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Review article

Smart farming: Agriculture's shift from a labor intensive to technology native industry

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ABSTRACT

Since human beings transitioned to an agrarian lifestyle, technological advancements have enabled evolutions in agriculture, resulting in greater varieties and yields of crops. However, as society faces the effects of climate change and the resulting social challenges, agriculture is at a unique point in its history. Recent advancements in a number of key technologies have placed agriculture at the precipice of another evolution that could not only affect the variety and yield of crops, but also climatological and social outcomes as well. Specifically, advancements with the Internet of Things, artificial intelligence, and robotics among others have enabled data-driven and automated agriculture. This paper intends to provide a review of current and emerging agriculture technology applications as well as research efforts by examining the advancement of these key technologies in the context of smart farming. We also present future directions for these agriculture technology applications.

1. Introduction

It is estimated that by 2050, the population will reach 9.1 billion people. The Food and Agriculture Organization (FAO) of the United Nations has stated that in order to feed the world's inhabitants by 2050, food production will have to increase by approximately 70% [1]. Additionally, according the 2018 National Climate Assessment by the U.S. Global Change Research Program, climate change presents numerous challenges to sustaining and enhancing crop productivity, livestock health, and the economic vitality of rural communities. While some regions may see conditions conducive to expanded or alternative crop productivity over the next few decades, overall, yields from major U.S. crops are expected to decline as a consequence of increases in temperatures and possibly changes in water availability, soil erosion, and disease and pest outbreaks [2].

Together, these trends indicate that the agriculture industry will be forced to transition away from the industrial era to one that will enable significantly greater productivity while dealing with an extensive scarcity of resources to achieve sustainable agricultural production. To feed the world's rapidly growing population, the new era will involve the use of "Industry 4.0" technologies, applications, and solutions that are transforming the production capabilities of all industries, including the agricultural domain [3].

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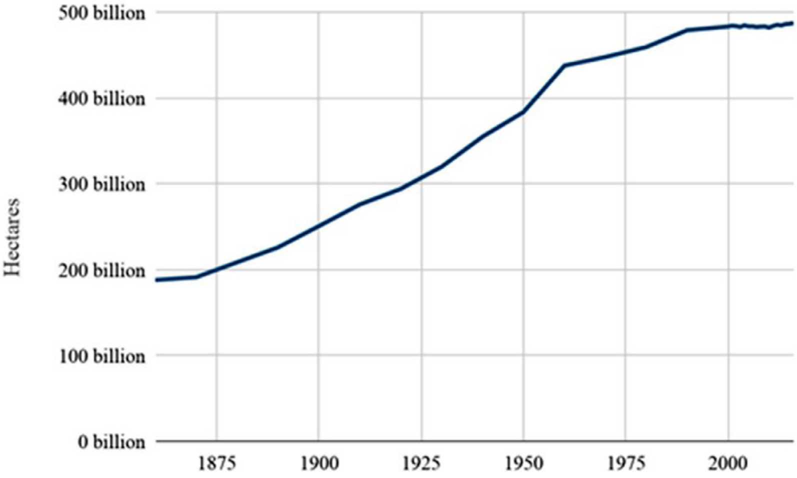


Fig. 1. Total agricultural area over the long-term in hectares [6].

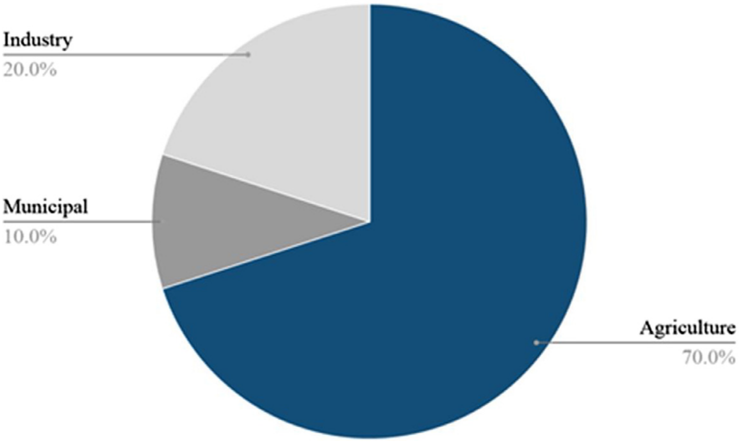


Fig. 2. Water withdrawals by sector [7].

Modern farms and agricultural operations will work differently primarily because they will use sophisticated technologies such as robots, sensors, cloud computing, big data analytics, and artificial intelligence, just to name a few. These advances will let businesses be more profitable, efficient, safer, and environmentally friendly [4].

It is important to acknowledge that biotechnology is also an important element in modern agricultural production as well as the importance of livestock production to the agricultural economy. However, due to the limit on length, the scope of this article will focus strictly on information technologies that affect crop production.

What follows in this article is a review of various technologies, applications and research that seek to enable the agriculture industry to overcome challenges in improving the efficiency and sustainability of food production. Current challenges facing the agriculture industry will be presented followed by a discussion of the enabling technologies as well as applications and solutions currently in use by the industry. Related research and development work are also presented at the end.

2. Challenges

For most of history, whenever we have needed to produce more food, we have simply cut down forests or plowed grasslands to make more farms. Agriculture's footprint has caused the loss of whole ecosystems around the globe, including the prairies of North America and the Atlantic forest of Brazil, and tropical forests continue to be cleared at alarming rates [5]. Today, as shown in Fig. 1, nearly 500 billion hectares are used for agriculture accounting for nearly 40% of the world's available land [6].

Agriculture has also become a substantial consumer of water, accounting for 70% of all of the world's water use as shown in Fig. 2 [7]. With the expansion of agricultural land, global water withdrawals for agriculture quintupled from 500 cubic

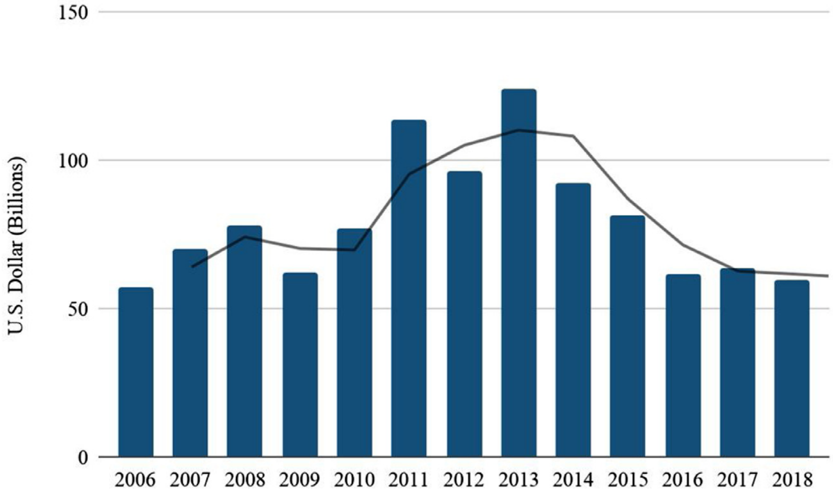


Fig. 3. U.S. farm profits tumble [9].

kilometers to over 2500 cubic kilometers. Given the considerable need for resources, the growing population as well as the impact of climate change present complex challenges to increasing food production.

As the population continues to grow, competition for water will increase between all sectors causing food security to remain a pressing challenge in several regions. Additionally, warmer temperatures increase the likelihood of drought thereby exacerbating the risk of water scarcity and presenting a key challenge to increasing food production.

Moreover, just as our collective land-use practices are degrading ecological conditions across the globe, humanity has become dependent on an ever-increasing share of the Earth's resources. Land use thus presents us with a dilemma. On one hand, many land-use practices are absolutely essential for humanity, because they provide critical natural resources as well as food, fiber, shelter, and freshwater. On the other hand, some forms of land use are degrading the very ecosystems upon which we depend [8].

Further complicating matters are the political and economic conditions of the agriculture industry. Farmers are experiencing increasingly narrow profit margins and looming trade wars have created uncertainty in the marketplace. As seen in Fig. 3, net income for farmers has fluctuated significantly over the last decade [9]. In order to realize the increase in food production, it will be critical to address marketplace challenges in addition to sustainability challenges.

It is clear that the agriculture industry has a need to transition away from current industrial practices and adopt applications and solutions that assist farmers in increasing land and water efficiency while also mitigating the risk of market uncertainty. These applications and solutions will be enabled by the convergence of several information technologies that have emerged in recent years, allowing the agriculture industry to enter into an era of data-driven management and automation.

3. Enabling technologies

The creation of the tractor marked the birth of industrial agriculture. Tractors pulled plows. They hauled loads and livestock. Tractors towed and powered the new planters, cultivators, reapers, pickers, threshers, combine harvesters, mowers, and balers that farm equipment companies kept coming out with every season. A tractor powered by an internal combustion engine that ran on gasoline was smaller and lighter than its steam-driven predecessors and ran all day on a single tank of fuel. The introduction of the internal combustion engine made this evolution possible. As an enabling technology, the internal combustion engine represented a fundamental shift in the way work was done and greatly increased the productivity of the farm.

With new complex challenges, agriculture is poised to transition to a new era once again. This transition will move the industry away from the industrial practices of the past to data-driven management and automation. This new paradigm will be possible through the development of applications and solutions that are driven by the convergence of several fundamental technologies including the Internet of Things, artificial intelligence, and robotics.

3.1. Internet of Things

Commodity devices connected to the web have become a powerful data resource for businesses. Over the period of several decades, multiple technologies have converged to give rise to what is commonly known as the Internet of Things; a network of physical devices embedded with electronics, software and connectivity that collect, process and share data for monitoring and control. Together, these technologies have enabled the Internet of Things to serve as a vast resource of data and control, able to measure and manipulate the physical world. This capability will be the key to data-driven management and automation of farms around the world.

As an example, a senior capstone project at the University of North Texas, sponsored by Nectar Agriculture, sought to create web-enabled control systems for the purpose of adapting the growing environment of crops. Using the connected nutrient and climate sensors that we had previously developed, the students developed systems to automatically control the lighting and nutrient balance delivered to crops based on set points received from the web.

This is a basic example of an Internet of Things system that opens the door to monitor and better control agricultural production processes. As we will show in our discussion of Smart Farming Applications, this solution only scratches the surface of what is possible to advance agriculture towards a technology native industry.

3.1.1. Microsensors

Central to the functionality of the Internet of Things are embedded sensors. Sensors have decreased in physical size over time creating microscopic scale sensors that are now small enough to be embedded into unique places unobtrusively. However, sensors don't operate alone — they are typically integrated with other devices such as microprocessors and radios. Over the last two decades, microprocessors have increased in computational power while reducing in size and cost providing greater accessibility and spurring development of a wide variety of Internet of Things solutions [10].

Additionally, these sensors are being combined to create devices that are capable of measuring multiple factors. For example, sensors that measure temperature are now being combined with sensors that measure barometric pressure into a unified device that is also capable of outputting that data in a digital format. Another example is the combination of gyroscopes and accelerometers, measuring both the magnitude and direction of motion. These developments are critical to enabling the Internet of Things and, in turn, smart farming. Data that was previously inaccessible can now be measured and analyzed, yielding important insights about crop production and the variables that affect outputs and the quality of food.

These trends have been due, in-part, to the development of three key areas in sensor technology: sensor structure, manufacturing technology, and signal processing. Advancement in these fields have enabled novel approaches to sensor systems and considerably improved sensor features.

Sensor structure: Shrinking physical size has enabled sensor structures that not only implement the sensor element to measure the quantity, but also include preprocessing units to create an adequately amplified and filtered signal, as well as digital signal processors to calculate the measured quantity with consideration to variances and influencing factors. Devices may also have self-test or self-calibration capabilities that enables calibration-free sensor systems, which is of utmost importance when devices are commercialized for the mass market.

Manufacturing technologies: Newer manufacturing technologies such as bulk micro-machining and surface micro-machining enable microsystems to integrate sensors, actuators, mechanical, and electronic units. In bulk micro-machining, a silicon wafer or other substrates are selectively etched by dissolving silicon which has been left exposed by using photolithography to transfer a pattern from a mask to the surface. In surface micro-machining, microstructures are built by the deposition and etching of structural layers on top of silicon or substrate.

Signal processing: Signal processing is increasingly shifting from hardware to software. Sensor signals are locally digitized enabling measurement data to be transmitted without significant loss of precision independent of the distance between the sensor and a higher processing unit. Instead of using mechanical or electrical trimming processes, variances and influencing factors can be considered as parameters within sophisticated signal processing methods enabling more precise measurements.

3.1.2. Networking technologies

What makes these devices valuable is not in the gathering of data but the transmission of that data. The signals from sensors often must be communicated over a network to other locations for aggregation and analysis. Networking technologies have progressed rapidly with significant increases in bandwidth and range while also reducing power consumption and cost.

According to the U.S. Bureau of Labor Statistics, prices for internet services were 20.19% lower in 2019 versus 2000. Internet services experienced an average inflation rate of −1.18% per year. This cost reduction also coincided with a growth in Internet users reaching 292.89 million people as of March 2019. This represents a penetration rate of 87.27%.

Even in rural areas and lower income countries where internet access lags behind urban areas and developed countries, Internet access continues to grow. The various existing and emerging networking technologies provide several alternative connection types making it possible to gather, transmit, aggregate, and analyze agricultural data including resource utilization data, mapping and imaging data, and yield information.

There are many different types of wired and wireless connection options available, each with a variety of ranges, bandwidth, and topologies. These technologies can be grouped based on their topology and further organized by their range as shown in Table 1.

As shown in Fig. 4(a), a star network is a common topology in which every host is connected to a central hub [11]. The hub acts as a conduit to transmit messages between hosts. Many protocols operate under this topology. Within this topology, there are three distinct categories of scope: personal-area networks, local-area networks, and wide-area networks.

Personal-area networks interconnect devices within the scope of and individual's workspace. They can be used for communication between devices or for connection to a higher level network and can be both wired and wireless.

Table 1
Network technology organization.

Topology	Star	Mesh
Technologies	**PAN**	
	USB	
	Bluetooth	
	Zigbee	
	LAN	Bluetooth Mesh Networking
	Ethernet	Wi-Fi Easy Mesh
	Wi-Fi	Zigbee
		Thread
	WAN	Z-Wave
	LTE	
	NB-IoT	
	LoRA	
	SigFox	
	LTE-M	

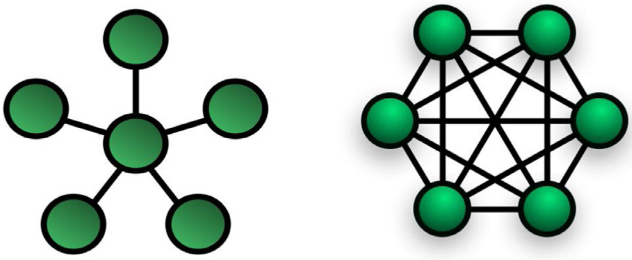

(a) (b)

Fig. 4. (a) Star network topology; (b) mesh network topology.

Personal-area network protocols include USB, Bluetooth, and Zigbee. Local-area networks interconnect devices within the scope of a limited-area, typically a building or campus. Just as with personal-area networks, they can be used for communication between devices or for connection to a higher level network, typically the Internet, and can be both wired and wireless. Local-area network protocols include Ethernet and Wi-Fi. Finally, within the star topology, wide-area networks extend over a large geographical distance. They are used to relay data between local-area networks from various locations across the world and are typically built and operated by Internet Service Providers. The most notable protocol on this type of network is LTE.

This scope has seen new development to address the needs of low data-rate devices powered by batteries that require long-range connectivity, typically in rural, remote and offshore locations. New wide-area network protocols include NB-IoT, LoRa, Sigfox, and LTE-M. Narrowband IoT (NB-IoT), also known as LTE Cat-NB1, is a low power wide area technology that connects devices on existing mobile networks and handles small amounts of infrequent data [12]. NB-IoT is characterized by its minimal power consumption, low cost, and deep penetration into buildings. It leverages direct sequence spread spectrum (DSSS) modulation technology, can operate in 2 G, 3 G, and 4 G bands, and supports up to 50,000 devices per network cell. However, the technology will likely have sporadic deployment around the world. Areas that have wider LTE deployments may not see much support for NB-IoT as they have more incentive to invest in LTE-M instead. A solution would be to utilize devices that support both NB-IoT and LTE-M, however those devices are more expensive than standalone devices. LTE-M, also known as LTE Cat-M1, on the other hand leverages LTE spread spectrum technology as well as two innovations that improve the battery life of edge devices: Power Savings Mode (PSM) to enter a “deep sleep” or extended discontinuous reception (eDRX) [13]. Much like NB-IoT, there may be sporadic deployment around the world. Areas that have not invested in LTE may not see much support for LTE-M.

A technology that is gaining significant traction in IoT is LoRa [14]. LoRa is a proprietary spread spectrum modulation technique that enables devices to communicate over long ranges using low power wireless networks. The LoRa Alliance has created and promotes the LoRaWAN protocol, a low power, wide area networking protocol that leverages unlicensed radio spectrum in the Industrial, Scientific, and Medical (ISM) band to connect battery operated devices to the Internet [15]. The network is deployed in a star-of-stars topology, using gateways to relay messages between devices and a central network server.

Finally, the pioneer in developing low power, long range wireless networks is Sigfox [16]. Founded in 2009, Sigfox leverages differential binary phase shift keying (D-BPSK) modulation, enabling high spectral efficiency, and operates in the unlicensed ISM spectrum as well. The network is deployed in a star topology to connect devices to Sigfox base stations. Sigfox is currently deployed and live in western Europe as well as parts of Africa and Asia and has plans to roll out coverage in the U.S., Mexico, Australia, and most of South America. As a point of comparison, all of these alternatives are designed to connect low power, low data rate devices to the Internet. Where they differ is the technology they use and their outcomes. Both Sigfox and LoRa use unlicensed spectrum limiting their data rates to achieve comparable range while NB-IoT and LTE-M use mobile networks enabling higher data rates and greater network accessibility.

A mesh network, as shown in Fig. 4(b), is typically a local network in which the hosts are interconnected directly and cooperate to route data between clients. Mesh networks self-organize and self-configure making them fault tolerant and resilient. Like wide-area networks, this topology has seen new development to address the low data-rate devices powered by batteries, typically used in home automation applications. Mesh network protocols include Bluetooth Mesh Networking, Wi-Fi EasyMesh, Thread, and Z-Wave.

3.1.3. Cloud and edge computing

The ability to rapidly provision and access computer system resources over networks has enabled the wide availability of applications, storage, and analysis tools. With cloud computing, sensor data has a destination where aggregation and analysis can happen at greater economies of scale and with speed and agility. The use of the term “cloud computing” has been used as a metaphor for configurable computer system resources available through the Internet [17]. Initial concepts of cloud computing took the form of time-sharing. At the time, this represented a major shift in the history of computing and became a prominent model of computing in the 1970s. Around the same time, the concept of virtual machines were created. With virtual machines, it became possible to execute one or more operating systems simultaneously in an isolated environment and was an important catalyst for the rise of cloud computing.

By the 1990s, telecommunication companies, in addition to single dedicated point–to-point data connections, began offering virtual private network connections. Instead of building out physical infrastructure to allow for more users to have their own connections, users now had shared access to the same physical infrastructure. The combination of these two developments enabled the modern form of cloud computing beginning with Amazon Web Services in 2006. Microsoft, IBM, Oracle, and Google followed shortly thereafter offering applications, platforms, and infrastructure as services. This enabled users to cut costs and focus on their core business instead of IT obstacles. Companies were also able to adopt new business models including most notably Software-as-a-Service (SaaS) whereby software applications are made available on-demand in exchange for a subscription fee enabling end customers to nearly eliminate the need to plan and maintain an IT infrastructure.

Recently, a new computing paradigm has entered the market that promises to turn machine-based data into actionable intelligence closer to where data is being created called edge computing [18]. Edge computing is simply computing infrastructure that exists closer to the sources of data. To date, edge computing has mostly been used to gather, store, filter, and transmit data to the cloud. However, coinciding with the rise in computing power in smaller footprints. Edge devices are becoming capable of analyzing and acting on data at the location where it is generated helping to reduce machine downtime, improving performance, and lowering maintenance costs.

Combined with cloud computing, edge computing can enable farming operations to have the flexibility to handle and meet a variety of computing tasks and storage needs. For example, when there is a need for speed or bandwidth constraints, edge computing will be able to handle those tasks while cloud computing handles tasks that require more computing power, such as machine learning, as well as managing large volumes of data.

3.1.4. Single-board microcontrollers and computers

Single-board computing devices integrate everything needed for a functional computer including microprocessors or microcontrollers, memory, and input-output circuits on a single printed circuit board. Single-board computers are most commonly used in industrial applications where they are used for process control or embedded within other devices to provide control and interfacing. They are frequently used in deep-sea exploration and space exploration because of the high integration and are often smaller, lighter, and more power efficient than multi-board computers. These device have existed since the 1970s to support software development on a particular processor family [19]. As PCs began to grab the market, fewer single-board computers were used in computers, giving way to motherboards with peripheral components located on daughter-boards. As more advanced chips reached the market, manufacturers were able to offer motherboards with I/O traditionally provided by daughter-boards such as SATA with RAID, Ethernet, and USB.

However, coinciding with the rise of the open-source movement and DIY maker culture, several projects and companies formed to make single-board computers and open-source components available for hobbyist and educational use. First starting with Arduino, other projects and companies that formed include SparkFun, Adafruit, and Raspberry Pi as shown in Fig. 5.

The Raspberry Pi in particular has become an immensely popular device. The computer is built around the Broadcom BCM2711 quad-core microprocessor which uses the ARM A72 core running at up to 1.5 GHz. It also includes 4 GB of LPDDR4-2400 SDRAM, as well as various input–output devices including Ethernet, HDMI, and USB. Additionally, it is capable of running a desktop class operating system, with a Debian-based operating system freely available to Raspberry Pi users.

Soon after, companies such as Texas Instruments and Intel followed suit with the BeagleBone, Galileo, and Edison. As devices have grown smaller and the pervasiveness of cloud and edge applications have risen, chip manufacturers such as NXP, STMicroelectronics, and Espressif Systems, have introduced boards that enable development for System-on-a-Chip (SoC)

Fig. 5. Raspberry Pi.

devices. SoCs combine all of the elements needed to collect, process, and transmit data on a single chip while only needing peripheral interfaces such as connectors and antennae.

The impact of these developments include not only teaching basic computer science and engineering skills but also making tools and technologies widely accessible for anyone to design and build technological solutions. As this market matured, new companies formed to offer connected technology products including wearables, drones, and other smart devices.

3.1.5. Application protocols

The application layer in computer networking models is an abstraction layer that specifies the communication protocols and interface methods used by hosts in a network [20]. These protocols have been developed since the standardization of the Internet Protocol Suite in the early 1980s.

The most notable and widely used protocol is Hypertext Transfer Protocol (HTTP) invented by Tim Berners-Lee in 1989 [21]. HTTP is the foundation of data communication for the World Wide Web in which hypertext documents include hyperlinks to other resources that the user can easily access.

HTTP functions as a request-response protocol in which the client submits an HTTP request message to the server and the server returns a response message to the client. The response contains information about the request and may also contain requested content in its message body.

HTTP enabled the rise of web services using the Representational State Transfer (REST) architectural style [22]. In a RESTful web service, requests made to a resource's Uniform Resource Identifier will elicit a response that can confirm that some alteration has been made to the stored resource and provide hypertext links to other related resources or collections of resources.

Another protocol that was developed was Message Queuing Telemetry Transport (MQTT) [23]. Developed in 1999 by Andy Stanford and Arlen Nipper, MQTT is a lightweight and bandwidth-efficient publish-subscribe-based messaging protocol originally designed to connect oil pipelines over unreliable, satellite networks.

An MQTT system, as shown in Fig. 6, consists of clients that may be either a publisher of information or a subscriber communicating with a server, often called a broker. Information is organized by topics in which a broker distributes the information published to any clients that have subscribed to that topic. MQTT is the most preferred protocol for machine-to-machine and IoT applications based on the publish-subscribe pattern and the connection simplicity between devices.

Finally, a new protocol for use with constrained devices and low-power, lossy networks called Constrained Application Protocol (CoAP) was introduced recently that provides a request/response interaction model between devices [25]. CoAP is designed to translate to HTTP for integration with the web, while also meeting IoT and M2M requirements such as multicast support, low overhead, and simplicity realizing the REST architecture in a suitable form for the most constrained devices and networks.

3.2. Artificial intelligence

First coined by John McCarthy in 1956, artificial intelligence has been studied for decades. The main advances over the past sixty years have been advances in search algorithms, machine learning algorithms, and integrating statistical analysis into understanding the world at large. Today, artificial intelligence is pervasive with a wide variety of applications from games to robotics to business processes.

Because of the abundance of data and inexpensive computational resources, one of the most active and popular areas within artificial intelligence is machine learning. In machine learning, computers use algorithms and statistical models to

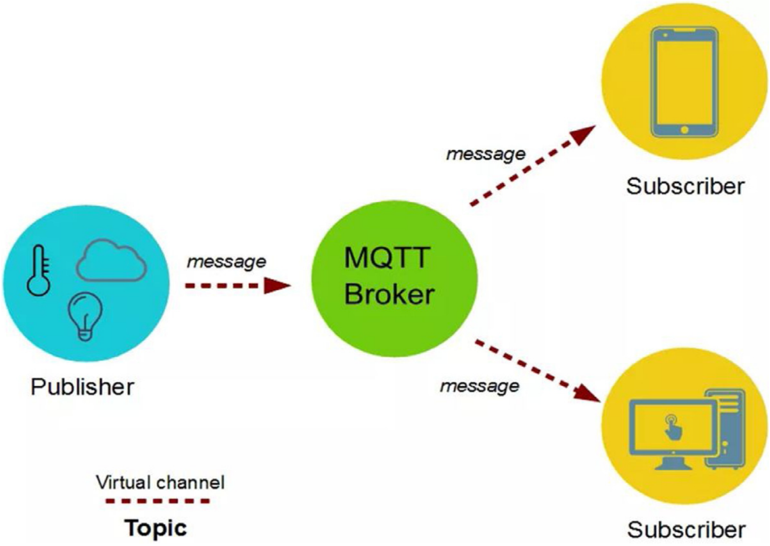


Fig. 6. MQTT protocol [24].

perform a specific task without explicit instructions. Machine learning involves creating a model and training it against a set of training data to make predictions.

One type of model that has gained significant attention is an artificial neural network (ANN). This type of model was inspired by the connections between neurons in the brain whereby a collection of nodes are interconnected and can transmit information to one another. ANNs have been used on a variety of tasks, including computer vision and natural language processing.

Within this model, there are several types of ANNs including feedforward neural networks and recurrent neural networks. In a feedforward network, information moves only from the input layer directly through any hidden layers to the output layer. Recurrent neural networks not only propagate data forward, but also backwards, from later processing stages to earlier stages.

One of the challenges to improving performance of ANNs was the need for a domain expert to identify features from the raw data in order to reduce the complexity of the data and make patterns more visible. Deep learning algorithms solved that problem by using multiple layers to incrementally extract higher level features from input data enabling feature extraction and classification with a single algorithm [26]. Today, deep learning powers applications in a variety of domains including autonomous vehicles, healthcare and finance.

In our discussion of Smart Farming Applications, we will show how deep learning and big data are enabling greater precision and predictability in the cultivation of crops in a variety of environments as well as the technologies that we may see in the future during our discussion of Related Research and Development and Future Directions.

3.3. Robots

Being an interdisciplinary branch of engineering and science, robotics combine mechanical engineering, electrical engineering, and computer science to create machines that perform complex actions. These types of machines have been conceptualized and developed for over a century. Famously, Isaac Asimov coined the term robotics while formulating the Three Laws of Robotics [27]. However, the first modern robots only appeared in the late 1950s with industrial robots. These were simple machines that performed basic manufacturing tasks in a fixed location. Since then, robots have propagated across a variety of industries including defense, medicine, and space exploration.

By the early 2000s, consumer robots were beginning to hit the market with products like the iRobot Roomba. Furthermore, robots were continuing to expand across multiple application areas and becoming more advanced. For example, in 2003, the Mars Exploration Rovers Spirit and Opportunity landed on the surface of Mars after the successful Mars Pathfinder mission in 1997. Each robot carried a set of scientific instruments to analyze the Martian atmosphere, climate, geology and the composition of its rocks and soil (Fig. 7).

Today, robots such as drones, self-driving cars, humanoids, as well as industrial robots are widespread and are employed for tasks which are too dirty, dangerous or dull to be suitable for humans. Typically, these devices are composed of the vehicle, a ground controller, and a communications system and may possess certain levels of autonomy. Robots are used in military and a wide variety of civil industries including manufacturing, transport, scientific research and exploration, construction, medicine, agriculture, journalism and entertainment.

Fig. 7. Example of an unmanned aerial vehicle [28].

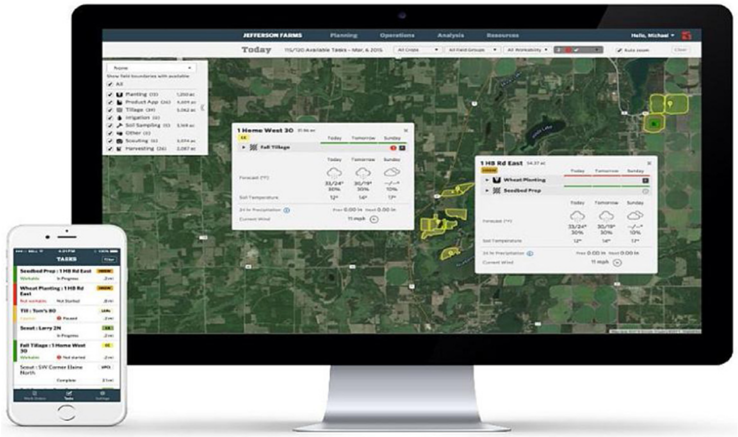


Fig. 8. Granular software interface [29].

In our discussion of Emerging Applications as well as Related Research and Development, we will show how robots are changing the need for labor in the agriculture industry and present several technologies that enhance operational efficiency of farms.

4. Smart farming applications

4.1. Current applications

Enabled by the fundamental technologies presented in the previous section, a wave of application development was catalyzed in the mid-2000s and gained significant momentum in the early 2010s, reshaping how the world cultivates and procures food. A range of software, services, and techniques were created with the aim of bringing more data and efficiency to the industry. These technology-enabled farming applications increase the efficiency of farms making it possible to ramp up food production with fewer resources. Keeping a farm productive and profitable is the highest concern for farmers. Like any other business, profitability is crucial to the long-term survivability of the farm. As a means of achieving and increasing profitability, farms must be productive and efficient which includes managing land and water resources, crop production and animals while optimizing energy and chemical use and mitigating risk.

Applications that have been developed to support farm-related decisions and management are typically web-based software applications that implement predictive analytics and machine learning algorithms. Companies such as Granular or FarmLogs provide a suite of web applications (shown in Fig. 8) to the farm business by gathering and analyzing data to create forecasts and recommendations [29,30]. These tools enable farmers to make decisions that can help them track and control costs, plan production, and make informed decisions.

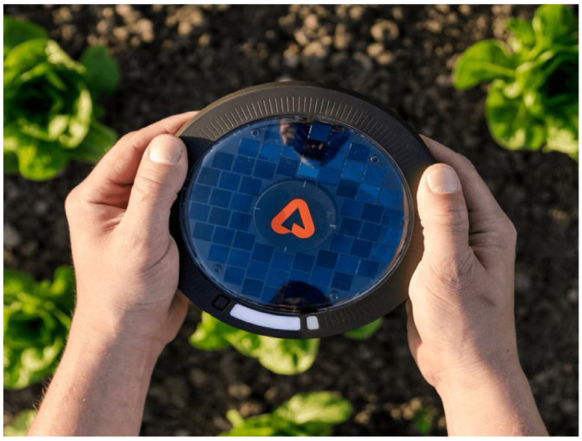
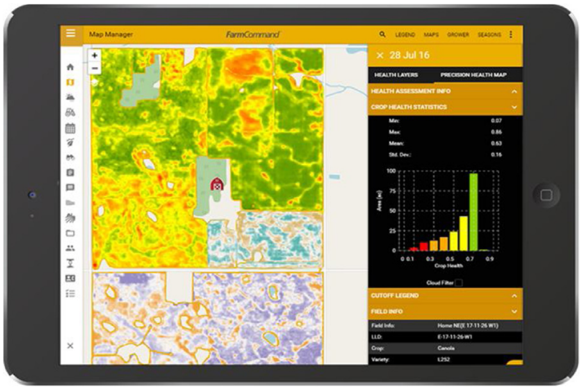


Fig. 9. Arable Mark [33].



Min: 0.07
Max: 0.86
Mean: 0.63
Std. Dev.: 0.16

Field Info: Home NE(E 17-11-26 W1)
LLD: E-17-11-26-W1
Crop: Canola
Variety: L252

Fig. 10. Farmer's Edge satellite imagery [34].

Farm management tools are not only analyzing the farm business, but also the farm operations as well. Using predictive analytics and machine learning, companies such as Agrilyst and Farmers Business Network are able to offer farmers tools to make decisions about crop production in order to increase yields [31,32]. These tools are also gathering data from novel sources such as with drone-mounted multispectral cameras, satellite images, and sensors. As an example of the systems that address the specific problem of weather risk, Arable offers an in-ground monitor as shown in Fig. 9 that collects and analyzes data about weather patterns, crop health, and soil quality [33]. However, sensors need not be stationary or located in the field in order to collect data.

Satellite imagery has become a highly valuable source of data. Farmers Edge, as an example, provides farm management software that collects and analyzes data from satellites, weather stations, as well as farm equipment [34]. Using image processing and analytics, farmers are able to make data-driven decisions about crop planning, cultivation, and harvesting (Fig. 10).

Data-driven management is only a first step towards achieving greater production with fewer resources while facing the impact of climate change. As time passes, the environmental and financial cost of labor and resources will continue to grow more expensive. The growing of importance of operational efficiency cannot be understated not only to the bottom line, but also to environmental outcomes. What comes next will be applications to first automate key processes and workflows and, ultimately, the entire farm.

4.2. Emerging applications

Achieving automation on the farm will require an iterative process that will begin with human operators and progress toward minimal human intervention. This transition has been under way with the emergence of applications that address a variety of technical and social challenges.

Representing the next step in moving towards automation is a Tel-Aviv-based company called Prospera which uses computer vision and artificial intelligence to help farmers analyze data gathered from their fields. Prospera has developed an autonomous crop management solution that leverages their existing algorithms to not only provide recommendations to

Fig. 11. Freight Farms Leafy Green Machine [37].

growers but also directly control center pivots. Working with Valley Irrigation, the leader in the center pivot irrigation market, Prospera is able to gather data from a variety of sensors, satellite imagery, drones, and soil probes and analyze it using their algorithms. After completing analysis, Prospera can send instructions directly to the center pivot for robotic operation and notify the grower to commence operation [35].

One issue plaguing the food system is the existence of food deserts, neighborhoods that lack healthy food sources. In 2015, the United States Department of Agriculture (USDA) reported that 12.8% of the total U.S. population live in low-income and low-access census tracts where at least 500 people or at least 33% of the population is greater than 1 mile from the nearest supermarket for an urban area or greater than 10 miles for a rural area [36].

A growing category of companies that utilize technology to mitigate this problem enable farming in locations that either cannot support traditional farming or lack access to food. They typically employ alternative farming methods such as hydroponics to grow food year-round regardless of location and climate and are capable of remote operation.

One such company is Freight Farms (shown in Fig. 11) which manufactures shipping container farms [37]. Shipping container farms, a growing segment of the agriculture technology landscape, are fully assembled, vertical hydroponic farming systems built inside a standard shipping container. These systems come fully packaged with automatic nutrient dosing and climate control systems that can be controlled with a mobile application. Another company is Plenty, a company that operates indoor vertical farms in warehouses [38]. They use infrared cameras and sensors to monitor temperature, humidity, and carbon dioxide in their facilities. The data generated by these devices are fed into artificial intelligence algorithms enabling Plenty to adjust the environment in order to increase the farm's productivity and enhance the food's taste.

Another key issue in the food system is the shortage of labor. The average annual employment of farmworkers has been on the decline while the average farm size has been steadily growing [39,40]. Much of this can be attributed to rising agricultural productivity due to mechanization, reducing the need for labor. However, there is another reason for the shortage. Despite greater productivity, the average age of farmers is rising and, as they retire, younger generations are less likely to take their place causing great concern about labor shortages in the agriculture industry over the next few decades [41]. Several applications have been created in order to not only make farming more precise but also a sustainable business (Fig. 12).

The applications use robotics and computer vision to do things such as detect crops and weeds, spray chemicals, and remove unwanted plants. As an example, Blue River Technology produces a machine that attaches to an existing tractor and precisely detects and applies herbicide to remove unwanted weeds from fields while avoiding crops [42]. Another example is FarmBot, an open-source robotics project that consists of a Cartesian coordinate machine that uses software to automatically plant seeds, detect and control weeds, and water plants [43]. The system enables a grower to use a web application to graphically plan the farm, schedule sequences, and control the machine in real-time.

However, despite their numerous advances, big tractors compact soil making it less able to absorb rainfall and thus increasing runoff and erosion. Additionally, plants have difficulty growing in compacted soil because there is little space for air and water, which are essential for root growth. One idea that has sought to address those concerns is the use of small robots instead of a big tractor.

Fig. 12. Blue River Technology See-and-Spray Machine [42].

UK-based The Small Robot Company is developing robots that seed and cultivate each individual plant in the field. They feed and spray the plants needed, providing precise levels nutrients and support, with little to no waste. Additionally, their small size reduces soil compaction mitigating the detrimental effects of runoff and erosion [44].

Together, these existing and new applications are an important first step in the transition towards minimal human intervention. New research is yielding innovative solutions and applications that are poised to enter the agriculture technology market and continue the march towards fully automated farms.

5. Related research and development

An explosion of interest and funding into research areas dealing with the Internet of Things, artificial intelligence, and robotics are yielding innovations that will soon be primed for commercialization into new products and services that advance the goal of a fully automated farm. Key research areas include computer vision, robotic motion and manipulation, and multi-agent coordination with applications in pest and disease detection, robotic harvesting, and multi-robot systems.

5.1. Pest and disease detection

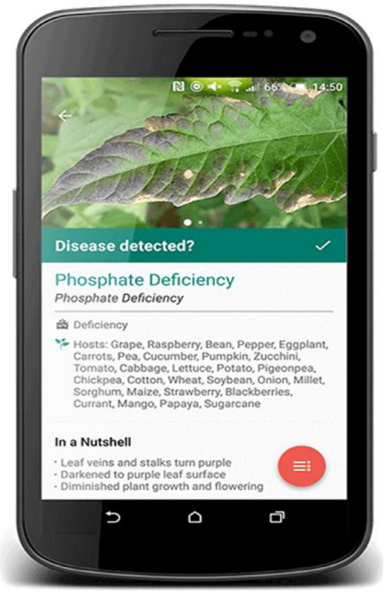
Detecting and managing the spread of pests and diseases is one of the most crucial aspects of farming. Pests and diseases represent existential threats to crop production and cause billions of dollars in crop loss every year. Increasing food production will require effective pest and disease prevention and management. Several applications that employ image recognition and machine learning algorithms have been developed by universities around the world to detect pests and diseases in various plants. As an example, researchers at Penn State University developed an app that uses transfer learning to train a deep convolutional neural network enabling it to detect multiple diseases in Cassava plants, fall armyworm infections in African Maize, potato disease and wheat disease as well as spotted lanternfly pests [45].

Another application is Plantix from PEAT GmbH [46], shown in Fig. 13. Founded in 2015, Plantix has built up the world's largest database of plant diseases and uses image recognition and deep neural networks to identify the plant type as well as possible disease, pest or nutrient deficiency. The app also provides information on treatment and preventive measures.

5.2. Robotic harvesting

Continuing to mitigate the effects of labor shortage, harvesting robots are developed and employed and typically utilize image recognition and robotic arms to grab and manipulate fruit. Research and technologies under development seek to create robots that have the ability to detect, recognize, and determine if fruit is ripe for picking and harvest without damage. Delicate fruits such as apples, pears, plums and citrus fruits are able to be harvested by Israel-based FFRobotics [47]. The system uses deep learning algorithms to identify the fruit, determine ripeness, and send a linear robotic arm to harvest the fruit. Depending on the fruit, the arm can have fingers or clippers used to collect the fruit (Fig. 14).

With the goal of harvesting more delicate fruit, AgroBot, based in Spain, has developed the first commercial autonomous robot that is able to detect and collect strawberries [48]. It autonomously navigates within rows using LiDAR and uses color and infrared depth sensors to generate 3D models of the plant to identify fruit and determine ripeness. Once detected, one of its 24 arms grip and cut the stem of the fruit and then place them into a field container.



Disease detected? ✓

Phosphate Deficiency

Phosphate Deficiency

Deficiency

Hosts: Grape, Raspberry, Bean, Pepper, Eggplant, Carrots, Pea, Cucumber, Pumpkin, Zucchini, Tomato, Cabbage, Lettuce, Potato, Pigeonpea, Chickpea, Cotton, Wheat, Soybean, Onion, Millet, Sorghum, Maize, Strawberry, Blackberries, Currant, Mango, Papaya, Sugarcane

In a Nutshell

- Leaf veins and stalks turn purple
- Darkened to purple leaf surface
- Diminished plant growth and flowering

Fig. 13. Plantix mobile application [46].

Fig. 14. Agrobot strawberry harvester [48].

5.3. Multi-robot systems

Farms are highly complex environments with multiple problems that, if solved correctly, can produce crops effectively. Given the growing size of farms, the geographic scope of each problem is also growing. That poses a scalability challenge to existing solutions; that is, solutions may become too expensive and difficult to scale up to manage across hundreds or even thousands of acres. Multi-robot systems offer a potential solution to this challenge while also improving accuracy as well as health and safety on the farm.

A consortium of 15 institutions and companies was formed to build and evaluate fleets of robots for chemical and physical weed management and tree crop spraying [49]. The Robot Fleet for Highly Effective Agricultural and Forestry Management (RHEA) involves a number of ground and aerial robots with on-board sensors and decision control algorithms that communicates with a base station providing supervision over the mission and enabling the robots to cooperate with one another.

6. Future directions

The agriculture industry's shift from labor intensive to technology native will continue over the coming decades and lead to new business opportunities as well as new business models. We are already starting to see basic versions of such new developments with a host of new services around field. In addition to offering drone hardware and software, companies are also building networks of drone operators and offering drone pilot services to growers [50]. But newer offerings will seek to minimize human intervention in crop production. For example, there may be products and services that treat crop production like recipes, following a set of steps in a carefully controlled environment to produce crops with consistent yields, textures and flavor profiles. This may also be possible in our own homes. This endeavor is already underway at the MIT Media Lab through the Open Agriculture Initiative [51]. Researchers are creating what they call personal food computers to grow crops in a controlled environment that can fit on a table in your home. Crops are monitored and cultivated based on sensor data while using analytics to improve the recipe.

The same technology will be used as man reaches for the stars and expands its presence in space. The further we venture out, the more critical it will be for crews to produce their own food. NASA has already begun experiments with growing produce on the International Space Station as a precursor to exploring and soon colonizing Mars [52].

Finally, as agriculture becomes a technology native industry, we may soon be able to “time share” our fields. Much like with cloud computing, with the push of a button, the tools and resources to grow any given crop may be allocated and the process automatically put into motion with only a single human being needed to manage tens, maybe even hundreds of thousands of acres operated entirely by autonomous robots.

7. Conclusion

Despite greater productivity, the agriculture industry faces new challenges that threaten human civilization. With a growing population and the complexity of climate change, the agriculture industry has been forced to transition away from industrial methods to data-driven management and automation in order to grow more food while using fewer precious resources. Such a new paradigm is possible with the adoption of applications and solutions that are driven by the convergence of several fundamental technologies including the Internet of Things, artificial intelligence, and robotics. Together these technologies keep a farm productive and profitable by collecting and analyzing data to help farmers manage their resources, produce better crops and animals while optimizing energy and chemical use and mitigating risk.

However, data-driven management has only been the beginning of the new paradigm shift. The environmental and financial cost of labor and resources will continue to grow as will the importance of operational efficiency. Ultimately, farms will shift from data-driven management to automation. The shift has been underway with new applications that require less human intervention and address systemic issues including food deserts and labor shortages as well as technical challenges such as growing in urban environments and recognizing plants through image processing.

Growing research interest and funding are yielding new innovations in areas include computer vision, robotic motion and manipulation, and multi-agent coordination. These innovations advance toward the goal of a fully automated farm with applications in pest and disease detection, robotic harvesting, and multi-robot systems. As such technologies develop and are commercialized into products and services, they will enable significantly greater productivity while dealing with an extensive scarcity of resources in an effort to not only feed a growing population but also eliminate potential food shortages in the future and mitigate the effects of climate change.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Imran Charania is a shareholder of Nectar Agriculture.

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