Patents and literatures at this stage mostly addressed agricultural working conditions, growing techniques, and physical characteristics of crops. Efforts are made to improve the human-crop-robot relationship and fit robots to agricultural operations.

(4) Rapid development (2006-2017): After 2006, agricultural robotics entered a stage of rapid development with a sharp increase in the number of patent applications and literature publications. In this period, intelligent, fast and cost-effective robots became the main subject of research. Modern robotics integrates cutting-edge technologies. Robots can equip with a variety of sensors similar to human eyes, ears, noses, hands, and brains. All these characteristics make agricultural robots an irreplaceable part in the agricultural production process.
3.2. Recent development

3.2.1 Strategic planning
The European Union: The EU has funded a number of robotics research projects through framework programs such as FP7 or "Horizon 2020". In 2010, the EU has funded the CROPS project for sustainable management of crops and forestry, aiming to develop a highly configurable, modular, and clever carrier platform that includes modular parallel manipulators and “intelligent tools” (sensors, algorithms, sprayers, grippers). Several technological demonstrators have been developed for high value crops like greenhouse vegetables, fruits in orchards, and grapes for premium wines. Large efforts have also been made in sensing and integrating sensors and learning algorithms[5]. In 2016, the European Commission invested 98.7 million euros to start the second "Horizon 2020" Work Program. Funded by the Program, TrimBot2020project will research the robotics and vision technologies to prototype the first outdoor garden trimming robot [6]. In the same year, the European Union released the "Robotics 2020 Multi-Annual Roadmap ICT 2016" that involves 6 technology clusters, namely systems development, human-robot interaction, mechatronics, perception, navigation and cognition [7].

The United States: In 2014, the National Institute of Food and Agriculture (NIFA), an agency of the U.S. Department of Agriculture (USDA) announced that it would spend US$3 million on the research and development of agricultural robotics. The grants focus mainly on researches into target recognition and algorithms and relevant robotics for sorting and handling plants and flowers in greenhouses [8]. In 2015, the National Robotics Initiative (NRI) awarded US$37 million to advance the development and use of co-robots. The initiative focused on 14 key topics, such as autonomous systems, sensing and perception, modeling and analytics, planning and control, and cognition and learning [9]. In 2016, the United States released the its third National Robotics Roadmap: From Internet to Robotics, addressing fields such as mechanisms and actuators, mobility and manipulation, perception, formal methods, learning and adaptation, control and planning, human-robot interaction, and Multi-agent robotics [10].

Japan: In 2016, Japan proposed in the “Fifth Science and Technology Basic Plan” that to enable Japan to instigate major change and to remain a world leader in this “era of drastic change,” the country is committed to strengthening the research and development of fundamental technologies for service platforms in super smart society, such as robotics and sensors. It will also flexibly leverage...
effective ICT or robotic technology to accelerate agricultural intelligence to ensure the stable food supply. In 2017, Japan formulated the “Artificial Intelligence Technology Strategy,” including “Industrialization Roadmap” that expected to use robots in unmanned farms around 2020 [11].

3.2.2 Research and development landscape

(1) Basic research

The focuses of basic research in agricultural robotics are mainly reflected by clustering themes of SCI literature. The co-occurrence of keywords in researches shows five clusters of works in agricultural robotics, relating to machine vision, positioning and navigation, harvesting robot, fishing robot and milking robot (Figure 2). Among them, milking robots have the largest number of relevant researches, concerning herd management, animal behavior monitoring, milk yield and quality testing, dairy cattle disease detection, cattle welfare, etc. Secondly, there is a large number of researches addressing positioning and navigation, and machine vision, the most fundamental supporting technologies in agricultural robotics.

![Fig.2 Basic researches by cluster in agricultural robotics](image)

(2) Technology R&D

The focuses of technology R&D are mainly reflected by grouping the topics of patent literature. At present, global patents in agricultural robotics can be roughly grouped by two themes, robotic technology and robot category (Figure 3). Of the themes, robotic technologies include manipulators and sensors; robot categories include mowing, sowing, picking, harvesting, spraying, irrigation, grafting, stacking, milking, and fish farming. Among these topics, milking robots and mowing robots are much-talked-about in the recent patents and research and development in agricultural robotics.
3.2.3 R&D performance analysis

(1) Asia, North America and Europe produce most of R&D results in agricultural robotics

In terms of the number of literature and patents, most of the top ten countries are in Asia, North America and Europe. Papers and patents in these regions accounted for 77% and 95% of the global total, respectively. Of the top ten, three countries are in Asia, China, Japan, and South Korea, and its outstanding performance enables China to top both the number of patents and papers in the world. The United States also performs well, ranking second in the number of papers and patents. In addition, five countries in Europe rank the top ten by volume of published researches and patents (Table 1).

Tab. 1 Top countries by volume of research papers and patents

| Country/Region | Paper/No. | Country/Region | Patent/No. |
|----------------|-----------|----------------|------------|
| China          | 870       | China          | 1282       |
| The US         | 624       | The US         | 693        |
| Japan          | 311       | Netherlands    | 544        |
| Spain          | 157       | Japan          | 348        |
| Germany        | 141       | Sweden         | 228        |
| The UK         | 137       | Germany        | 184        |
| Netherlands    | 125       | ROK            | 145        |
| Australia      | 124       | Canada         | 73         |
| Italy          | 92        | The UK         | 64         |
| ROK            | 87        | France         | 46         |

(2) Europe and the United States produce researches of high quality and impact

The United States holds the largest volume of the top 10% of highly cited papers in this field, accounting for a quarter of the total, and the fourth largest average number of citations per article. At the same time, the United States holds the largest number of patents assigned, up to 366, and it ranks first in the number of patents applied under the PCT (Patent Cooperation Treaty) and third in the average number of citations per patent, which indicates the importance the United States attaches to
the international market, and reveals the high quality and impact of its articles and patents. The Netherlands takes the fifth place in terms of the average number of citations per article, second in terms of the number of patents assigned, and third in terms of the number of patents applied under the PCT. Its relevant patents are mainly granted in European and American countries, namely in Europe (37%), the United States (20%), Germany (11%). Sweden ranks first in the average number of citations per article and second in both the number of patents assigned and the average number of citations per patent. Its outstanding performance indicates the top-notch quality and impact of Swedish articles and patents. Canada has the largest average number of citations per patent, which shows the significant impact of its patents.

3) Universities, research institutes and enterprises have clear roles in the innovation value chain

In basic research, research institutes and universities are the main driver in agricultural robotic research. Of them, Chinese universities have outstanding performances, with six out of the top ten institutes coming from China. China Agricultural University ranks first with 122 articles, and next to it is Jiangsu University, ranking second with 112 articles. Wageningen University and Research in the Netherlands also takes a noticeable position, ranking third with 78 papers.

In technology research and development, enterprises are the main driver behind research and development in agricultural robotics. Among them, the top three players are Maasland N.V. in the Netherlands (258), Technologies Holdings Corp. in the United States (190) and DeLaval in Sweden (166). At present, some companies have developed commercial products, such as AG1000, the auto-grafting robot by Yanmar with a capacity of 1000 plants/h; in 2010, Lely, the Dutch company developed the latest generation Milking robot named “Astronaut”; Delaval, the Swedish company has developed the VMS, a fully automatic milking system.

4) Largest number of articles on gardening robotics, and the largest number of patents on farming robotics

In general, patents largely outnumber research articles in agricultural robotics. The trend is mainly reflected in field robot and farming robot. By the number of articles on agricultural robots of different purposes, gardening robotics has the largest number of relevant articles, 1,640, accounting for 43.6%; followed by farming robot, with 631, accounting for 17.1% and field robot as a theme has fewest articles, 527, accounting for 14.2%. By the number of patents, farming robot has the largest volume of relevant patents, 2131, accounting for 38.7%; the number of patents for gardening robots ranks second, accounting for 29.7%; the third place is field robot with 17.8% (Figure 4).

![Fig.4 Articles and patents by robots of different purposes](image_url)
4. Global research frontiers of agricultural robotics

4.1. Strategic planning in research frontiers by foreign countries and regions

Analysis of strategic planning by various countries shows that robots developed in Europe and the US are mainly meant for gardening the high-value crops, and their researches focus on important fields such as perception, control and planning, and human-robot interaction. For example, the EU's FP7 Clever Robots of Crops (CROPS) project has developed robots for greenhouse vegetables, fruits, grapes, etc., and TrimBot2020 has developed the first outdoor garden trimming robot; NIFA, a federal agency within the United States Department of Agriculture (USDA) has funded the relevant researches on sorting robots, greenhouse and gardening robots, etc. In terms of technology, the EU’s CROPS project has carried out a lot of researches on perception, intelligent sensor fusion and learning algorithms. Road maps released by the EU and the United States both address areas such as perception, control and planning, and human-robot interaction.

4.2. Analysis of highly cited research papers

By clustering and analyzing the Highly Cited Paper and Hot Paper in the ESI database, this study reveals the basic research frontiers. In agricultural robotics, 4 highly cited papers and hot papers are revealed. Of them, the earliest literature was published in 2008, concerning weeding robot; the latest literature was published in 2017, talking about an automated robotic crop monitoring platform (Table 2). Research topics are as follows: 1) Application of machine vision in automatic inspection of fruits and vegetables; 2) Four core technologies, such as navigation, detection and recognition, precise weeding and mapping in weeding robotics; 3) Vegetable grafting technology, specifically developing efficient rootstock and convenient grafting tools, always an interesting and hot research topic in this field; 4) The fully automated crop monitoring robotic platform. The research has established a dedicated sensor array to precisely monitor the development of the canopy throughout the life cycle of the crop.

| No. | Title                                                                 | Topic                                                                 | Corresponding author/organization | Citation | Publication |
|-----|-----------------------------------------------------------------------|----------------------------------------------------------------------|-----------------------------------|----------|-------------|
| 1   | Advances in Machine Vision Applications for Automatic Inspection and Quality Evaluation of Fruits and Vegetables | Application of machine vision in automatic inspection of fruits and vegetables | Spain Inst Valenciano Invest Agr | 165      | 2011        |
| 2   | Autonomous robotic weed control systems: A review                      | Weeding robot                                                        | The US Univ Calif Davis           | 199      | 2008        |
| 3   | Current status of vegetable grafting: Diffusion, grafting techniques, automation | Vegetable grafting technology and automation                          | RoK Kyung Hee Univ                | 162      | 2010        |
| 4   | Field Scanalyzer: An automated robotic field phenotyping platform for detailed crop monitoring | Crop monitoring robotic platform                                      | The UK Rothamsted Res             | 11       | 2017        |

4.3. Core patented technologies

According to the patent strength scale (90-100) by INNOGRAPHY database, this study has selected 115 core patents in the field of agricultural robotics. Cluster analysis is used to reveal the topics of the technology frontiers (Figure 5). These topics involve robotic technologies such as robotic arms and image processing, as well as robot types for purposes such as breeding, harvesting, milking, and mowing. These core patents mainly come from the United States, the Netherlands, Sweden, Canada, Israel and Germany (Table 3). Among them, Technologies Holdings, an American corporation has the largest number of patent applications, up to 20; followed by John Deere of the United States and Lely of the Netherlands, each with 10 patent applications; Technologies Holdings and Lely focus their patented technologies on robotic milking, while John Deere’s patented technologies focus on field
operation robots. Only one patent from Jiangnan University in China has been involved as the research frontier, with the topic on "a multi-joint flexible manipulator".

![Fig. 5 Topics of core technologies](image)

**Tab. 3 Countries and patentees (by the number of patents)**

| Country       | Patents by country | Patentee                      | Patents by company |
|---------------|--------------------|-------------------------------|--------------------|
| The US        | 43                 | Technologies Holdings Corp.   | 20                 |
|               |                    | John Deere                    | 10                 |
|               |                    | iRobot                        | 9                  |
| The Netherlands| 30                 | Lely                          | 10                 |
|               |                    | CNH Industrial                | 4                  |
| Sweden        | 15                 | DeLaval Corp                  | 8                  |
|               |                    | Husqvarna                     | 7                  |
| Canada        | 7                  | Great Lakes Intellectual Property PLLC | 4          |
| Israel        | 7                  | F. Robotics Acquisitions      | 7                  |
| Germany       | 6                  | Bosch                         | 2                  |
|               |                    | CLAAS                         | 2                  |

5. **Conclusion**

5.1. *Robotics to witness mature applications in the next ten years*

Agfunder, the online agri-tech venture capital platform has adapted Gartner Hype Cycle to show the maturity of agricultural technologies. The report thinks that agricultural robotics is still at the stage of Technology Trigger [12]. At this stage, media hype and irrational interpreting will make products household names. However, as defects, problems, and limitations of these technologies or products emerge, cases of failure will outnumber those of success.
In addition, institutes and consultancies believe that agricultural robotics still need to wait for mature applications. According to a report by the Canadian Institute for Advanced Research (CIFAR), agricultural robotics will become a mainstream technology by 2020 and will be widely disseminated and applied in 2021. Boston Consulting Group and IDTechEx, a research and consulting firm in the UK, has respectively analyzed the recent development of agricultural robot R&D and forecasted the future market trends, and they believe that robots will be widely used on farms in the next few years.

5.2. More types of agricultural robots to be available in the market
At present, the application of agricultural robots in many countries and regions is mostly limited to certain purposes, such as harvesting and milking. These types of robots are widely accepted and used thanks to the relatively mature technology. However, agricultural robotics for vegetables, fruits, and animal husbandry is still underdeveloped. In the future, market demands and better technologies will make it possible for researchers to develop agricultural robots for more purposes, such as vegetable harvesting, and fruit picking with higher precision and productivity. These efforts in turn will make agricultural robotics accessible to all stages of agricultural production for an overall improvement of agricultural productivity. According to the IDTechEx report, by 2023, weeding robots, vegetable and fruit harvesting robots, strawberry picking robots, and apple picking robots will gradually roll out, and more types of agricultural robots will be available in the market moving forward [13].

5.3. Agricultural robots to be more intelligent
Becoming intelligent has been an inevitable trend for future agricultural robotics. Intelligent robots will be more capable of decision-making and analytics, more adaptable, and easier to operate. Farmers can operate their robots through smart phones in the field. These robots can also operate with precision. For example, an intelligent in-orchard robot can leverage the navigation system and infrared system to automatically find, harvest, and grade fruit on site. In the new agricultural production models and applications of new technologies, agricultural robots, as a new generation of intelligent agricultural equipment, will inevitably require more in-depth research on visual and non-visual sensor technologies, and image acquisition and processing algorithms, so that they can be more capable of identifying and avoiding obstacles, reducing damage rate, and truly replace humans to operate intelligently, efficiently and precisely. In addition, countries’ strategic planning also attaches importance to intelligent robotics. The EU CROPS project aims to develop a highly configurable, modular, and intelligent carrier platform; Multi-Agent Robotics is one of the focuses in the third National Robotics Roadmap: From Internet to Robotics by the United State.

5.4. A large market potential in the future
Consultancies and research institutes have made market forecasts for agricultural robotics. According to Tractica, agricultural robot shipments will increase from 32,000 units in 2016 to 594,000 units in 2024, and the revenue will reach $74.1 billion in 2024. In China, as agriculture becomes more intensive and manufacturing more intelligent, more agricultural robots will be required in large-scale agricultural production.

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