Smart Farming: Opportunities, Challenges and Technology Enablers

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***Abstract*—Agriculture is taking advantage of the Internet of Things paradigm and of the use of autonomous vehicles. The 21st century farm will be run by interconnected vehicles: an enormous potential can be provided by the integration of different technologies to achieve automated operations requiring minimum supervision. This work surveys the most relevant use cases in this field and the available communication technologies, highlighting how connectivity requirements can be met with already available technologies or upcoming standards. Intelligence is considered as a further enabler of automated operations, and this work provides examples of its uses.**

I. Introduction

Remote sensing techniques utilizing Unmanned Aerial Vehicles (UAVs) are in constant development and the use of tiny MEMS sensors (accelerometers, gyros, magnetometers, and often pressure sensors), small GPS modules, powerful processors, and a range of digital radios makes drones small, low cost and quite easy to use. In just under five years, UAVs have gone from a toy for gadget junkies to an essential tool in many application fields; today, agriculture is one of the fastest growing markets for the commercial UAVs industry. In 2014, the Massachusetts Institute of Technology classified agricultural drones at the primary position among the ten breakthrough technologies [1], helping the farmer in a better utilization of the land. As an example of drone utilization in farming (see Figure 1) in the wine production sector, multi-spectral cameras mounted on drones have highlighted the close correlation between the quality of the grapes and the health of the plants. Another example of drone utilization is the reduction in waste of water around a farm: drones can be fitted with remote sensing equipment (multispectral, hyperspectral or thermal sensing systems) in order to quickly and easily identify the driest sections of a field, thus allowing farmers to allocate their water resources more economically. Even the amount of chemicals ground penetration for fighting pest and fungal infestations can be reduced if drones effectively scan the ground of a farm and spray the correct amount of chemical substance modulating the distance from the ground. Moreover, a drone can survey a crop at any requirement of the farmer, thus showing any dangerous changes or other events of interest. Unmanned Ground Vehicles (UGVs) already help farmers in reducing their physical effort: tractors autonomously plant seeds with very high precision, and GPS-guided harvesters can reap the crops with high accuracy. In a close future, farmers will provide human supervision to automated operation from a control center. An experiment in this direction has already been done in the UK with the project *The hands-free hectare*[1], where the cultivation of one hectare of land in the rural region of Shropshire has been worked thanks to the use of a tractor and a self-driven combine-harvester. The vehicles have been modified with cameras, lasers and GPS navigation systems. At the same time, an UGV was tasked with the collection of soil samples, while an UAV was monitoring the work from above. A further technological challenge is constituted by a drone driving an autonomous vehicle: while the terrestrial vehicle has a limited view of possible immediate obstacles, the drone can update the prescription maps in real-time thanks to its vision from above. Whatever the scenario is, communication is a fundamental aspect among UAVs and UGVs. This paper presents the relevant use cases for the Internet of Things (IoT) paradigm in smart farming scenarios, the enabling wireless technologies and the network functional requirements. A brief survey of ground and aerial vehicles is also presented, together with the vision systems usable on board the UAVs. To assist the identification of the differences that characterize the UAV missions, we also propose a simple taxonomy in smart farming scenarios.

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II. IoT for agricultural applications

In Section II-A, we discuss the most relevant use cases for the use of IoT in smart farming, while in Section II-B we analyze the enabling wireless technologies. The functional requirements from the network viewpoint are discussed in Section II-C, thus mapping use cases to enabling wireless technologies.

[1]Details available at http://www.handsfreehectare.com.

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Fig. 1: EFESTO is an UAV developed by CNR, mounting a thermal imaging camera, a multi-spectral snap, and two hyper-spectral fiber optic sensors for smart farming applications.

Fig. 2: Treatment of the processionary moth by a second UAV made by CNR. Three precision sprayers are mounted at the edges of the UAV payload.

A. Relevant Use Cases

The Agricultural Electronic Foundation (AEF) is an international Association of the major industries and research centers involved in the research, design, and production of agricultural machines and systems. AEF is deeply involved in precision agriculture technologies, which are enabled by ISOBUS [2] on board agricultural machines. ISOBUS is a mature standard, but the same cannot be said if looking at the evolution of standards to enable wireless communications in smart farming scenarios, which are not yet ready for standardization. A cause can be found in the difficulty of promoting a single standard in the vast ecosystem of wireless technologies and automated functions. The recent announcement of ISOBUS evolution towards a *time-sensitive networking* based on the Ethernet and BroadR-Reach [3] physical layer, due to the upcoming standard in the automotive sector, will enable high speed communications from/to agricultural machines, supporting processes from the farm and enabling distributed control systems, and thus an IoT paradigm.

In order to analyze and understand the requirements for the communications standards, agricultural domains and use cases have to be firstly discussed. The first variable is the cultivation type that defines the environment structure. For crops, especially in north and south America and in continental Europe and Russian Federation, large fields must be considered, with extensive cultivations of grain, maize, soy beans, rice, sugar cane. Here, huge machines are needed, requiring direct (i.e., in absence of infrastructure) and real-time communications in a cluster of machines working in parallel, as well as communications with the farm to update working plans and to collect data from machines in absence of strict real-time constraints. In this scenario, where large amount of data are exchanged, specialized communication is necessary among UGVs and UAVs: in fact, the latter collect very precise multi-spectral images of the parcels to be worked, thus enriching the information in the prescription maps used by the UGVs. All these functions are an important evolution of the *variable rate in treatments* (VRT), one of the key features of precision farming. Figure 2 shows an example of a VRT application by relying on another UAV developed by CNR: the image was taken during the treatments of processionary moth. To enable such a scenario, a real-time, high throughput and multi-hop machine-to-machine (M2M)/IoT wireless communication is crucial for the cluster management and of the direct data acquisition from the UAV, as shown in Figure 3; on the other hand, an infrastructure-based high bandwidth communication is also important for downloading and updating operations of prescription maps, further than data upload in control servers. A collective management of all the involved machines enables energy-saving and work optimization techniques. The software suite enabling data exchanges [4] are today referred to as *Farm Management Information Systems* (FMIS), and a high speed protocol for data exchange with machines in the fields (under standardization) is referred to as *Extended FMIS Data Interface* (EFDI).

Moving to orchards and vineyards, the overall scenario can be quite different. The first difference is the field structure and cultivation setup, which is based on rows of plants precisely positioned and structured, in order to work the entire cycle with automated and specialized machines. The first notable difference w.r.t. extensive crops is that the use of cluster of machines is currently very rare. The second difference is that sensors in the field are largely used for data collection from the orchard and winery. In fact, this scenario hugely relies on several sensor types (in the terrain, for sunlight and humidity), typically placed in rows along the cultivation. Data can be collected via gateways connected to Internet. UAVs can be used to collect data in the field, but Wireless Sensor Networks (WSNs) are more common due to the difficulty of evaluating the state of fruits in the plants while flying over the field. UAVs have been used in experimental VRT testbeds; such a

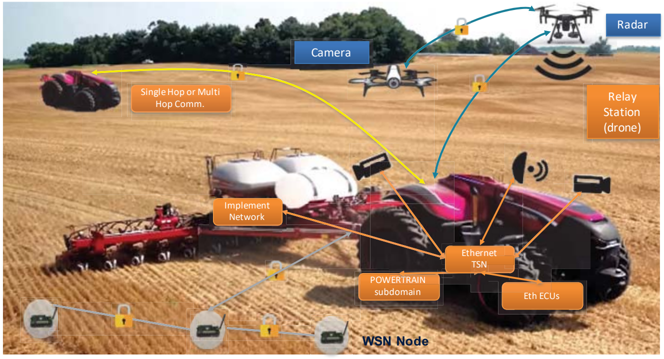

Fig. 3: A real-time, high-throughput, and multi-hop M2M/IoT wireless communication scenario for a cluster of UGVs and UAVs.

role is expected to further grow thanks to smaller and smaller payloads and to precise positioning. To do so, long-range communication must be in place to enable data exchanging with the control center.

B. Enabling wireless technologies

One of the key aspects of precision farming is the necessity to transmit data from/to other devices, in particular for: *i)* retrieving big amount of data to be exchanged and elaborated; *ii)* pushing command and control data; *iii)* high-speed real-time communication and cooperation among clusters of devices operating in the same ground, and *iv)* sharing sensed data. To account for these different characteristics, several communication standards can be used to implement the *smart farming* paradigm. In the following, we classify these standard in terms of short- and long-range communication capabilities.

For short-range applications, IEEE 802.15.4-based protocols are those most suitable. IEEE 802.15.4 is intended for low-rate and Low-Power Wide-Area Networks (LPWANs). It operates over different frequency bands (433 MHz, 868 MHz, and 2.4 GHz (EU), 915 MHz, and 2.4 GHz (US)) with teorical data rates ranging from 20 kbps to 250 kbps, and a maximum outdoor Line of Sight (LoS) range of approximately hundred of meters. Differently, IEEE 802.11 standard applies to a huge set of application scenarios with medium range connectivity requirement, in continuous evolution. In particular, the IEEE 802.11p amendment was released in 2010 to support scenarios with a high mobility degree. Compared to the other releases, IEEE 802.11p appears to be of large interest in agriculture scenarios due to its maximal legal transmission power of 1W, its large transmission range, and the usage of the less interfered band of 5.9GHz ISM frequency.

When coverage is a concern, long-range technologies are the only feasible solutions. In case of large amount of data and real-time constrains, Long Term Evolution (LTE) or 4G and its future releases appears the most suitable standard for precision agriculture, even if its availability cannot be assured in rural areas. LTE data rate is in the order of 3 Gbps in downlink and up to 500 Mbps in uplink with latency values less than 10 ms in the LTE-Advanced Release 10. Besides LTE, the fifth generation (5G) communication system is expected to provide real-time device to device (D2D) communication, thus enabling vehicle positioning and support for a huge number of devices per square kilometer. Compared to LTE, 5G can operate on higher frequency bands, exploiting wider channel bandwidths. In particular, in rural areas, 5G technology may bring very high data rates further than just connectivity to areas that today may even lack coverage, thus enabling new capabilities on farm equipment under the paradigm of real-time connectivity. Yet, the question about 5G economical feasibility in rural areas is still to be answered [5].

Today, LTE can be also considered for connecting moving vehicles. Indeed, from Release 12, the D2D functionality and the corresponding channel structure, namely *sidelink*, were introduced to enable direct communications [6]. Motivated by the increasing interest for the vehicular market, 3GPP has then started working on specific features for V2V. Although enhancements are included in Release 13, V2V was included only in Release 14. Compared to the IEEE802.11p, two are the main advantages of LTE for V2V communications: *i)* the same technology in use for cellular communications, which implies exploiting the same hardware and most protocols; *ii)* orthogonality of resources, thus allowing higher multiplexing, with a possibly significant increase in reliability and capacity.

Among long-range air interfaces for IoT, it is worth mentioning just a few other emerging technologies, which are 802.11ah and LoRA/LoRAWAN. The former is an amendment of the IEEE 802.11 family, published in 2017, whose purpose is in supporting IoT scenarios, like smart metering. It uses 900 MHz license-exempt bands, and benefits from lower energy consumption when compared to Bluetooth and IEEE 802.15.4, also providing a wider coverage range. It aims at providing connectivity to thousands of devices with a single access point up to one-kilometer radius of coverage. Last but not least, we mention LoRaWAN technology, which, at the present time, is one of the most promising LPWAN specifications intended for battery-operated wireless things. LoRaWAN technology has already shown proof of concepts and demonstrators for the application in smart agriculture at one of the world's most important mobile trade fairs, the *Mobile World Congress*. LoRaWAN is a closed spread-spectrum modulation technique, which allows sending data at extremely low data-rates towards a network concentrator, providing extremely long ranges (tens of kilometers in open space rural areas) in a star topology. LoRaWAN uses license-free sub-gigahertz radio frequency bands (169 MHz, 433 MHz, 868 MHz (EU) and 915 MHz (US)) with data-rates of 0.25-12.5 kbps with narrow bands, down to 125 KHz. It promises massive deployments at very reasonably prices.

C. Network functional requirements

In the case of orchards and vineyards, high bandwidth is necessary because of precision farming data and telemetric data to be collected in the farm servers, and because of download/update operations of prescription maps. In case of greenhouses and horticulture, a totally different scenario must be analysed. Greenhouses are connected to the electrical grid, thus opening to the use of gateways, which can be too power hungry for batteries. 4G/5G connections can substitute fixed lines, but also WiFi can be taken into account for Internet connection. Similarly, a gateway between the WSN and the infrastructure can be available, so that small agricultural machines can exchange data. In a near future, the machines used in this kind of environment will probably be totally autonomous, thus requiring a fast, robust and safe communication for a productive working environment. Livestock farming shows basically two scenarios: shred and free animals pasture in the fields. The former one is very similar to greenhouses, where wireless sensors are worn by the animals, while the latter is very similar to the case of extensive crops - with the notable difference that information from the field is related to collection of data from animal sensors, relying on UAVs or agricultural machines.

Another issue to be considered is the necessity to ensure a safe traveling to agricultural machines in public roads. The basic idea is to provide a M2M-based advertisement notifying the presence of slow machines, so including agricultural machines in Intelligent Transportation Systems (ITS) standards [7]. The ETSI 542 task force is currently working on this topic. This use case enforces the adoption of 802.11p for mid-range and M2M communications, to be compatible with the standard adopted for passenger cars. Candidate protocols for both Internet infrastructured connectivity and long range communications are both 3G/4G communications and, in a close future, 5G and LPWAN air interfaces that will enable IoT data management paradigms, i.e., the so-called *Agricultural Internet of Things* (AIoT). Machines will exchange data with servers providing high computational power, real-time elaboration of the data coming from fields, from satellite imagery, and from historical data repository to provide enhanced functionalities, still prohibitive for on board controllers. 802.11p represents a robust solution for mid-range communications, both infrastructured and direct. On the other side, a standard WSN protocol for long- and short-range communication is not yet available. Because of this, all the aforementioned protocols shall be included in the ISO16867 standard *Tractors and machinery for agriculture and forestry* for wireless communication in agriculture.

III. Unmanned Systems

In the following, we briefly survey UGVs and UAVs that can be used in the scenarios described in Section II.

A. Unmanned Ground Vehicles

UGVs have a longer history than UAVs because they pose less threats to (human) security. In fact, a large number of works can be found in the literature, as well as existing platforms on the market. For instance, a valuable survey is provided in [8], which highlights how custom mobile robots are the most common choice, exploiting GPS, odometry, path plans, and several other as navigation strategies. On the ground, also rails and pipes can be used to precisely move a vehicle. Along with affirmed solutions, more innovative but still risky solutions are to be taken into account, as sphere robots. Bio-inspired, sphere vehicles can move on a large variety of terrains with few difficulties, thus enabling several new scenarios.

TABLE I: Classification of UAV platforms based on operating altitude and capabilities.

	Platform	Operating Altitude (km)	Endurance	Payload (Kg)
sUAS	MAV/NAV	0 - 0.3	$<$ 0.5 h	$<$ 0.5
	VTOL	0 - 3	1 - 2 h	2 - 25
	LASE/LALE	0 - 3	$<$ 12 h	2 - 25
UAS	MALE	$<$ 12	$<$24 h	up to 1000
	HALE	up to 30	up to 30 h	N.A.

B. Unmanned Aerial Vehicles

In this section, we briefly discuss existing UAV platforms, and then safety concerns in smart farming scenarios. In order to ease the reader, we propose a simple but effective classification based on a three-tier model in Figure 4. The first tier contains the general mission types, used in precision agriculture but also common to a variety of other application fields. This includes Intelligence/Reconnaissance, Transport, Communication, Treatment, Supervision. The second layer expands the mission type of the first level, by characterizing the effective role of the UAV in the specific mission category. In addition, the third tier specifies the modalities in which UAVs operate, thus providing additional elements to derive the operational requirements and the choice of the suitable platform, payload, and communication technology. Table I provides a simple but useful overview of the currently available UAV platforms according to operative altitude, endurance, and payload support. According to the requirements that different scenarios may need, the choice of the most appropriate platform can be done, starting from the classification of the platform itself. Referring to Table I, small Unmanned Aerial Systems (UASs) can be further classified into *i)* Micro/Nano air vehicles (MAV/NAV) of reduced size, easily transported but with limitations on flight time; *ii)* Vertical Take-Off & Landing systems (VTOL); and *iii)* low altitude systems, i.e., short-endurance (LASE) and long-endurance (LALE) drones. On the other hand, if looking at larger UASs, Medium (MALE) and high (HALE) altitude devices are to be taken into account as winged systems larger than LALEs/LASEs, and able to provide the coverage of areas up to hundreds of kms.

The use of UAVs is less affirmed than that of UGVs because of security concerns, but an increasing interest can be identified both in the literature and in the private sector. Nonetheless, their use is currently limited by national regulations. The risk in using UAVs is expressed as the product of the occurring probability of an event and the extent of the damage caused by the event occurring. Two types of events may occur during the use of UAVs: in-flight collisions with other objects or on the ground, and direct or indirect damage to them. Starting

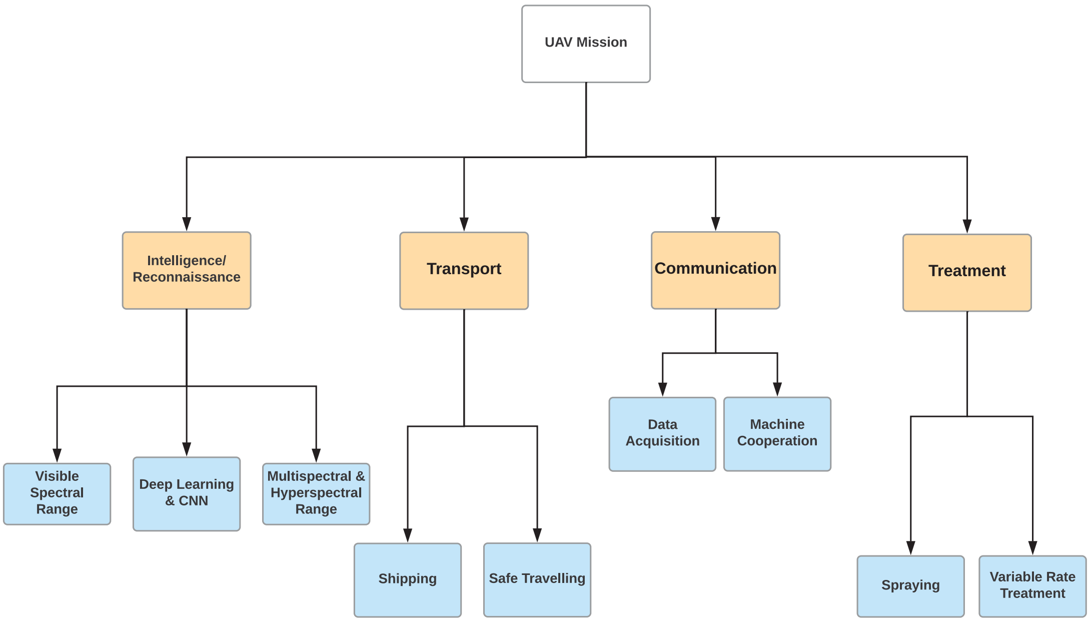

Fig. 4: Taxonomy for UAV missions in smart farming scenarios.

from the standard operating procedures for the use of the UAVs, the implementation of effective operational limitations is mandatory (for instance: flight autonomy limitation, redundancy of communication channels for command and control, redundancy of pilots on the field, identification of additional automatic landing zones), in order to reduce any risk as much as possible. If considering the use of UAVs in smart farming scenarios [9], [10], the flight scenario is usually identified by rural areas with low population density and a visual LoS (VLoS) flight. In this case, both the collision probability on the ground and the generated damage should be considered almost negligible. Differently, geofencing a fraction of the airspace may have different implications: in fact, if excluding the case of a *type G* airspace (uncontrolled airspace), more strict security requirements have to be obeyed. If the area is large enough, a Beyond-VLoS (BVLoS) flight mode should be considered. In this case, the possibility of aerial collisions should be carefully evaluated. Currently, BVLoS flight has not yet received clear guidelines and, therefore, it is not allowed (at least in Italy). This is mainly due to the possibility - as mentioned before - of overflying areas where the risk can be high, or invading no-flight zones. Operating an UAV in BVLoS requires implementing additional technologies, like collision avoidance systems, and a proper control and traffic management. In [11], several possible civilian uses of UAV swarms have been analyzed, discussing operating scenarios in BVLoS or in urban areas, even if those are yet to come. To this aim, the Single European Sky ATM Research (SESAR) project is going to standardize an Unmanned Aircraft System Traffic Management (UTM) that will be mandatory for aeromodelling, also making possible for the police to identify UAVs, to prohibit the air traffic of no-flight zones, and to terminate the flight of unauthorized or unidentified systems.

IV. Vision Systems and Deep Learning

Computer vision is today experiencing a revolution thanks to the progress of Deep Learning architectures, and in particular of Convolutional Neural Networks (CNNs). These techniques have been successfully applied in agricultural applications that exploit aerial images. With the continuous decrease in the cost of UAVs and UGVs, there is an increasing interest in applications for monitoring the state of the crops or for plant counting and identification [12]. A machine-vision system is described in [13]: an UGV is equipped with a vision system enabling autonomous and non-autonomous scenarios. Machine vision systems can operate in the visible spectral bands and/or in those outside the visible range. For instance, Near Infrared, Short Wave Infrared, and up to the Long Wave Infrared are examples of the latter. Such devices are referred to as multi-spectral and hyperspectral imaging sensors, providing high resolution imagery. With the recent great diffusion of agricultural drones, hyperspectral sensors are being re-designed to be lighter, smaller, more compact, and more affordable. In fact, there are many applications in which hyperspectral imagery from an UAV can make the difference [14], such as: *i)* agriculture parameter estimation and retrieval (e.g. carotenoid, chlorophyll, and anthocyanin content, nitrogen status, water content, biomass and leaf area index); *ii)* crop classification and crop/material detection; *iii)* disease early detection and monitoring (e.g. disease due to bacteria and fungi or caused by insect infestation); *iv)* machinery guidance in pre/post crop tasks (e.g. early sowing, precision fertilizer application, precision irrigation). In these applications, hyperspectral data exploitation is conducted not only by evaluating narrow-band spectral indexes (e.g. normalized difference vegetation index or photochemical reflectance index), but also employing approaches taking into account the whole shape of the spectral signature (e.g. supervised classification, spectral clustering, machine learning methods). When considering visible spectral bands, specific colors can be accentuated in order to acquire data about greenness (the case of green), or soil segmentation (the case of red and green) [13].

Machine vision systems can be complemented with the use of CNNs, as for instance in [15], where the imagery of paddy fields acquired by UAVs at low altitudes is used for training CNNs and assessing the yield of the paddy fields. Deep learning can also be used for grass classification and to measure the level of weed infestation, as discussed in [16], or to optimize water consumption [17]. One of the great advantages introduced by the use of deep learning approach consists in the possibility of exploiting the output of the intermediate layers of a neural network as features for computing similarities between images or for classification purposes. In [18], the features learned thanks to the use of a CNN were used to train a support vector machine to obtain cultivated land information from UAV imagery. The features extracted from a new type of neural network, called *capsule network*, are used to recognize rice images captured by an UAV [19]. Several challenges are yet to be overcome on the joint use of UAVs and learning techniques in the context of precision agriculture [20], but this topic is fascinating for both researchers and private companies.

V. Conclusions

This paper presented an overview of IoT technologies in several smart farming scenarios. Different agricultural domains have been analysed in this work, highlighting the most relevant communication requirements, and providing a mapping between the presented use cases and the enabling technologies. We considered UGVs and UAVs, surveying different uses and their requirements. In particular, we have proposed a simple taxonomy for UAVs missions, which can be used in identifying the differences among different missions. On the other side, the joint use of UGVs and UAVs seems to be still missing from smart farming scenarios. We are convinced that deep learning architectures and CNN techniques can be key enablers for their joint use, thus opening to a better understanding and management of the farmland.

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