A Life Cycle Framework of Green IoT-Based Agriculture and Its Finance, Operation, and Management Issues

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The large-scale application of IoT systems in agriculture is facing challenges such as huge investment in agriculture IoT systems and non-tech-savvy farmers. To identify these challenges, the authors summarize the applications of IoT techniques in agriculture in four categories: controlled environment planting, open-field planting, livestock breeding, and aquaculture and aquaponics.

This work was supported in part by National Natural Science Foundation of China under Grants 71703122, 71531002 and 71503199, the National Special Fund for Modern Agricultural Industry Technology System on Oats and Buckwheat under Grant CARS-07-F-1, China Ministry of Education Social Sciences and Humanities Research Youth Fund Project under Grant 16YJC630102, the Natural Science Basic Research Project in Shaanxi Province under Grant 2016JQ7005, Science and Technology Plan Projects of Yangling Demonstration Zone under Grant 2016RKX-04, the Fundamental Research Funds for the Central Universities under Grant 2018RWSK02, and The Hong Kong Polytechnic University Internal Project under Grant G-UADM.

Digital Object Identifier: 10.1109/MCOM.2019.1800332

Abstract

The increasing population in the world forces humans to improve farm yields using advanced technologies. The Internet of Things (IoT) is one promising technique to achieve precision agriculture, which is expected to greatly increase yields. However, the large-scale application of IoT systems in agriculture is facing challenges such as huge investment in agriculture IoT systems and non-tech-savvy farmers. To identify these challenges, we summarize the applications of IoT techniques in agriculture in four categories: controlled environment planting, open-field planting, livestock breeding, and aquaculture and aquaponics. The focus on implementing agriculture IoT systems is suggested to be expanded from the growth cycle to the agri-products life cycle. Meanwhile, the energy concern should be considered in the implementation of agriculture IoT systems. The construction of green IoT systems in the whole life cycle of agri-products will have great impact on farmers' interest in IoT techniques. With the life cycle framework, emerging finance, operation, and management (FOM) issues in the implementation of green IoT systems in agriculture are observed, such as IoT finance, supply chain and big data financing, network nodes recharging and repairing, and IoT data management. These FOM issues call for innovative farm production modes and new types of agribusiness enterprises.

Introduction

The development of the Internet of Things (IoT) has been reshaping various fields such as industry, transportation, and healthcare. In the literature, increasing attention is paid to both IoT techniques and their practical applications. The penetration of IoT in the agriculture sector is deepening. In practice, governments and companies are often reported to be applying some advanced IoT techniques into agriculture.

The potential and superiority of IoT in agriculture result in its current popularity. It is a challenging and must-be-solved task to sustainably feed the world's growing population, which is predicted to reach 9.6 billion people by 2050 [1, 2]. Precision agriculture aims to maximize crop yields while preserving resources, and is indeed proved with high productivity [3]. To implement precision agriculture, farmers need to monitor the growth environment and make optimal production decisions. This is where IoT systems can help farmers. Through various sensors and actuators, farmers can know in real time the growth status and environment in their farms, and make timely actions to keep the optimal growth status.

However, the costs of implementing IoT systems in agriculture are huge. In current practice, most existing IoT devices are deployed in controlled environment agriculture such as greenhouses and livestock farms [4]. Large-scale promotion in open-field agriculture, which is the key to solving the world's food problem, is still not coming. Two aspects that probably limit the promotion are observed. First, IoT-based agriculture should be viewed from a life cycle of agri-products, not just a cycle of growth. Both the quality of agriculture ingredients and the circulation of harvested agri-products have important impacts on yields and production behaviors. Without a whole life cycle equipped with IoT systems, it is difficult to attract farmers' interest in deploying IoT devices. Second, the implementation of IoT systems in agriculture is not only a technical issue but also involves some challenging finance, operation, and management (FOM) issues. The costly investment is the first concern to consider. Neither large-scale nor small holder farmers are willing to undertake the costs without attractive benefits and conveniences. Unfortunately, most existing studies focus on the technical issues in the growth cycle.

Meanwhile, the energy concern should be considered in the implementation of agriculture IoT systems. Motivated by these observations, in this article we try to formulate a life cycle framework of green IoT-based agriculture, including ingredient supply, growth, processing and packaging, distribution and storage, and consumption. Through analyzing the applications of IoT systems throughout the life cycle, we identify some FOM issues that need to be solved to make IoT systems fully cover agriculture. These FOM issues such as IoT finance in agriculture, supply chain and big

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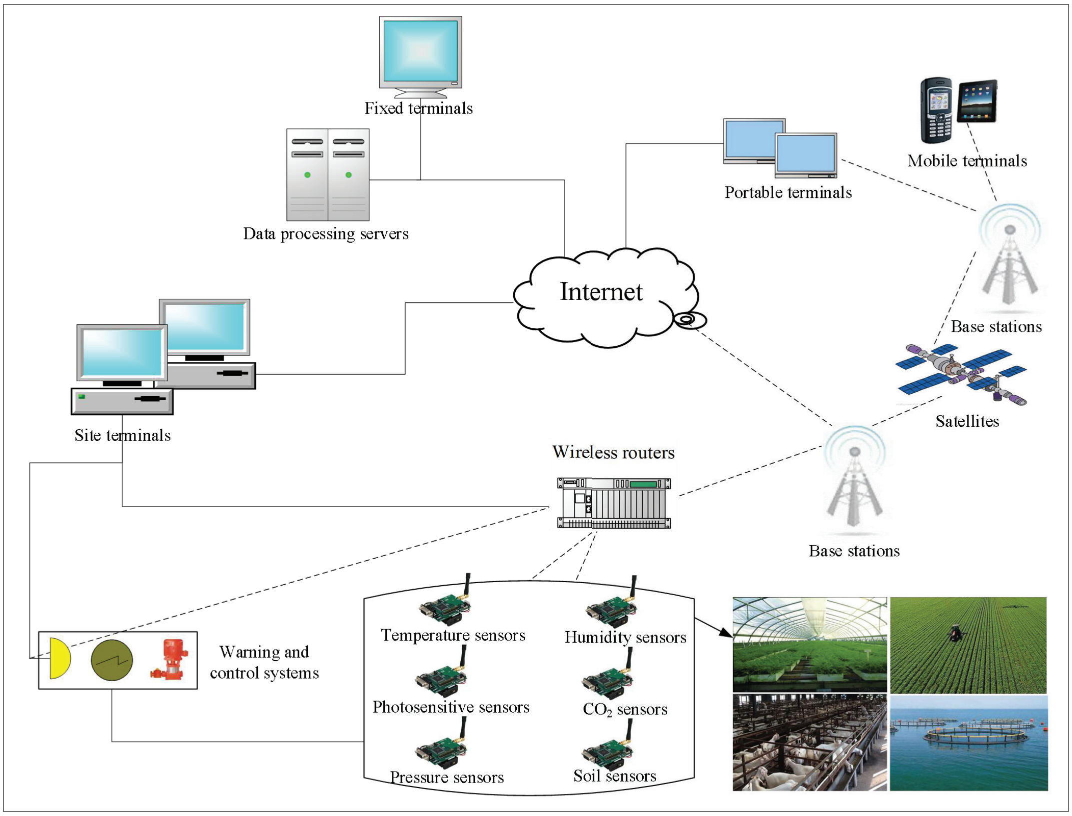

Figure 1. A basic framework of IoT-based agriculture.

By adjusting the environment, farmers can control the growth of greenhouse plants and thus achieve expected harvests. However, the unit costs of applying IoT techniques in controlled environment planting are high. It is a challenging task to make IoT-based greenhouses attractive and profitable for market-oriented farmers.

data financing in IoT-based agriculture, farm-to-door delivery optimization, IoT-based reception box layout, and agriculture IoT data management have the potential to call for innovative farm production modes and new types of agribusiness enterprises as well as extended or novel theories and methods in academia.

Toward a Life Cycle Framework of Green IoT-Based Agriculture

Categories of IoT-Based Agriculture

In industry and academia, various IoT definitions have been reported. One well-recognized definition is from the report "Internet of Things: Strategic Research Roadmap" [5], that is, *Internet of Things is an integrated part of Future Internet... and could be conceptually defined as a dynamic global network infrastructure... where physical and virtual "things" have identities... and are seamlessly integrated into the information network*. The concept can be understood from three aspects. First, since IoT is an infrastructure, its worldwide implementation is necessary for popular application but will take a huge amount of energy and funds. Second, IoT is based on various access, communication, and application protocols such as Bluetooth 4.x and IEEE 802.15.4. Third, both physical and virtual things are connected in IoT systems, so running modes and rules in various fields probably have big changes.

Based on the above definition, we formulate a basic framework of IoT-based agriculture, as Fig. 1 shows. Various sensors are located at agriculture areas, collecting and sending data to the Internet by communication networks. With support of rules and technical tools in data processing servers, users can access the data and send commands from mobile, portable, and fixed terminals. Actuators implement warning and control functions based on user commands.

In order to formulate a life cycle framework of IoT-based agriculture, we briefly review the categories of IoT-based agriculture. As the International Labour Organization has defined [6], *agriculture is the cultivation and breeding of animals and plants to provide food, fiber, medicinal plants and other products to sustain and enhance life*. According to types of agricultural products and controllable degree of growth environments, we summarize the categories of agriculture applying IoT techniques into controlled environment planting, open field planting, livestock breeding, and aquaculture and aquaponics, as in Table 1.

Controlled Environment Planting: The greenhouse is the main form of controlled environment planning. Due to limited and closed spaces, IoT devices and communication systems can be well equipped in greenhouses, so the inside environment can not only be collected using sensors (temperature, humidity, pressure, etc.) but also be adjusted using actuators (heaters, pumps, fans, etc.) [7]. By adjusting the environment, farmers can control the growth of greenhouse plants, and thus achieve expected harvests. However, the unit costs of applying IoT techniques in controlled environment planting are high. It is a challenging task to make IoT-based greenhouses attractive and profitable for market-oriented farmers.

Open Field Planting: Constructing IoT systems in open field planting needs far more sensors to monitor the wild environment as well as the grow-

Categories	Examples with the application of IoT techniques
Controlled environment planting	• Greenhouse environment monitoring • Greenhouse automatic control • Greenhouse plant growth monitoring • Greenhouse pest management
Open field planting	• Field environment monitoring • Crop growth monitoring • Crop disease detection • Precision irrigation • Farm machinery positioning and navigation
Livestock breeding	• Livestock farm and pasture environment monitoring • Livestock healthcare monitoring • Livestock positioning and behavior recognition • Livestock identification
Aquaculture and aquaponics	• Water quality monitoring and control • Fish detection • Precision feeding • Aquaponics related applications

Table 1. The application of IoT techniques in the agriculture growth cycle.

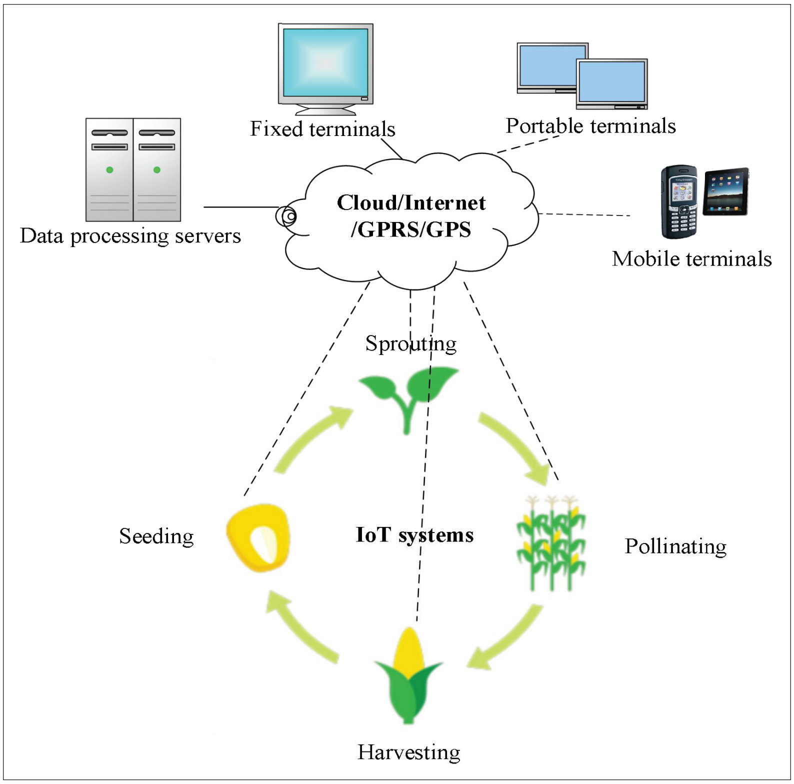

Figure 2. A growth cycle framework of IoT-based agriculture.

ing crops. In order to ensure efficiency, moving sensors and drones have great potential to collect data in open field agriculture. With enough data from the IoT networks, it is possible to perform disease detection and precision irrigation for large-scale farms. Moreover, farm machines equipped with GPS and navigation systems are more efficient in tillage, fertilization, harvesting, and so on. Obviously, sensors and actuators are helpful for farmers to make production decisions. However, due to the huge investment and non-tech-savvy farmers, currently it is difficult to implement IoT systems in open field agriculture. The huge energy consumption is another concern of implementing IoT systems in open field agriculture. Two kinds of measures can be considered to reduce the energy consumption. One is to minimize the used sensors by optimizing network design and applying moving sensors, and the other is to use low-power and even clean-energy sensors.

Livestock Breeding: IoT techniques present obvious superiority in improving livestock management for both space-constrained farms and vast pastures. One basic function of IoT-based farms is to make livestock grow in expected environments by collecting and controlling the temperature, humidity, and so on. Livestock healthcare monitoring and behavior recognition are two emerging directions with the further application of new-type IoT devices such as wearable sensors and three-dimensional accelerometers [8]. IoT systems are also helpful in updating pasture management by monitoring herbage growth environments and positioning livestock. Other applications of IoT techniques in livestock breeding include identifying animal livestock and recording feeding details [9].

Aquaculture and Aquaponics: Fish farms equipped with specific IoT sensors have realized convenience and benefits in monitoring water quality including water temperature and level, dissolved oxygen, salinity, pH, and so on [10]. In controllable fish farms, actuators can take corresponding actions such as oxygen generation and water filling to maintain the water quality in optimal situations. With ultrasonic detectors and underwater cameras, it is easier for farmers to locate fish groups and do precision feeding. Aquaponics, a junction of aquaculture and hydroponics, is another potential application area of IoT systems. IoT-based aquaponics helps to monitor the growth conditions of both aquatic creatures and hydroponic plants. Thus, more sensors and actuators as well as processing rules than those in separate aquaculture and greenhouse are often required.

A Life Cycle Framework of Green IoT-Based Agriculture

Most existing studies applying IoT systems in agriculture focus on the growth cycle of plants, livestock, and aquatic creatures. In the growth cycle framework shown in Fig. 2, various sensors, actuators, drones, and routers are connected as wireless sensor networks (WSNs) under different kinds of protocols such as Zigbee, WiFi, and Bluetooth. The collected data from WSNs are transferred to local or remote data processing servers through cloud, Internet, GPRS, and GPS networks. Managers and users can monitor the growth status and send out control commands anywhere by fixed, portable, and mobile terminals.

The aim of sustainable agriculture is to provide enough and safe agri-products with minimum energy consumption, so we need to monitor not only the growth cycle but also the whole life cycle of agri-products. In practice, many quality and safety problems of agri-products are not from the growth cycle but from the outside links including ingredient supply, agri-products processing, transport, storage, and distribution. Meanwhile, the construction of IoT systems in the whole life cycle of agri-products can help farmers recognize the quality of agriculture ingredients and produce agri-products creditable to the market, further attracting farmers' interest in IoT techniques. However, employing more sensors often means more energy consumption, so the green norm should be considered in the implementation of agriculture IoT systems. Thus, it is necessary to apply IoT systems througout the whole agri-products supply chain considering the green norm, that is, to construct a life cycle framework of green IoT-based agriculture, as shown in Fig. 3. Some typical applications of IoT techniques in the life cycle of agri-products are listed in Table 2.

Ingredient Supply: The application of IoT techniques in ingredient supply can improve the efficiency and effectiveness of ingredient management. Given inventory control policies, farmers who equip their ingredient inventory with IoT techniques are able to monitor in real time the level and status of various ingredients and do precise ordering automatically. When ingredients such as seeds and fertilizers arrive, it is easy to detect their quantity and quality by reading RFID smart tags and assessing the ingredient tracing systems. Meanwhile, IoT systems are also helpful for ingredient suppliers to cultivate seeds and produce fertilizers.

Processing and Packaging: Agri-products classification marketing is an efficient strategy for improving farmers' returns. Traditional classification is manual and low efficiency. In agriculture IoT systems, nondestructive determination techniques such as near infrared spectroscopy analysis and odor sensors have been applied to automatic classification, especially on fresh fruits. Moreover, processing environment monitoring and control is necessary for perishable agri-products. A specific application is processing optimization on multiple varieties of fresh produce that need different processing environments. Another work-related IoT technique in this link is to formulate intelligent labels using the data from ingredient supply and growth links, and attach these labels onto packaged agri-products.

Distribution and Storage: The storage environment has direct impact on the quality change of agri-products. More and more IoT-based warehouses are built for reducing the loss of fresh agri-products in practice. Through vehicle-mounted sensor networks and GPS, managers can monitor the status of in-transit agri-products and the position of refrigerated trucks. Warning messages will be sent out when the environment in refrigerated trucks is harmful to the quality. Meanwhile, downstream retailers and consumers can track their ordered agri-products in real time, which facilitates making timely receiving plans. Automatic sorting is another important function resulting from IoT systems, especially for the fulfillment of online agri-products orders.

Consumption: Agri-products with RFID tags or QR codes on the retail shelf make it easy for consumers to identify the variety and origin, which can avoid consumers buying fake and shoddy goods. Moreover, consumers can access the details in the whole life cycle from the tracing system, such as fertilization and pesticide records. IoT devices in the supermarket are also helpful for consumers to quickly detect additives and pesticide residue. Even when some agri-products are found with safety problems, it is easy to make recalling precise with the help of life cycle IoT systems.

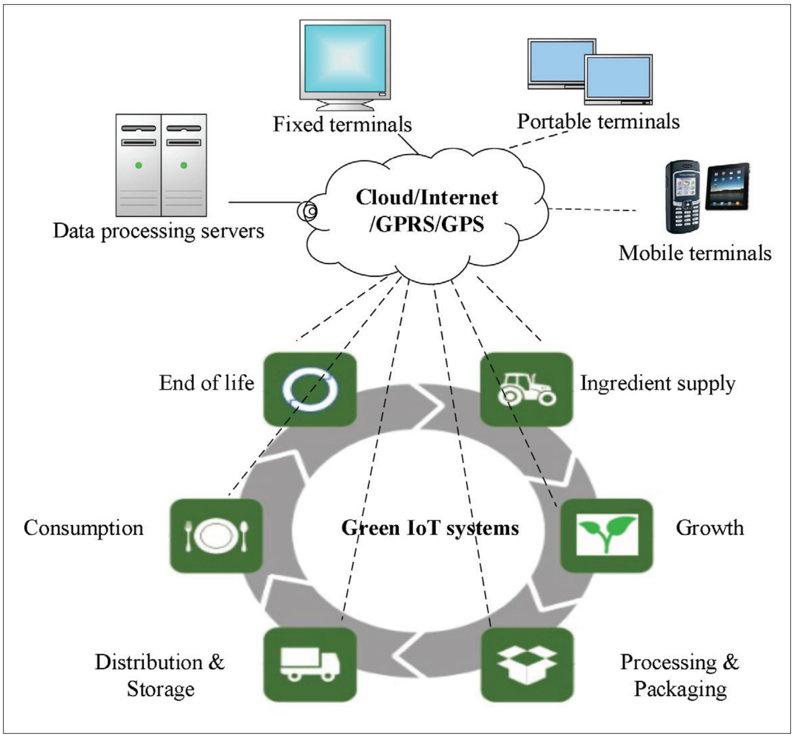

Figure 3. A life cycle framework of green IoT based agriculture.

Links in agri-products life cycle	Examples with the application of IoT techniques
Ingredient supply	• Ingredient inventory environment monitoring • Automatic ingredient ordering • Ingredient detection and tracing • Ingredient transportation monitoring • Ingredient cultivation & production monitoring
Growth	See Table 1
Processing and packaging	• Agri-products automatic classification • Processing environment control • Intelligent labels formulation
Distribution and storage	• Refrigerated warehouse management • Refrigerated truck monitoring • Agri-products real-time tracking • Agri-products automatic sorting
Consumption	• Agri-products identification • Agri-products life cycle review • Agri-products quality detection • Agri-products precise recall

Table 2. The application of IoT techniques into the agri-products life cycle.

FOM Issues in the Life Cycle of Green IoT-Based Agriculture

IoT technical issues in agriculture have attracted much attention in the literature, such as agriculture sensors design, low-power WSNs, communication protocols in agriculture, and agricultural fog computing [11]. As mentioned above, the huge investment is hampering further application of IoT systems in agriculture, so it is urgent to solve the financial issue through innovative financing modes. Meanwhile, digital agriculture certainly faces new operation and management issues that face various challenges to existing theories and methods. In addition, minimizing energy consumption (i.e., the green norm) should be con-

More efforts are needed to fully cover open field agriculture by IoT systems, such as innovative financing modes. Since agriculture data are required by agricultural researchers and enterprises, crowdfunding is one possible way to raise funds for implementing agriculture IoT systems.

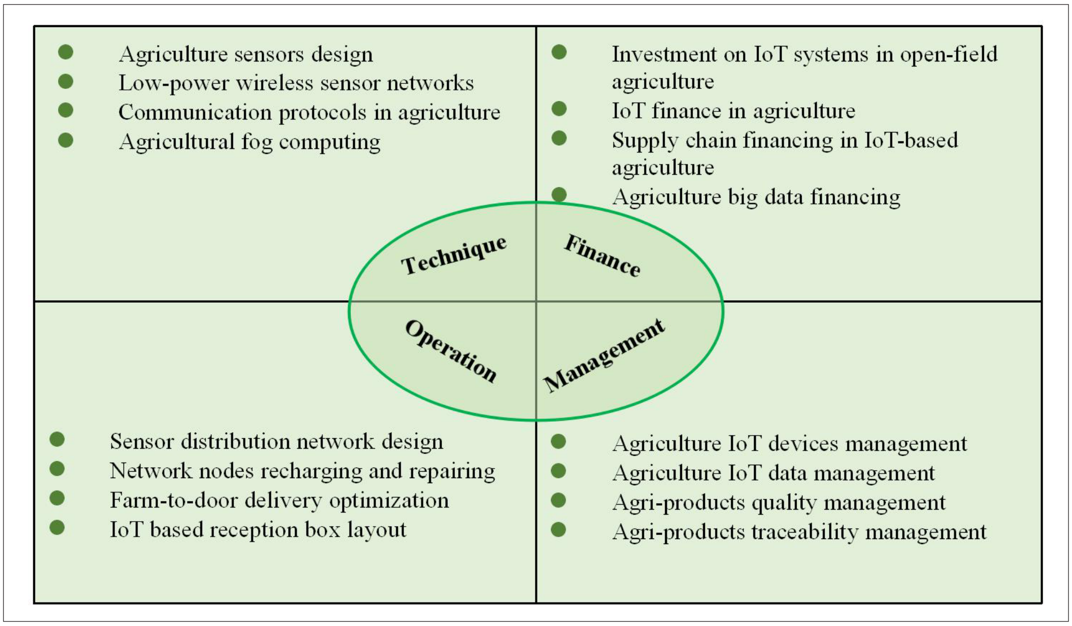

Figure 4. Examples of technical and FOM issues in green IoT- based agriculture.

sidered as a criterion in dealing with these issues. Figure 4 shows some examples of technical and FOM issues in green IoT-based agriculture.

Finance Issues

Investment in IoT Systems in Open Field Agriculture: IoT systems in agriculture are a capital-intensive infrastructure [5, 11]. Energy and communication are two key obstacles, because constructing enough power and Internet facilities to support IoT systems, especially in open field agriculture, with the current technologies needs enormous investment. Neither large-scale nor small holder farmers can afford to make the investment. Some countries and companies are currently making plans to promote the construction of IoT infrastructures in agriculture, such as Britain's 2013 UK strategy for agricultural technologies [12] and Microsoft's FarmBeats project. Low energy consumption, even with higher costs, is recognized as one basic norm to construct their agriculture IoT platforms. However, more efforts are needed to fully cover open field agriculture fully by IoT systems, such as innovative financing modes. Since agriculture data are required by agricultural researchers and enterprises, crowdfunding is one possible way to raise funds for implementing agriculture IoT systems.

IoT Finance in Agriculture: In the era of IoT, people can make real-time and objective assessments on the value of any connected thing, making it possible to build a thing-oriented credit system. Due to this situation, IoT finance will come true. As stated in 2016 China's first IoT Finance White Paper, IoT finance is just emerging, but will bring about new profit models and commercial operating modes [13]. A revolution caused by IoT finance will also happen in agriculture. IoT systems, when fully covering agriculture, will make any "thing" in farms transparent to relevant stakeholders. Bankers can make credible loans to farmers after precise assessment of their growing crops, grazing livestock, and swimming fish. Insurance companies will quickly collect agriculture damage conditions after severe weather and compensate objective insurance to farmers. However, one major concern in IoT finance is people's willingness to thoroughly expose their "things," which may have impact on some farmers' interest in implementing IoT systems.

Supply Chain Financing in IoT-Based Agriculture: Supply chain finance has attracted increasing attention in the current literature and practice to deal with difficulties such as making credit ratings, determining trade credit quantity, and trading off between bank credit and trade credit [14]. These difficulties will become easy in the IoT world. To be specific in agriculture, ingredient suppliers are clear about each farmer by assessing the "things" status of the farmer. Farmers can obtain credits and loans from suppliers, wholesalers, retailers, and even consumers just by showing the quality of their agri-products, and can also give reasonable credits to their partners who make their "things" status accessible to farmers. Meanwhile, it is easy to implement green standards by the rule that agri-products with lower energy consumption are more popular at higher prices. As we can see, some existing complicated and various equilibrium models of agri-products supply chain finance may be invalid or unnecessary in the IoT-based agriculture.

Agriculture Big Data Financing: Seen from the development of platform-based firms such as Amazon and Alibaba, data seem to be another important productive force, as well as technology, capital, and labor. Through agriculture IoT systems, big data on the growth environment and status can be constructed. These data are not only helpful for farmers to make decisions, but also valuable to other related bodies such as seed companies, pest control companies, fertilizer companies, agri-product processing companies, and related research institutes. Seed, pest control, and fertilizer companies can use the data to observe the performance of their products and improve the production efficiency and product quality. Agri-product processing companies can easily check the quality of agri-products and do differentiated processing. Agricultural scientists should be interested in the data for conducting their research. Thus, agriculture big data can bring about innovative investment and financing modes.

Operation Issues

Sensor Distribution Network Design: The distribution of sensors has direct impact on the monitoring and control precision in agriculture. This issue is more challenging in open field planting, often taking place over wide spaces. Given specific regional and monitoring requirements, the operation objective is to design an optimal sensor distribution network under constraints such as sensing ranges and sensor costs. The optimization criteria may be multiple and conflicting, such as minimum costs and maximum precision. Moreover, the operation models will be different when sensors are movable. Thus, besides static sensor network optimization models, multi-objective and dynamic optimization ones are also needed. The consideration of clean energy sensors such as solar sensors will bring different operation models and optimal network designs.

Network Nodes Recharging and Repairing: Agriculture IoT systems consist of a large number of nodes with limited battery lifetime, and most of the nodes in remote areas are not connected to power grids or solar panels. In addition, network nodes may break down due to unexpected events such as farming activities and severe weather. Thus, it is necessary to make operation plans for recharging and repairing network nodes located in agriculture, which is often a complicated operation problem. Node battery lifetimes are often not balanced due to different loads, battery types, discharge rates, and environments, so regular recharging plans with long intervals may risk failure of some nodes. However, frequent plans are cost-prohibitive for massive agriculture IoT nodes. Recharging drones may bring convenience to the problem, but will face another operation issue: the route planning problem.

Farm-to-Door Delivery Optimization: An ideal way for consumers to get agri-food is to personally pick them at convenient farms, which is impossible for most people living in urban areas. With the development of ecommerce and express services, farm-to-door delivery for various agri-food is feasible and attracting more and more consumers. One difficulty in farm-to-door delivery is to maintain freshness and quality. Through lifecycle-based IoT systems where all-around information on agri-food is available, it is possible to optimize the farm-to-door delivery as a whole process. However, farm-to-door delivery optimization models are very different from classical vehicle routing problems in the last mile. The former need to consider more constraints such as processing time and truck transport capacity. IoT-enabled delivery also makes it possible to precisely consider the energy consumption and then produce the most energy-efficient delivery modes.

IoT-Based Reception Box Layout: The idea of a reception box was reported early in the literature and applied in practice as an efficient solution to the last mile issue [15]. However, conventional reception boxes are mainly applicable to common products that are not sensitive to the environment. When agri-food and fresh produce are delivered to consumers' doors, a place whose inside environment is controllable is needed when nobody is at home. IoT-based reception boxes with freezing or cooling functions can meet the requirement. These intelligent boxes are located at a convenient place in the community. After delivery persons place the ordered agri-food into the box, a message with the password will be sent to consumers. When consumers go home, they can pick up the agri-food. It is an operational issue to optimize the layout of IoT-based reception boxes, where additional constraints such as energy consumption and agri-food quality should be considered.

Management Issues

Agriculture IoT Devices Management: Various sensors, actuators, and other network nodes will exist in agriculture IoT systems, so device management is basic, mainly consisting of reliability management, security management, maintenance management, and energy management. Reliability management aims to make sure IoT devices run normally by remote configuration and online updating. Attacks on IoT devices will be as common as those on Internet devices, so security management should attract the attention of managers in charge of agriculture IoT devices. Should failure occur on IoT devices, timely responses are needed to fix these failures, which is maintenance management. Energy management is the function to minimize energy consumption by controlling the running status of any agriculture IoT device.

Agriculture IoT Data Management: As the sensors in agriculture IoT systems collect and send data to storage servers, massive data will be formulated in limited hard disk space. Thus, the storage problem is a difficult issue in data management. Cloud storage may provide a technique to collect separate data but is also cost consuming. The key to solve the difficulty is to determine reasonable data collection intervals that may minimize the required storage space. Although agriculture IoT data are valuable for farms and other stakeholders, complete data sharing is impossible due to investment shares and trade secrets. Thus, access management is another key problem in data management. Similar to other fields, big data analysis on agriculture IoT data is a necessary task of data management.

Agri-Products Quality Management: The improvement of agri-products quality management using IoT systems mainly consists of two aspects. One is to maximize the quality in the growth stage, by controlling the growth environment and status of agriculture products as well as the quality of ingredient supplies. The other aspect is to minimize the quality loss in the farm-to-door stage, which currently results in about one third of the loss of fresh food in China. If IoT systems are used in the whole life cycle, from ingredient supply to growth to final consumption, it will be easy to address, both nationally and internationally, the agri-food security issue. Thus, the agri-products quality management heavily depends on the management of life cycle agriculture IoT devices and data.

Agri-Products Traceability Management: The traceability management of agri-products is often more important than that of common products

Should failure occur on IoT devices, timely responses are needed to fix these failures, which is maintenance management. Energy management is the function to minimize energy consumption by controlling the running status of any agriculture IoT device.

The full application of IoT in agriculture will truly achieve precision agriculture, and notably contribute to solving the world's food problem with an increasing population. Technological advances providing cheaper sensors and safer networks will boost the further application, but the drive must be hastened by overcoming facing challenges in order to catch the pace of growing population.

since it involves the safety and health of consumers. The traceability techniques have developed from bar code to QR code to RFID smart tag. The application of these traceability techniques in agri-products is helpful for consumers to recognize the details in the growth and processing stages and buy goods of expected quality, which in turn prompts farmers to concentrate on agri-products quality. In IoT- based systems, more information can be recorded using sensors. However, some specific management issues are not solved well in practice. For example, what information should be recorded for different kinds of agri-products? Corresponding standards based on the agriculture categories should be formulated. Another issue is how to realize cross-border traceability among countries with different quality standards.

Conclusion

The full application of IoT in agriculture will truly achieve precision agriculture, and notably contribute to solving the world's food problem with an increasing population. Technological advances providing cheaper sensors and safer networks will boost further application, but the drive must be hastened by overcoming the challenges faced in order to match the pace of population growth. One obvious challenge is how to make farmers as interested in implementing IoT systems as much as they are keen on high-yielding seeds and high-efficiency machines. Life cycle IoT-based agriculture is necessary to solve the challenge by helping farmers recognize the quality of agriculture ingredients, improve the yields as well as the quality, and produce creditable agri-products for the market. Besides technical issues, emerging finance, operation, and management issues are gradually observed in the digitization of agriculture using IoT techniques. Innovative farm production modes and new types of agribusiness enterprises will arise to solve these issues. Meanwhile, this study calls for more attention in academia to provide corresponding theoretical and methodological support for these emerging FOM issues.

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