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Drones in Manufacturing: Exploring Opportunities for Research and Practice

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Drones in Manufacturing: Exploring Opportunities for Research and Practice

ABSTRACT

Purpose

Although the industrial application of drones is increasing quickly, there is a scarcity of applications in manufacturing. The purpose of this study is to explore current and potential applications of drones in manufacturing, examine the opportunities and challenges involved, and propose a research agenda.

Research design

The paper reports the result of an extensive qualitative investigation into an emerging phenomenon. The authors build on the literature on advanced manufacturing technologies (AMT). Data collected through in-depth interviews with 66 drone experts from 56 drone vendors and related services are analyzed using an inductive research design.

Findings

Drones represent a promising AMT that is expected to be used in several applications in manufacturing in the next few years. This paper proposes a typology of drone applications in manufacturing, explains opportunities and challenges involved, and develops a research agenda. The typology categorizes four types of applications based on the drones' capabilities to "see," "sense," "move," and "transform."

Research implications

The proposed research agenda offers a guide for future research on drones in manufacturing. There are many research opportunities in the domains of industrial engineering, technology development, and behavioral operations.

Practical implications

Guidance on current and promising potentials of drones in manufacturing is provided to practitioners. Particularly interesting applications are those that help manufacturers "see" and "sense" data in their factories. Applications that "move" or "transform" objects are scarcer, and they make sense only in special cases in very large manufacturing facilities.

Originality

The application of drones in manufacturing is in its infancy, but is foreseen to grow rapidly over the next decade. This paper presents the first academically rigorous analysis of potential applications of drones in manufacturing. An original and theory-informed typology for drone applications is a timely contribution to the nascent literature. The research agenda presented assists the establishment of a new stream of literature on drones in manufacturing.

Keywords: *unmanned aerial vehicles; drones; advanced manufacturing technologies; factory operations*

1 INTRODUCTION

Recent advancement in technologies challenge the way companies manufacture and deliver products. For example, additive manufacturing technologies change the processes used to manufacture customized products, collaborative robot technologies enable new assembly processes, augmented reality technologies offer new ways to train operators, and artificial intelligence replaces or assists human operators in customer service processes (e.g., Deradjat and Minshall, 2017, Fox, 2010, Hedelind and Jackson, 2011, Steenhuis and Pretorius, 2017). Another promising technology is the unmanned aerial vehicle (UAV), which is commonly known as a drone. Over the past decade, the capability of drone technology has improved, its price has plummeted, and its availability has greatly increased. Hence, many manufacturers have begun to consider the benefits of drone technology for their businesses. This paper contributes to the manufacturing literature by presenting the first academically rigorous analysis of current and potential applications of drones in manufacturing. We examine the opportunities and challenges involved and proposes a research agenda.

A breakthrough in the use of drones in industry occurred in 2006 when the US Federal Aviation Administration issued the first commercial drone permit. Coincidentally, the Chinese drone company SZ DJI Technology was founded in the same year. This company now holds about three quarters of the global consumer drone market (The Economist, 2017). Since then, interest in the professional application of drones has grown rapidly. In 2018, the research and advisory company Gartner Inc. described drones as an "emerging technology that will become a source of competitive advantage over the next decade" (Panetta, 2018). Nevertheless, drones have hardly found any profitable applications in manufacturing. Why?

There is a rich research on the technical capabilities of drone technology (e.g., robotics, control, and computer vision), but much less research on the practical application of drones in industry. Currently, there is a gap between the technological developments of drones ("what drones can do") and the profitable applications they can offer to manufacturing ("what it makes sense they do"). This is in part, due to the novelty of the technology and in part due to a focus of drone development for other purposes than manufacturing. The current industrial applications of drones are mainly in the *outdoors*. Their profitable applications in industries such as agriculture, construction and infrastructure, energy, logistics, and mining (see, Goldman Sachs, 2016, Mazur and Wiśniewski, 2016) take advantage of their ability to fly quickly and safely at high altitudes to places that are difficult, hazardous, or expensive to reach. Manufacturing operations, on the contrary, are almost exclusively *indoors*.

In manufacturing facilities, drones compete with conventional technologies that can be mounted to fixed installations (such as floors, pillars, walls, or ceilings) or moving installations (such as cranes, conveyors, or vehicles). While outdoor drones can use conventional global positioning systems (GPS) for localization, positioning, and routing, indoor drones require complex technologies, such as laser rangefinders (e.g., simultaneous localization and mapping [SLAM]), ultra-wideband radio signals (a form of "indoor GPS"), or more expensive technologies, such as motion capture systems (e.g, Khosiawan and Nielsen, 2016). Safety, noise, and privacy also remain of considerable concern. Moreover, doors, cables, cranes, equipment, and people limit the maneuverability of drones, and the confined spaces in manufacturing facilities can create turbulence. However, indoors also have advantages. Indoor settings are not subject to governmental legislation regarding open air flight (Floreano and Wood, 2015) and weather conditions are irrelevant.

This study aims to bridge the gap between the current capabilities of drone technology and its potential applications in manufacturing, as well as to set the stage for the future of drones in manufacturing. To do so, we explore the potential use of drones in manufacturing by drawing on rich qualitative data collected in interviews with experts. We start with three research objectives. The first research objective is to develop and propose a typology of drone applications in manufacturing. The second research objective is to evaluate the related opportunities and challenges. The third research objective is to use the insights gained in this study to propose a research agenda. We enter the field informed by the knowledge from the rich literature on advanced manufacturing technology (AMT).

2 THEORETICAL BACKGROUND

Although the application of drones in manufacturing has not received much attention in the operations management literature, the application of comparable manufacturing technologies has of course been studied. The drone technology can be classified as an AMT. An AMT is a computer-based technological innovation used in manufacturing processes (Udo and Ehie, 1996, Gouvea da Costa and Pinheiro de Lima, 2008). AMTs include a range of modern technologies used in manufacturing, such as computer numerical control (CNC) machines, industrial robots, flexible manufacturing systems (FMS), automated storage and retrieval systems (AS/RS), radio frequency identification (RFID), additive manufacturing ("3D printing"), and automatic guided vehicles (AGV), among others (Jonsson, 2000, Boyer et al., 1997).

Drones as an advanced manufacturing technology

An AMT is a technological system that consists of hardware, software, and support processes (Bessant and Buckingham, 1989, Cagliano and Spina, 2000, Chung and Swink, 2009) (see Appendix 1, Figure A-1, for a high level architecture of a drone system). The *hardware* of a drone system includes the aircraft, the remote controller, the installed payload (cameras, sensors, carriers, etc.), local navigation support systems, energy supply system, and the information technology (IT) infrastructure. The *software* consists of the programs and algorithms that control the drone's flight and payload tasks, as well as communicate with the controllers, navigation system, and IT systems. The s*upport processes* cover a range of drone operations that involve humans, such as manual piloting or establishing and maintaining the infrastructure required for automatic or autonomous flights, and interpreting the data collected by the drone.

An AMT application can be "stand alone" or it can be linked or integrated with other technologies (Meredith and Suresh, 1986, Small and Yasin, 1997, Small, 2007). Most current drone applications are stand-alone designed to do a specific task. Examples include the inspection of hard to reach equipment using video and thermal cameras in the oil and gas industry, aerial photogrammetry for developing three dimensional modelling during factory planning, and delivering spare parts during maintenance operations (see, Barth and Michaeli, 2018, Maghazei and Netland, 2018, ZF Friedrichshafen AG, 2018). Linked AMTs conduct their own tasks, but also communicate and coordinate with other technologies. An example of a linked drone system is applications used in inventory cycle counting to automatically update inventory records in a warehouse management system. Integrated AMTs are dependent on the tasks of other technologies. Only very few current drone applications qualify as integrated AMTs.

Physical versus analytical capabilities of advanced manufacturing technologies

AMTs can be classified according to their physical and analytical capabilities (e.g., Bessant and Buckingham, 1989, Kotha and Swamidass, 2000, Kotha, 1991, Steenhuis and Pretorius, 2016). The *physical capability* of an AMT is its ability to conduct physical tasks. For example, radio frequency identification (RFID) readers and sensors have relatively low physical capabilities and computer numerical control (CNC) machines, conveyor systems, AGVs, and industrial robots have relatively high physical capabilities.

Following Kotha (1991) and Kotha and Swamidass (2000), we define the *analytical capability* of an AMT as its ability to process data. What separates high from low analytical capability is not necessarily associated with tedious programming but is decided by the degree of data processing during use. For example, a simple special-purpose CNC machine has a high programming setup, but the machine usually simply runs its program during use and is therefore an AMT with low analytical capability. An advanced FMS, however, needs high analytical capability to synchronize the real-time flows between machining processes, machine tools, and materials.

The capabilities of AMTs are improving quickly due to the advancement of complementary technologies such as sensors, robotics, cloud computing, big data and analytics, to name a few (Guo and Qiu, 2018, Frank et al., 2019). Such technological advancements are improving both the physical and the analytical capabilities of AMTs. For instance, Steenhuis and Pretorius (2016) discuss that the growth of consumer 3D printing is due to the advances of both its physical capabilities (e.g. extruder movement and speed), as well as its analytical capabilities (e.g. using open source software packages). In a study of the evolution of automated guided vehicles (AGV) in flexible manufacturing systems (FMS), Buyurgan et al. (2007) show how the physical capabilities of AGVs are enhanced with analytical capabilities such as autonomous travel without guided paths.

The separation of analytical capabilities versus physical capabilities of AMTs makes intuitively sense for drone systems. A drone with low analytical capability only captures input data without processing it; examples are simple photography or filming. A drone with high analytical capability converts the input data to other forms of data or information. For instance, a drone system that is equipped with a thermal camera receives input data and produces thermogram images of temperature radiation. A drone with low physical capability is not able to perform any physical operation other than flying. A drone with high physical capability has the ability to conduct physical tasks such as move objects (in addition to the mounted payload) (e.g., parcel-, part-, or tool delivery), or to perform a physical operation in addition to flying (e.g., spraying chemicals or repairing scratches).

Using the separation of analytical capabilities versus physical capabilities, we derive a conceptual framework from the AMT literature (Figure 1). The combination of low and high for these two capabilities suggests that AMTs can be classified into four different types: respectively, low-low, high-low, low-high, and high-high configurations of analytical versus physical capabilities.

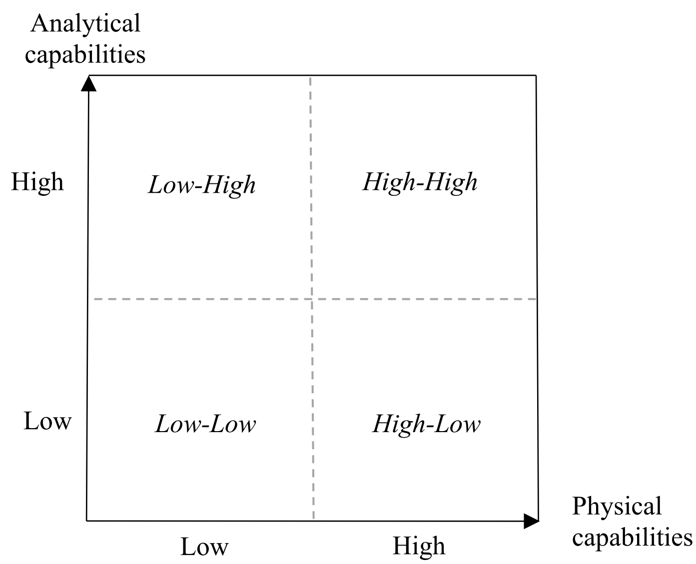

Figure 1. Classifying AMTs as a combination of physical and analytical capabilities.

A conceptual framework explains graphically "the main things to be studied" and can "evolve as the study progresses" (Miles et al., 2014, p. 20). We use the theory-informed framework in Figure 1 as a conceptual underpinning when we go to the field to study the applications of drones as a new form of AMT in manufacturing.

3 RESEARCH METHODOLOGY

In this study, we explore an emerging phenomenon. Due to the novelty of drone applications in manufacturing, there is little empirical evidence in the operations management literature. Qualitative research is "particularly oriented toward exploration, discovery, and inductive logic," which allows us to determine the emergence of meaningful categories or dimensions (Patton, 2015, p. 64), and to establish a knowledge base for the phenomenon studied (Karlsson, 2016, Patton, 2015). When a field of research is nascent or unexplored, qualitative research is helpful for identifying promising propositions, hypotheses, and theories, which can be tested with quantitative methods at a later stage (Barratt et al., 2011).

We selected the qualitative research method of interviewing experts (Bogner et al., 2009), which has been used extensively in industrial sociology, educational research, policy research, and political science

(Meuser and Nagel, 2009), but less so in the operations management literature. According to Bogner et al. (2009, p. 5), "expert interviews are, of course, not only a popular way of gathering information; they are also a totally legitimate method for some forms of research." Moreover, interviewing experts is an appropriate and complete method in research that aims to reconstruct explicit expert knowledge (Pfadenhauer, 2009). We also followed the general advice regarding the analysis of qualitative data in operations management (Meredith, 1998, Ketokivi and Choi, 2014).

3.1 Selection of experts

We searched for informants who possessed technical knowledge, procedural knowledge, and interpretive knowledge in the field of industrial drone applications (Bogner and Menz, 2009). These experts were required to have first-hand experience in applying drones in industrial settings because they would then be "in a position to actually put their own interpretations into practice" (Bogner et al., 2009, p. 7). Identifying experts using objective measures (such as years of experience or number of flight hours) was infeasible because of the unavailability of data. Therefore, we selected informants using the purposeful sampling strategy combined with intensity sampling, reputational sampling, and snowball sampling (Patton, 2015). First, we visited locations where drone experts gather, such as drone exhibitions, technical conferences, and drone seminars. Second, we searched the Internet for media articles, white papers, and commentaries written by, or mentioning, drone experts. Finally, we used word-of-mouth to access the network of drone experts whom we had already interviewed.

We focused the data collection procedure on drone vendors and drone service providers. Although we searched intensively for informants about cases of drone implementation in manufacturing, we could only identify a few companies that had run experiments with drones in that industry. Moreover, most of these companies were reluctant to share their experiences, which we speculated was for reasons of confidentiality, concerns about intellectual property rights, or the failure of experiments.

3.2 Data collection

The expert interviews were conducted during the European Drone Expo held in March 2017 and March 2018 in Brussels, Belgium; the UAV Expo in June 2017 in Brussels, Belgium; and the UAV Expo in April

2018 in Amsterdam, the Netherlands. Other interviews were carried out in Switzerland and Germany, and a few were conducted in video conferences (see Table 1). Almost all the expert interviews were conducted face-to-face, which was recommended by Christmann (2009). In total, we conducted 66 interviews with drone experts from 56 companies headquartered in 13 countries worldwide. We decided to stop conducting new interviews when we reached the saturation of information (Eisenhardt, 1989). The companies included drone manufacturers, drone service providers, drone insurance companies, regulatory bodies, training centers, software developers, and part suppliers. Typical in this industry, most of the companies were small- and medium-sized, which enabled us to communicate with C-level executives and the founders of many of the firms.

Table 1. Place and time of interviews

Place and time	**No. of interviews**
European Drone Expo 2017, Brussels, Belgium, 10–12 March 2017	19
UAV Expo 2017, Brussels, Belgium, 20–22 June 2017	10
European Drone Expo 2018, Brussels, Belgium, 9–11 March 2018	17
UAV Expo 2017, Amsterdam, the Netherlands, 11–12 April 2018	7
Zurich, Switzerland, 17 May 2017–4 September 2018	5
North Rhine-Westphalia, Germany, 22–23 May 2017	4
Online video conference, 12 May 2017–15 August 2018	4
Total	66

We conducted semi-structured interviews. We first designed an interview guide based on the guidelines of Bryman and Bell (2015). It was organized into four different topics: evaluation of drone applications; implementation of drone applications; results of drone applications; and lessons learned from experiments and implementation. We used the same version in the interviews conducted between March 2017 and March 2018. After conducting more than half of the interviews, we conducted a preliminary analysis and reduced the survey to questions that had not yet reached saturation in their responses. We used this second version in the interviews conducted after March 2018. Versions of both the early and the late interview guide are included in Appendix 2.

The experts' perceptions of the interviewer's technical, procedural, and interpretive knowledge could have affected the quality of the interviews (Bogner and Menz, 2009). Because we are experts in manufacturing, we qualified as an "interviewer as an expert from a different knowledge culture." However, we were laypersons regarding drones. During the initial interviews, we therefore assumed the role of a "knowledgeable layperson" (Froschauer and Lueger, 2009). We researched drone technologies, attended introductory courses for drone pilots, attended drone exhibitions and seminars, and acquired a set of drones. As the interviews progressed, we became accustomed to drone technology, terminology, and applications. After conducting about 25 interviews, we classified ourselves as "co-experts" (Bogner and Menz, 2009).

To increase the validity of our findings, we collected complementary data from other sources. For example, we analyzed 39 keynote presentations and 28 recorded keynote talks given at the first and second FAI International Drones Conference and Expo in Lausanne in Switzerland in 2017 and 2018, respectively. We also tape recorded 13 keynote addresses and panel discussions at the UAV Expo 2018 in Amsterdam. Another important source of data was obtained in our review of 474 pages of catalogs and manuals from over 35 different companies, which we collected from the exhibitions, seminars, and visits. We also reviewed 57 white papers and industrial reports amounting to 830 pages of text; we read more than 100 media articles; and we viewed online videos about drone technology and its applications.

3.3 Data analysis

We followed the six-step analytical approach to analyzing expert interviews, which was recommended by Meuser and Nagel (2009): 1) transcription, 2) paraphrasing, 3) coding, 4) thematic comparison, 5) sociological conceptualization, and 6) theoretical generalization. This approach is similar to thematic analyses aimed at identifying, analyzing, and reporting patterns (themes) within data with high flexibility, which allows researchers to interpret various aspects of the research topic (Braun and Clarke, 2006). Steps 1 through 4 involve objective processes, whereas Steps 5 and 6 rely on subjective interpretation and ingenuity. As usual in explorative qualitative research, this process was iterative (Eisenhardt, 1989)

First, we transcribed 47 of our interviews and took notes on 19 interviews, which resulted in more than 600 double-spaced pages of raw text. We were not able to tape record and transcribe 19 interviews mainly because of the noisy environment and in a very few cases, because no tape recording was allowed. For these exceptions, we took notes during and immediately after the interviews. All interview recordings and notes were stored in a research database. Second and third, we used the software package ATLAS.ti to paraphrase and code the text from the interviews by using the closest possible language to the data (Strauss and Corbin, 1990). In paraphrasing, the text was sequenced according to thematic units. The open coding resulted in a list of 409 codes, of which 142 codes described use cases that corresponded to the first part of the interview guide. In the fourth step, we performed thematic comparisons by classifying similar codes into 57 empirical themes.

In the fifth step, we started to extract new knowledge from the sorted and coded data. In sociological conceptualization, "the specific characteristics of the commonly shared knowledge of experts are condensed and categorizations formulated" (Meuser and Nagel, 2009, p. 36). We aggregated the empirical themes into 17 conceptual categories. The final step was to "arrange the categories according to their internal relations" (Meuser and Nagel, 2009, p. 36) seeking generalization by developing a typology of industrial drone applications that builds on the conceptual framework developed through the review of the literature. A typology is a "conceptually derived interrelated sets of ideal types" (Doty and Glick, 1994) that assist the theoretical progress of a field by breaking it down into subparts with distinct characteristics (Miller, 1996). After developing the typology, we drew on the rest of the data from the interviews to discuss both opportunities and challenges in drone applications.

4 FINDINGS

4.1 Industrial applications of drones

Table 2 shows our data reduction structure for the industrial applications of drones (e.g. Gioia et al., 2013, Ramus et al., 2017). The left column shows the empirical themes that describe the current applications of industrial drones, which directly emerged from the transcription, paraphrasing and coding of interview data. The middle column shows the conceptual categories that emerged from the thematic comparison of the empirical themes. We summarized empirical themes (i.e. drone applications) into generic concepts (i.e. areas of application) based on similarities through a process of abstraction (Flick, 2014, p. 404). For example, drone applications for gas detection and noise monitoring were summarized into the area of "hazard identification." The right column shows our theory-informed generalizations of activities that a drone can provide: see, sense, move, and transform. We derived the four aggregate dimensions by elaborating on the relations between concepts through further abstraction. For instance, we aggregated all the application areas of drones in relation to visual capabilities into "see".

Table 2. Data reduction structure for industrial applications of drones

Empirical themes	Conceptual categories	Aggregate dimensions
Visual inspection of equipment, such as flare stacks, silos, boilers, chimneys, pipelines, etc.	Visual inspection	See
Visual inspection of transportation infrastructure, such as roads, bridges, railroads, etc.		
Visual inspection of power lines, high-voltage electricity pylons, telecommunication masts, etc.		
Monitoring the safety of staff	Monitoring	
Monitoring human factors and ergonomics		
Regulatory compliance		
Security patrols		
Traffic management		
Aerial imaging	Photography and filming	
Filming		
Photography		
Media		
Thermal inspection of equipment, such as flare stacks, boilers, chimneys, pipelines, etc.	Thermal inspection	Sense
Thermal inspection of solar panels		
Thermal inspection of wind turbines		
Thermal inspection for search and rescue		
Thermal inspection for surveillance		
Gas detection	Hazard identification	
Noise monitoring		
Dry film thickness measurement	Non-destructive testing (NDT)	
Ultrasonic thickness measurement		
Corrosion detection (e.g., corrosion in conductors)		

Cycle counting	Inventory management	
Tracking		
Finding lost pallets and slots		
3D factory planning	3D mapping	
Process mapping		
Stock measurement in open-pit mining	Volume measurement	
Measuring containers and gaps between containers in the ship industry		
Land surveying	Remote sensing	
Topographic map		
Photogrammetry		
Terrain mapping		
LiDAR scanning		
Archeological research		
Multispectral imaging		
Hyperspectral imaging		
Computing vegetation	Calculating environmental-science indices	
Tree study in forestry		
Wildlife management		
Mapping crops	Precision agriculture	
Mapping fertilizers		
Mapping pesticides		
Last-mile logistics	Delivery	Move
Intra-logistics		
Transportation of medicines		
Transportation of blood samples		
Spraying for firefighting to support HSE	Manual spraying	
Spraying crops		
Order picking	Warehouse management	Transform
Order sorting		
Carrying tools and repair	Maintenance management	
Carrying spare parts and assembling		
3D printing spare parts and assemble		
Spotting drowning victims and providing rescue kits	Lifesaving and disaster management	
Spotting victims and delivering emergencies in volcanic events, hurricanes, flooding and major storms, and earthquakes		
Bringing emergency supplies and delivering medical kits, CPR, etc.		

"See" is the capability of collecting visual data; often in the forms of images and videos. In the manufacturing industry, examples are the visual inspection of equipment, such as gas flare, silos, boilers, drums, tanks, chimneys, and pipelines (both above and below ground). These are common tasks in many process industries (e.g., petrochemical industry, offshore and onshore oil platforms). Drones that "see" are also used to monitor the safety of staff, such as during maintenance operations where fixed cameras are not economically feasible. Some large plants apply drones to monitor security instead of closed-circuit television (CCTV) or human patrols. Drones are also tested in applications used to monitor of safety, ergonomics, and regulatory compliance.

"Sense" is the capability of collecting data and transforming it into the other forms of data or structured data (i.e., information) without performing additional physical operations. Some relevant examples in manufacturing include the following: the thermal inspection of equipment, machines, chimneys, and stacks; gas detection and noise monitoring to identify hazards in the oil, gas, and petrochemical industries; non-destructive tests such as measuring the thickness and detecting corrosion of equipment; cycle counting, tracking and trace, and finding lost pallets and slots for inventory management; 3D factory planning and process mapping for the optimization of factory layouts and material flows.

"Move" is the ability of a drone system to grasp and carry objects or perform physical operations (e.g., spraying). A typical example in manufacturing consists of intra-logistics operations, such as delivering light components, spare parts, or tools especially during maintenance operations. Drones can also be used to spray paint on the corrosion in equipment and buildings and to spray foam during fires.

"Transform" is the ability of a drone system to collect data and transform them into information while performing physical operations (e.g., carrying objects). It combines the capabilities of see, sense, and move. Current examples of "transform" in industry are scarce, but a few promising pilot studies are underway. For instance, a drone system with a camera can simultaneously inspect equipment and perform simple repair operations using mounted tools (e.g., patching, painting, and sealing). Drones can perform pick up operations in a warehouse. Both examples are technically complex and not economically feasible in the current state of the technology. For example, in e-commerce warehouse management, order picking and order sorting require advanced drones that grasp items and carry them reliably. This operation also requires multiple sensors (e.g., barcode-, data matrix-, or RFID readers) to manage inventory and update warehouse management systems in real time. An efficient operation would require a swarm of autonomous drones with the capability of recognizing obstacles and applying avoidance algorithms.

Building on the theory-informed classification of AMTs in Figure 1, we can now use the empirical findings to propose a typology of drone applications in manufacturing. It is illustrated in Figure 2. Seeing is a low analytical and low physical capability. Sensing involves a high analytical capability and low physical capability. Moving represents high physical capability and low analytical capability. Transforming requires high analytical and high physical capabilities. We use this typology to discuss the current state of drone applications in manufacturing, propose a research agenda, and propose implications for practitioners.

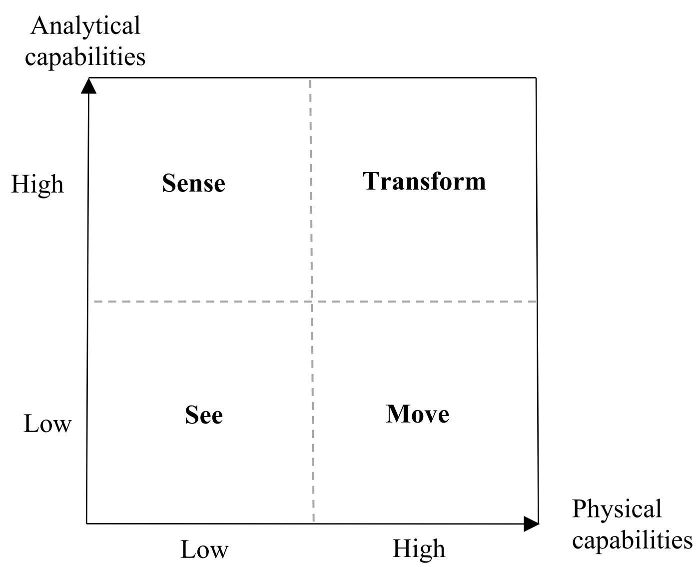

Figure 2. Typology of industrial drone applications

4.2 Potential benefits of drones

We asked all interviewees about the potential benefits of using drones in manufacturing. Although the real benefits are related to specific use cases and contexts, the data analysis showed that the potential benefits fell into five broad categories:

1. Cost savings
2. Task speed
3. Safety improvements
4. Efficient data collection
5. Public relations (PR) and marketing

First, drones can increase productivity and hence reduce the costs of manufacturing. In particular, in manufacturing plants in inspection-intensive process industries, drones can bring a significant cost saving. Inspections carried out by drones reduce the amount of labor-intensive work and eliminate the need for scaffolding. Regarding an extreme non-manufacturing example, one interviewee reported that in an inspection project on one of the biggest oil platforms in the North Sea, the introduction of drones reduced a 700 person-day inspection of 14 objects to 28 person-days. Furthermore, the inspection of flare exhausts required a shut down in which time was an extremely precious resource valued at USD 7 million per day. Another frequently reported example was the use of drones to count stocks in large warehouses. The cost savings in this application were derived from replacing human work, eliminating rework due to human errors, and improving order fill rates, thus increasing customer satisfaction and decreasing safety stock levels. Similar findings were reported by Hoffmann (2017), in which an estimated annual operating cost savings of USD 300,000 was derived in scanning 1,000,000 barcodes per year in a warehouse of 500,000 square feet.

A related potential benefit is the increased speed of performing tasks. Using drones for the inspection of hard-to-reach equipment and installations speed up the operations because of the shorter setup time and higher maneuverability compared to traditional processes involving scaffolding, ladders, and rope access. Shorter setup times and higher maneuverability can also increase the frequency of inspections, allowing for the faster detection of incidents such as gas leakages. Another example is the use of drones for the inventory management of bulk raw material, in which light detection and ranging (LiDAR) scanning with drones can increase the speed and efficiency of inventory counting compared with handheld scanners. Another example was provided by an interviewee who explained that drones can speed intra-logistics operations:

> *Imagine an assembly line in the automotive sector where parts are not working or are missing. The normal process is then that a human being is running or biking to get the part from the warehouse. This could take between 10 and 15 minutes in normal cases.*

With the drone, you could fly over infrastructure and by that, you could do it in 3 to 4 minutes. These are real numbers we measured in an automotive factory.

Safety improvement was the most frequently mentioned benefit of drones. According to the president of a global drone association and the CEO of a drone start-up, “Dull, dirty, and dangerous, those are the jobs that drones improve on.” Drones can reduce hazardous tasks in many operations. In particular, drones can replace manual human inspection of hard-to-reach equipment and hazardous areas. Moreover, drones can be a supportive tool in conducting health, safety, and environment (HSE) activities, such as sniffing for contamination and gas leaks or search and rescue operations during emergencies in large manufacturing plants. Drones can also film emergency drills to improve the responsiveness of HSE teams during evacuations.

A fourth benefit is that drones can increase data collection efficiency and assist acquisition of data that has not been collected before. For example, one interviewee explained, “A drone can get high quality, more consistent, and repeatable datasets, and that’s important because if you inspect the same structure many times, you see trends.” This capability is particularly promising in maintenance operations in process industries. Drone users can also increase the capability of data collection using multiple sensors. For example, drones can be used to provide digital 3D models of factory floors to support layout planning and redesign (Barth and Michaeli, 2018, Melcher et al., 2018). In general, the increased amount of accurate data collected by drones can be used to support managerial decision-making. An interviewee shared, “We use a drone to inspect and with all that data you can make decisions on what you do. Do I fix, do I inspect it again, or do I do nothing?” Drones that include complementary software packages for data analysis can provide decision makers with meaningful reports in easy-to-understand formats.

A fifth and more subtle benefit of drones is their use in PR stunts. Media outlets and newspapers have been quick to report on pilot studies of drones in factories. Consistent with the findings of previous works, press coverage and media attention is usual for companies that are early adopters of robots and other AMTs (Meredith, 1987). A few recent examples of press coverage for drones are reports of applications used in cycle counting in Mercedes warehouses (e.g., Banker, 2016), intra-logistic applications in ZF

Friedrichshafen (Dellinger, 2018), and inspections of hard-to-access equipment in a Ford factory (Hatt, 2018), the Pilsner Urquell brewery (Margaritoff, 2018), and Royal Dutch Shell's oil and gas facilities (Castellanos, 2018). Companies that use drones may be perceived as innovative and future-oriented, which can have positive effects on recruitment, public goodwill, and brand value.

4.3 Challenges for drone applications

We identified five generic categories of challenges and drawbacks related to the use of drones in manufacturing:

1. Technological challenges
2. Operational challenges
3. Organizational challenges
4. Legislative challenges
5. Societal and mental challenges

It is not surprising that major challenges to the industrial application of drones are related to technological limitations, the most frequently mentioned of which related to constraints in current battery technologies. The limited battery capacity implies that drone users must balance flight endurance with payload. As of 2019, commercially available industrial drones will have a flight time between 2 and 25 minutes. After the mission, the batteries must be replaced or recharged. Recharging often takes 45 minutes or longer. One interviewee observed, "If the battery technology gets better or we can find a way to make something lighter, then we have more range." Another solution is to eliminate the need for batteries by using tethered drones, which have a direct power supply and use wired data transmission. Tethered drones are a promising solution in applications that require high flight endurance and low hovering capabilities (e.g., inventory management). Other technological challenges include indoor navigation, reliable data transfer and communication, danger of explosion, safety mechanisms, and noise. For example, indoor drones may need a combination of positioning systems, object recognition and collision avoidance algorithms, SLAM algorithms, as well as a combination of multiple sensors, including an inertial measurement unit (IMU).

The second challenge relates to the operation of the drone. Most current drone applications are manual pilot operations that are flown within the line of sight. The alternatives are automatic or autonomous flights. All operation modes pose a range of challenges. Manual operations require alert and skilled pilots. In long operations, pilot fatigue can quickly become a source of human error. Automatic and autonomous flights require a continuously maintained navigation infrastructure. In both cases, drone flights need to be reliable and safe, especially around people. Redundant systems, such as parachutes, extra propulsion, and safety algorithms in autonomous flights, can make drones failsafe. Furthermore, the current drone technology is a poor fit in factory environments that are at risk for explosions or are sensitive to electrostatic discharge (ESD). The gates, doors, pillars, ventilation, fire protection installations, cranes, utility gateways, and large machines in factory environments are challenging to navigate even by experienced pilots.

The organizational challenges include the need for skilled drone pilots, who not only must be able to fly drones safely but also must have a deep understanding of the tasks and missions involved. Human issues such as workers' knowledge and technical experience, training, and involvement in planning are key determinants for the success of technology adoption (Chung, 1996, Walton, 1987, McCutcheon and Wood, 1989, Pagell et al., 2000). The data collected in the interviews revealed that human error is a greater problem than technological error in drone operations. For example, pilots need to be trained in the use of a drone as an inspection device as well as to collect and deliver useful data. However, the use of autonomous drones may overcome the challenge of training drone pilots and keeping them alert. According to one interviewee, "autonomous drones are safer than drones with human pilots." Other organizational challenges of adopting drones are related to developing a convincing business case that provides an acceptable return on investment. This is similar to the debate on measurable benefits of adopting AMTs in manufacturing industries (Swink and Nair, 2007, Udo and Ehie, 1996). On one hand, it is difficult to specify the potential savings that drones can provide in manufacturing. The costs, on the other hand, are visible to everyone. Therefore, risk averse managers often do not invest beyond trials. Yet, the results from trials can help managers to set expectations and to develop a risk profile for drone programs in their settings (Hottenstein and Dean Jr, 1992). Furthermore, organizations that plan to invest in drone operations face the "make-or-buy" dilemma. The data collected in the interviews indicated that this decision should depend on the availability of internal and external skills and the sensitivity of both the processes and the data. An additional challenge concerns dealing with the data that are collected. In many firms, drones are only a small part of their "digital transformation." Often, the use of drones must wait for the slow preparation involved in digitalization and data management. The co-founder of a leading drone service provider shared, "It's not that drones can't fly, it's the fact that digitization of these big industries is difficult and lengthy." This has also been pointed out in the AMT literature, which suggests a prevalence of stand-alone AMT applications and islands of automation with limited integration (Sun, 2000).

The fourth challenge concerns legislative rules and regulations. Although the number of drone applications is increasing, the regulations concerning their use is lagging. A main benefit of using drones in indoor applications is that the regulations are more relaxed compared with outdoor applications. There are large variations between countries in terms of drone legislation. The licenses (or the lack of them) define how, where, and what applications the manufacturer can use drones. As in many emergent technologies, it has been difficult to regulate drones, which is because of the rapid improvement of the technology, safety and security issues, the lack of clarity of who should draft the regulations, and the lack of knowledge about many real applications (Khanna, 2018). For instance, flying beyond the visual line of sight (BVLOS) is prohibited in many countries, which reduces the applications of drones as well as the areas of coverage in outdoor applications; however, some countries make exceptions for flying BVLOS.

Finally, there are societal and mental challenges related to the use of drone applications in manufacturing. For example, the common use of drones as a military weapon affects public opinion. Many members of the public have negative perceptions of drones as a new technology. People are also concerned about the safety of drone technologies, the intimidating appearance and noisiness of drones, and the invasion of personal data. In a case in Australia, drones were used to monitor staff behavior, but the practiced was stopped because it violated workers' privacy (Opray, 2016). In operations that use heavy drones or payloads, safety concerns are justified.

Interestingly, only two of our 66 interviewees mentioned price as a drawback. This finding was surprising. Only few years ago, price would have been a major challenge. The recent affordability of drone technologies is because of the mass production enabled by SZ DJI Technology and other manufacturers of drones in China (Khanna, 2018). However, when manufacturers need solutions that are tailored to sense, move, or transform capabilities, the price of drones, consulting, and infrastructure will increase significantly.

5 DISCUSSION

In our proposal of a research agenda for industrial applications of drones in manufacturing, we first summarize the current state of drones in manufacturing, and then we discuss the findings in light of the AMT literature. We also discuss the implications for practice.

5.1 Current state of drones in manufacturing

The following observation by a drone vendor serves to illustrate the current state of drones in manufacturing:

> *Everybody wants a flying Swiss-army knife. But drones aren't capable of doing everything. It's really about trying to give the customer real expectations and tailored capabilities; it's about trying to figure out their primary goals and what they are trying to accomplish with the data.*

In 2018, there were few established applications of drones in manufacturing. Many companies are now experimenting with the use of drones in different applications, and a few manufacturers have already begun to use drone applications in warehouse operations and inspection tasks. Nevertheless, there is a significant potential for further drone applications. As drone technology continues to develop during the next 5–10 years, we expect a range of new use cases to emerge across many manufacturing industries. Figure 3 provides a summary of current drone applications used in manufacturing industries.

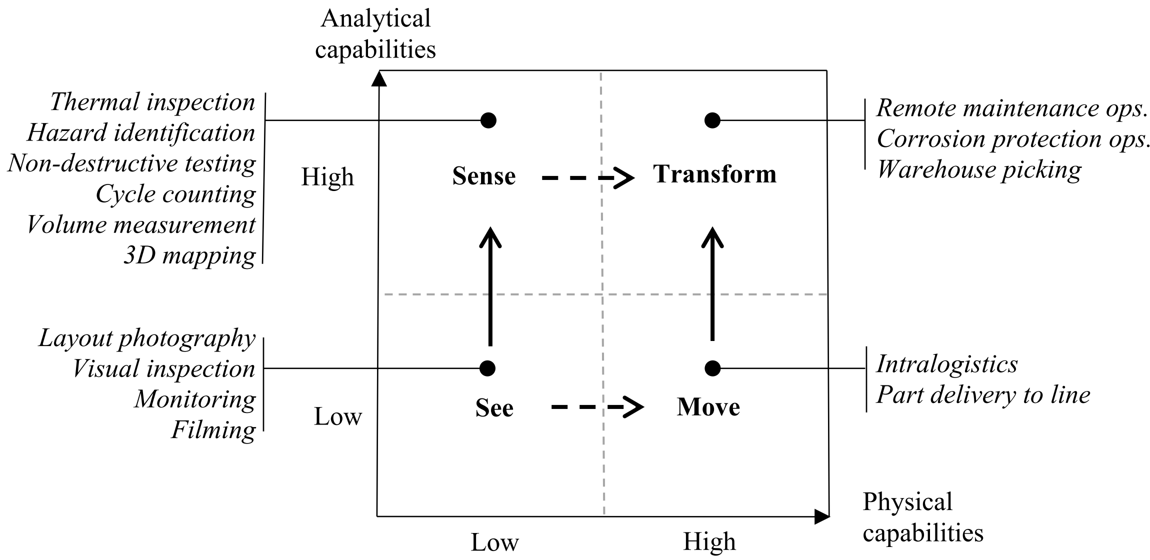

Figure 3. Current drone applications in manufacturing

The majority of the current applications of drones are the "see" and "sense" types. The first drone experiments by most manufacturers involve off-the-shelf commercial drones with high-definition cameras for photos and videos. Many manufacturers employ at least one drone enthusiast who brings his or her interest and expertise to producing aerial photos and videos of the facilities. These applications are inexpensive and simple, and they do not require specialized drone technology or consultation. Learning-by-doing with inexpensive drones helps accumulate knowledge and enables incremental innovation (Bourke and Roper, 2016, Sohal et al., 2006). For manufacturers with large facilities, tanks, hazardous areas, cranes, conveyors, or high machines that require regular inspections, the next stop is to consider whether drones could replace manual inspections. In many cases, drones are an economical alternative to traditional inspections. These "see" capabilities could be enhanced to "sense" capabilities by integrating advanced sensors and software. Standard video cameras could be replaced by thermal cameras to detect heat loss from machines and buildings. Gas-sniffing sensors could be used to detect gas leaks. Laser or ultrasound sensors could be used to conduct non-destructive testing in hard-to-reach areas. Barcode or RFID readers could be used to identify objects on high shelves. LiDAR scanners could be used in volume measurement and the indoor 3D mapping of factories, which could help in designing layouts and in factory redesign projects. There are examples of all these drone applications in current manufacturing practices.

It is harder to improve the physical capabilities of drones than it is to improve their analytical capabilities because of their physical limitations, especially their payload and battery capacity restrictions. In “move” or “transform” tasks, which require high physical capabilities, drones are typically inferior to tools, sensors, or cameras that are mounted to grounded infrastructure, AGVs, cranes, walls, or ceilings. “Move” operations, such as intra-logistics and part delivery applications, are rare, and their use is practical only in small, light, and urgent “emergency” deliveries. A non-manufacturing outdoor example is the delivery of blood samples from hospitals to test laboratories, which already is in daily operation for example in Lugano and Zurich in Switzerland (Müller, 2018). Indoor applications are more difficult to justify. Even in the case of missing parts on an assembly line (see quote in section 4.2); the better option is to remove the root cause of the error. “Transform” operations are rare not only in manufacturing but also in all industries. Some applications are in the experimental stage in the oil and gas industry and the construction and infrastructure industries. In manufacturing, remote maintenance operations and corrosion protection may be promising business cases in nuclear power plants, metal smelting plants, shipyards, petrochemical plants, and other large process industry plants. However, the risk of explosion remains a technical hurdle for the full adoption of drones in these contexts.

5.2 A research agenda

Our insights suggest that by 2025, drones will be applied in many manufacturing plants. This should provide a rich opportunity for empirical research in this area. In the support of an efficient development of a literature on drones in manufacturing, we call for three broad streams of research: 1) operations management and industrial engineering issues; 2) technology development and customization for manufacturing; 3) socio-cultural and behavioral issues.

We call for conducting both descriptive-oriented and solution-oriented research on the applications of drones in manufacturing industries (see, van Aken, 2005). Operations management scholars could extend the literature on the evaluation, implementation and measuring effects of adopting drones in manufacturing.

As a starting point in particular, scholars can build frameworks for supporting “make-or-buy” decision-making. Industrial engineering scholars could study specific-use cases and develop design guidelines for different applications. The typology presented in this paper could help focus attention on these areas on research. Because the majority of applications in manufacturing will continue to be of the “see” or “sense” types, we suggest focusing on “sense” as the most promising type of application. Because this field of research is in the early stage, we suggest that qualitative empirical methods should be used to advance the research on drones in manufacturing. Expert interviews, which were used in the present study, is a promising method for explorative research. Action research and design science research can support the development of solution-oriented theories and practical artifacts. Modeling and simulation can help explore and evaluate opportunities in virtual environments. As the number of cases in industry continues to increase, case research and survey research will allow for the exploration of the tangible benefits and challenges of the implementation of drones in manufacturing. The theoretical literature on AMT is a valuable starting point. For instance, reviewing AMT literature shows the potential of survey research to determine the industries that are more likely to benefit from each type of applications, as well as elaborating on the contingency factors (such as proximity to know-how, size of the companies, and organizational culture) that influence drone adoption in manufacturing companies.

There is also much work to be done in the engineering sciences and in product development regarding the application of drones in manufacturing. The further development of drone technology, such as the capability of carrying heavier loads, conducting long missions (e.g., drones with hydro engines), and improving the technology of BVLOS with advanced object recognition and object avoidance algorithms, will increase the number of future applications. Research could also help improve battery life, communication and control processes, safety systems, the availability of sensors, and other technological aspects. Wu et al. (2015) suggested that cloud-based design and manufacturing could increase the productivity of the design, prototype, and production of future drones, thus enabling faster reactions to market needs.

The most promising technological research in terms of manufacturing applications is the development of automatic drones. Replacing manual work by a piloted drone produces only marginal benefits. Replacing manual work by automatic drones is a much better business proposition. Automatic drones require complementary technologies, such as ground stations, multiple sensors for object recognition and avoidance, and algorithms that control flight. The next step after automatic flight is autonomous flight by artificially intelligent drones that make decisions in changing environments (Floreano and Wood, 2015). One interviewee from a leading provider of drone-based inspection stated, "We are long way away from autonomy, but we are close to automation." Autonomous micro aerial vehicles is another research area with promising potentials in manufacturing operations (Kumar and Michael, 2012). Furthermore, the "swarming drone" technology could offer unprecedented opportunities to scale drone applications for inventory management and material handling (Khosiawan et al., 2018a). However, this technology would require robust wireless communication, three-dimensional trajectory data, precise flight control, and scheduling task execution (Khosiawan and Nielsen, 2016, Khosiawan et al., 2018b), all of which is worthy of future research.

Drones differ from many other AMTs because they are negatively portrayed by media. In addition, drones exhibit animal-like behavior, they are noisy, and they can be hard to see until they are close to their target. People know that drones collect data and can potentially film them while they are working, which poses serious questions about personal data protection rights. In addition, drones and robotics in general evoke the fear that people will lose their jobs to machines (Stewart, 2015). In short, drones involve a trust problem that is more serious than that involving many other AMTs. To establish trust for drone applications in manufacturing, past studies on AMT advice managers to develop an innovation-supportive culture that supports experiments with new technologies (Khazanchi et al., 2007). Because drones are quite different from other "grounded" AMTs, socio-cultural and behavioral aspects of drone implementation represents a particularly promising research area. Such research on behavioral aspects could be based on ethnographic, field experiment, interview, or survey methodologies.

5.3 Implications for practice

Drones are a new form of AMT that will be applied in many manufacturing industries, especially in large, technology-intensive facilities in process industries. The overview of current use cases shown in Figure 4 could provide manufacturers with a perspective on what is possible today. An important point is that current drone applications are mainly “see” and “sense” types of applications.

Where should manufacturers start? As the arrows shown in Figure 4 indicate, manufacturers could start with simple experiments related to the “see” capabilities. From there they could move to “sense” applications, “move” applications, or both. However, the transition to “move” applications is currently the most challenging. By following this advice, manufacturers could start running experiments with off-the-shelf drone technologies. Such actions could foster learning and champion drone technology through familiarization and promotion (Dimnik and Johnston, 1993, Kolb, 1976). That would help in discerning opportunities and challenges, as well as justifying investment (Boyer, 1999, Kolb, 1976). As suggested in previous work on AMT, learning from the experiences of other manufacturing companies can help managers avoid common mistakes and assist them during the planning phase of a drone program (Sohal, 1996). Manufacturers that have gained experience in using drones in “sense” or “move” tasks could consider further integrating technology to make their drones capable of performing “transform” tasks. Evidence from the adoption of other AMTs imply that such integration needs financial and strategic justification, readiness for organizational change, investment in infrastructure, and support from top management (see, Small, 2007, Gouvea da Costa and Pinheiro de Lima, 2008, Dean Jr et al., 1992, Zammuto and O'Connor, 1992, Boyer et al., 1997, Percival and Cozzarin, 2009, Bessant, 1994).

6 CONCLUSION

In the present study, we explored the current and potential uses of drone technologies in manufacturing. We proposed a typology of drone applications, discussed the related benefits and challenges, and recommended a research agenda. The proposed typology separates four types of applications based on the combination of the physical and analytical capabilities of drones: “See” applications have a low analytical capability and a low physical capability. “Sense” applications have a high analytical capability and a low physical capability.

“Move” applications have a low analytical capability and a high physical capability. Finally, “transform” applications are characterized by a high analytical capability and a high physical capability.

We conclude that drones are on the verge of being adopted for use in many manufacturing industries. Particularly promising and cost-efficient applications are those that help manufacturers “see” and “sense” data in their factories. Examples are the inspection of hard-to-reach areas or in hazardous areas, the detection of gas leaks in large plants, and cycle counting in large warehouses. Applications that “move” or “transform” objects are scarcer, and they make sense only in special cases in very large manufacturing facilities. Our findings show that drones could have higher potential in process industries than in discrete manufacturing.

We present a research agenda that promotes research within three domains. First, operations management and industrial engineering scholars could develop descriptive and normative knowledge about drone applications in manufacturing. Expert interviews, simulation and modelling, action research, design science research, and survey research offer good opportunities to explore and explain the dynamics of using drones in manufacturing. Second, scholars from engineering sciences and product development should continue the development of drone technologies in order to improve the physical and analytical capabilities, improve design and drive down cost. The most promising current areas of technological development are concerned with the development of automatic drones, autonomous drones using artificial intelligence, micro aerial vehicles, and swarming technology. Third, socio-cultural and behavioral research perspectives on drone applications in manufacturing are needed in order to ensure technology acceptance. In short, drones offer rich opportunities for future research.

Despite the great amount of technological development during the past decade, there are still technological, organizational, and regulatory challenges to the implementation of drones. Drones will not revolutionize manufacturing alone, but they have the potential to radically improve the efficiency of certain tasks in manufacturing. In 2025, drones are likely to be a much more common sight in manufacturing facilities than they are today.

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APPENDIX 1: HIGH LEVEL ARCHITECTURE OF A DRONE SYSTEM

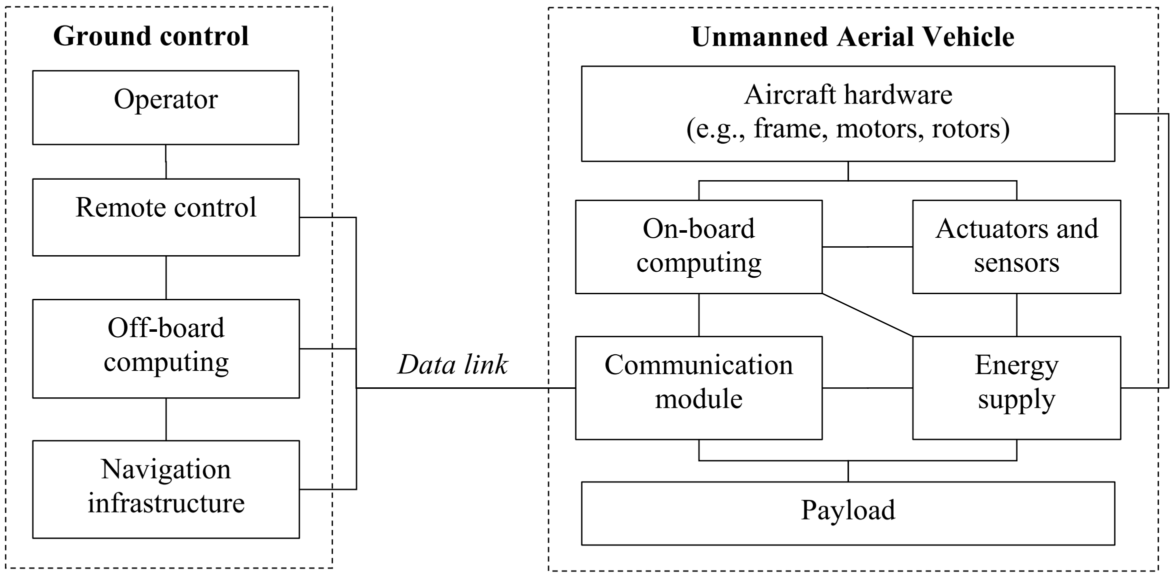

Figure A-1. High-level architecture of a drone system

APPENDIX 2: INTERVIEW GUIDES

Original interview guide (March 2017 to March 2018)

Part I The interviewee and the company

- Briefly introduce yourself, your company, your position, your experience, and your responsibilities.

Part II Applications of drones in your company

1) What applications does your company provide for its customers? Which industries? Indoor or outdoor?
2) What are the benefits for industries of using drone technology?
3) What challenges in using drone technology limit its wider use and application?
4) How do you measure the performance of drones for your customers? What performance indicators do you use?
5) What capabilities do your drones have?
6) What are the advantages of your drones and services compared with your competitors?

Implementation phase

1) How many flying hours have you recorded so far? How many pilot projects has your company implemented?
2) What were the main challenges during the implementation?
3) How does your company coordinate implementation processes with customers? Which business functions are involved? What is the involvement of customers in your projects?
4) Do you implement the project during normal working hours? Are the employees and workers present during the implementation? What are the employees' reactions?
5) How do you collect data from drone(s)? How do you analyze the data?
6) What safety measures are used during the implementation?
7) How does your company deal with the regulations and laws regarding implementation?
8) How do you deal with the characteristics of countries, governments, and organizations in the implementation?
9) If you do not mind sharing this information, in which companies and industries have you implemented your drone technology?

Service specifications

1) Do you provide standardized solutions or do you customize solutions? What is the ratio? What customization criteria do you consider?

2) Is your pricing regime based on customized products and missions or it is standardized?
3) What is the degree of autonomy in conducting drone projects? To what degree are they fully autonomous?
4) What are the payloads and speed?
5) Do you include checklists in the missions or manuals for your products? Do you provide training?

Implications

1) What are the main best practices for the application of drones in your company?
2) What are the lessons learned? To what degree is this knowledge transferable?
3) Did the drone application change the business process of your customer's company? How?
4) Can you describe the organizational structures?
5) How does drone technology impact employees, organizations, and societies?

Part III Future applications

1) Do you plan to expand the use of drone technology to a wider range of applications?
2) What other future applications do you envision for drone technology? What are the barriers?
3) Will drones be used in the manufacturing industry?
4) Will drones be used in indoor applications?

Part IV Open question

- Based on your experience in this area, what are the potential application of drones and in which industry will they be used the most?

Reduced interview guide (after March 2018)

Part I The interviewee and the company

- Please briefly introduce yourself, your company, your experience, your position, and your responsibilities.

Part II Current applications of drones

1) What are the current top five applications of drone technology? In which industries?
2) What are the top three benefits of using drone technology for industries? Please provide an example.
3) What are the top three challenges in using drone technology? Please provide an example.
4) How do you collect the data from drone(s)? How do you analyze these data?

Part III Future applications in manufacturing operations

1) What are the top five applications that you envision for the use of drone technology in manufacturing operations within five years?
2) What will be the top three main reasons for using drones instead of existing technologies?
3) What will be the top three challenges?
4) Will drones be used in indoor applications?
   a. What applications will be used in warehouse operations?
   b. What applications will be used for inspections in confined spaces?

Part IV Open questions

- What applications do you predict for drone technology if there are no limits to technological, social, and regulations?
- Open discussion: Typology of the industrial applications of drones