

DRONE BASED INSPECTION SERVICES IN INDUSTRIAL CONTEXTS: RISK ASSESSMENT AND MARKET OPPORTUNITIES

Giuseppe Aiello^(a), Fabrizio Hopps^(b), Mario Venticinqu^(c), Domenico Santisi^(d)

^{(a),(b)} Università di Palermo – Dipartimento Di Innovazione Industriale e Digitale - DIID

^(c) Institute for Agriculture and Forestry Systems in the Mediterranean of the National Research Council of Italy (CNR-ISAFOM).

^(d) Leonardo Engineering and Research s.r.l.

^(a)giuseppe.aiello03@unipa.it, ^(b)fabrizio.hopps@unipa.it, ^(c)ventimario@inwind.it, ^(d)d.santisi@leonardoengineering.net

ABSTRACT

Unmanned Aerial Vehicles (UAVs) is an emerging technology with the potential of introducing disruptive innovation in a large number of industrial and civil applications. In particular, many studies have highlighted the achievable advantages for “three Ds” (i.e., dull, dirty, or dangerous) missions, which actually represent their natural market niche. A huge potential market in such sense is constituted by high-risk industrial installations including Oil&Gas, chemical, power generation, shipbuilding, etc. where significant improvements can be achieved in terms of safety and ergonomics. This paper proposes a comparison between traditional inspection approaches and innovative drone-based services in high risk industrial contexts, with the objective of obtaining a clear picture of the safety risks involved.

EXTENDED ABSTRACT

Unmanned Aerial Vehicles (UAVs), commonly known as drones, is a new technology that can significantly outperform existing solutions in many commercial and industrial contexts such as surveillance, firefighting, inspection of industrial plants as well as agriculture, logistics, disaster recovery, etc.. In particular, UAVs are often preferred for “three Ds” (i.e., dull, dirty, or dangerous) missions, which actually represent their natural market niche. As a consequence of the important potential benefits in these business areas, a significant global market growth is inevitably expected in the near future, involving Europe, the US and China in a role of market leaders. A recent economic analysis of the drones value chain reported in the European Drones Outlook Study by SESAR (2016) reveals a potential European market exceeding 10 billion euros annually by 2035 and further growing past 15 billion euros annually by 2050. In particular, value added services (“Drones-As-A-Service”) are expected to represent the largest market opportunity, since the high number of typologies of UAVs and the recent advances in sensing and monitoring technologies, make the landscape of possible applications extremely ample and variegated. Referring to the industrial context, UAVs can efficiently perform

various tasks (e.g. inspections, monitoring, surveillance, etc.), drastically lowering the exposure of human operators to safety risks and health threats. A huge potential market in such sense is constituted by high-risk industrial installations including Oil&Gas, chemical plants, power generation, shipbuilding, etc. where significant improvements can be achieved in terms of safety and ergonomics.

Coherently with this objective, this paper proposes a comparison between traditional inspection approaches and innovative drone-based services in high risk industrial contexts, with a specific focus on the issues related to safety. In fact, industrial plant structures and equipment are constantly monitored through frequent periodic inspections within appropriate maintenance plans, because a failure can be an extremely dangerous event with catastrophic hazardous consequences. Nevertheless, several major industrial accidents occurred in the past, such as the ConocoPhillips, UK in 2001 and, more recently, the Caribbean Petroleum terminal in Bayamon, Puerto Rico in 2009 and the Chevron, US in 2012. A detailed analysis of recent accidents occurred in EU and OECD countries, has been recently issued by the Joint Research Centre of the European Commission (Wood et al, 2013). The report takes into account more than 400 accidents and reports material degradation as a frequent cause of failure, attributing to poor maintenance the main responsibilities. To avoid failures, the risks related to material degradation such as corrosion in metallic structures, are strictly monitored. Industrial plants, hence, normally require frequent inspections, which are generally carried out by external service providers. Although safety is the most important element decision makers take into account when selecting a service provider in critical industrial contexts, in some cases, it is not easy to have a clear perception of the risks, particularly when a new technology is employed. In this paper a detailed risk assessment approach is proposed referred to traditional (scaffolding and rope access) and drone based inspection services. Traditional inspection methods are a well-known cause of hazards, mainly related to the working at height condition. The risk associated to these operations, are generally considered

very high due to the relatively high probability of occurrence and to the severity of their consequences severe consequences like fatalities, injuries or illnesses. Determining the risk profile of an inspection is more complex when dealing with drone-based operations, since this is a new technology and the regulatory system, particularly in the EU, is still under development and frequently updated. In addition EU regulation concerning the safety of flying UAVs is extremely fragmented, since it relies on national regulatory systems which do not benefit from mutual recognition. This clearly constitutes a strong limitation from a market point of view since it prevents operators to perform EU-wide activities. In the following, the risks related to drone operations will be discussed with reference to the Italian regulation, which follows the same regulatory principles of many other countries in EU, although some slight differences may apply. According to the regulation, the general risk profile of a drone system is related to few main hazards, namely: midair collisions with other aircrafts, and ground impact with people or structures. The most frequent causes of hazard are failures, human errors and environmental conditions. In the following paragraph such elements are discussed considering the risk assessment procedures prescribed by the regulations.

System reliability and criticality of operations

The reliability UAVS results from their technical features, and requires a preliminary distinction between Remotely Piloted Aircraft Systems (RPAS), and unmanned autonomous systems (UAS). The term "drone", which stands for Dynamic Remotely Operated Navigation Equipment and is commonly used to broadly address RPAS. According to the regulations, a risk score (C_{RPA}) is assigned to the type (manual or automatic) of flight control. The risk profile of RPAS is generally considered less critical compared to UAS, thus risk contribution of 0.1 is assigned in case of manual operations and 0.5 in case of automatic operations. The risk contribution of drones, falling in the class of RPAS, is thus equal to 0.1.

The other preliminary element of risk assessment is related to the characteristics of the operations performed by means of the drone. Safety regulations, in fact, typically distinguish between critical/non-critical operations and offensive/inoffensive drones. The critical nature of operations depends on their location: those operations conducted in areas where a midair collision is impossible and an impact on the ground cannot cause fatal injuries to people or severe damage to the infrastructures are classified as "non critical". Non-critical operation hence do not involve, even in the event of system failures and malfunctions, overflights of urban areas and infrastructures, restricted areas, transport systems and industrial plants. Non critical activities, in addition, must be performed within "V70" air volumes, at an adequate safety distance from congested areas, in daylight conditions, and outside airfield traffic zones (ATZ). Such activities must be conducted in visual line of sight (VLOS) and at a minimum distance of 8 km from

the perimeter of an airport and from the paths of approach/take-off. The difference between critical and non-critical operations is important since they undergo a different authorization process. For non-critical operations the assessment of operational risks is demanded to the operator, who must simply submit a declaration of compliance to civil aviation authority (ENAC in Italy). Critical operations, on the contrary, require a specific authorization from the aviation authority, which is granted only after satisfactory assessment of the related risks.

A further distinction must be made between offensive and non-offensive drones. Such classification is related to the weight of the UAV and to other technical features such as: maximum wing surface, maximum wing loading, etc. ENAC regulation applies to vehicles with a total weight less than 150 kg, and classifies them in Very Light (300 g < MTOW < 4kg), Light (4 kg < MTOW < 25kg) kg, Heavy (MTOW > 25kg). Critical operations with UAVs under 25 kg over urban areas have been recently allowed, provided specific safety conditions are met (ENAC, 2016), however flying over groups of people remains prohibited in any case. On the contrary, operations with RPAS whose maximum take-off mass is less than or equal to 2 kg are always considered non-critical, provided that the RPAS design ensures its inoffensive nature, as assessed by ENAC. Recently a new regulatory framework has been issued for RPAS with MTOW less than 300g (mini drones), which are considered intrinsically inoffensive. These systems can operate freely in urban or industrial contexts, provided they do not overfly crowded areas.

According to the regulations, hence, flying a RPAS in an industrial plant must be considered critical operation, unless an intrinsically inoffensive drone is employed.

Ground impact

Ground impact (g.i.) risk refers to the possibility of a drone crashing on humans or structures on the ground. The probability of fatalities in such case is closely related to probability of impacting persons, which, in turn, depends upon the population density in the area of operations. In particular, in non-populated areas the contribution to risk related to human impact can be considered null, while in populated areas, the probability of impacting people is calculated by the following equation:

$$E(fatalities) = N_{exp} P(fatality|exposure) \quad (1)$$

Where N_{exp} is the number of people exposed to the crash event, which assuming a uniform population density, can be calculated as the product of the expected crash area (A_{exp}) by the population density (ρ).

$$N_{exp} = A_{exp} \cdot \rho \quad (2)$$

For the determination A_{exp} the regulations refer to 3 zones: the area of operations, the buffer area, and the adjacent area. The area of operations is the area directly

interested by the flight plan, the buffer area is a safety distance around the area of operations, and the adjacent area is the area which is not involved in the RPAS crash event, unless in case of uncontrolled flight. The determination of the safety (buffer) area is a topic frequently addressed in the literature, and several theoretical and empirical models have been proposed by researchers. The theoretical models generally applied in the industrial practice, are based on different assumptions: steep descent, uncontrolled glide and parabolic fall. In the steep geometric model (Weibel and Hansman, 2003, Clothier and Walker, 2006; Dalamagkidis et al 2008), the aircraft instantly loses its lift (e.g. due to a failure in the wings or in the propulsion system) and the crash area can thus be approximated by the frontal area of the aircraft augmented by a small buffer to account for the width of an average human person (approx. 0,25m, see for example Waggoner, 2010). The Uncontrolled gliding model (Lum and Waggoner, 2011) assumes a total loss of power on a fixed wing aircraft, meaning loss of thrust and control. Since the airframe is intact, the aircraft starts gliding at some angle γ , typically dependent upon the lift to drag ratio of the air vehicle. The impact area thus consists of a rectangle as wide as the wing span of the vehicle ($W_{aircraft}$) and as long as the descent from the top of a theoretical standing person's head to the point of impact. Finally, a third theoretical model is obtained considering a parabolic fall trajectory from the apogee with an initial horizontal velocity V_{0x} . In such case, the UAV will maintain its initial velocity until the ground crash (neglecting the air friction). The radius of the area interested by the fall event can thus be calculated according to the formulas reported in the following table.

Model	Radius Formula
Free fall	$A_{exp}^{steep} = R_{UAV} + R_{human}$
Uncontrolled glide	$A_{exp}^{glide} = (W_{UAV} + 2R_{human}) \left[L_{UAV} + 2R_{human} + \frac{H_{person}}{\tan(\gamma)} \right]$
parabolic	$A_{exp}^{parabolic} = V_{0x} \sqrt{\frac{2h}{g}}$

Table 6 – theoretical ground impact models

ENAC (2015) regulations for critical operations prescribe the use of flight termination system designed to allow the pilot to completely shut down the RPAS power system in order to minimize the risk of uncontrolled flight. For RPAS, hence, the buffer area can be calculated according to following formula, based on a parabolic fall model augmented by the time required for the pilot to activate the flight termination system (3s):

$$r = V_{0x} \sqrt{\frac{2h}{g}} + V_{0x} T \quad (3)$$

For example if we refer to a commercial mini drone such as the DJI Spark, which is one of the smallest system currently available on the market, the following

parameters are set: V_{0x} =max horizontal velocity (including maximum wind speed)=20 m/s; h =50 m; R_{UAV} =0.2 m, R_{human} =0.3m, $\gamma = 30^\circ$ (for a quadcopter) and Length (L_{UAV})= 0.143m. The resulting radius of the buffer area is approx. 125m. Considering also the operations area, the total potential crash area may easily extend for a radius of approx. 200m from the center of operations. In order to evaluate the number of people exposed to the ground impact risk, the density of population in this area must be estimated. This is generally done referring to institutional/statistical data of the territory involved. In case of nonhomogeneous population density areas, the area is subdivided in homogenous circular sectors and the weighted sum is calculated. Finally, the degree of protection provided by existing structures (e.g. buildings) in the area overflown is taken into account by means of a shelter factor ranging from 0,1 (industrial areas) to 1 (no obstacles.). In the case the drone is operated into an industrial area, and no houses or offices are present in a range of 120m from the area of operations. The corresponding ground risk can therefore be considered null. In addition, as a prevention measure the safety area can be fenced and interdicted to workers, so that no human operators (except the pilot) will be present in the area.

mid-air collision risk

The second critical hazard of UAV operation is related to midair collisions, which refers to the case of an Unmanned Aerial System (UAS) facing a Manned Aircraft (MA) in a potential collision trajectory. Quantitative risk assessment models to evaluate likelihood of a mid-air collision event based on the gas particle model are dated back in the 70's although more recent formulations can be found in the literature (Lum and Waggoner, 2011). Applying this model for UAV risk analysis in practice is considerably complicated, and rarely required in practice, because in operations performed within V70 airspaces, the possibility of mid-air collisions is negligible. This is generally the situation when the drone is employed to inspect the surface of a structure in an industrial plant, unless in case of inspecting tall towers or chimneys. To ensure operations within V70 airspaces, a retention cable may be employed in order not to exceed the maximum altitude. In such situations, the midair collision risk can be actually considered negligible.

Human errors and environmental conditions

Finally an additional source of risk can be represented by human factors and environmental conditions. In order to control such risk factors, the regulations prescribes that pilots attend a specific training in order to get qualified for operations. According to the risks related to environmental conditions, it will be part of the risk assessment process to select the dates of inspection taking into account the wind speed and the external temperature. The operations will thus be scheduled in dates when environmental conditions are compatible with the limits prescribed by the RPAS manufacturer, and adequate for operating in safety.

Level of acceptable risk

Once the hazards have been analyzed, and the related probabilities of occurrence have been determined, the risk assessment procedure for RPAS prescribes a final step based on Target Safety Standard (TLS) approach, well established in the civil aviation. The methodology consists in comparing the risk evaluated for a specific mission with a reference maximum acceptable value defined as TLS, generally referred to the likelihood of the worst possible outcome (fatality). The metric used to measure the TLS is fatalities per flight hour (FH), which is coherent statistics already in use by the Authorities. For small RPAs the Italian regulation considers an acceptable risk of 10^{-6} per FH referred to the ground impact, and an acceptable risk of 10^{-6} per FH. According to this method, the mission risk, is calculated as the event probability multiplied by its impact. In the case of ground impact, the mission risk is the multiplication of the RPAS falling in the expected crash area, multiplied by the number of people present in the area:

$$R_c = P_c N_{exp} \quad (4)$$

The Safety Objective (SO), associated to the acceptable mission risk is thus calculated as:

$$SO = \frac{E_c}{P_{GI}} C_{SAPR}, \text{ for the case of Ground Impact} \quad (5)$$

$$SO = \frac{E_c}{P_{MAC}} C_{SAPR}, \text{ for the Midair Collision} \quad (6)$$

Where E_c is the expected casualty measured in number of victims per flight hours (10^{-6} acceptable risk), and C_{sapr} is equal to 0.1 and 0.5 for manual and automated operations respectively.

The Safety Objective (SO) must finally be compared to the acceptable probability of a top (catastrophic) event (PTE), which is considered equal to 1 unless evaluated empirically by means of a statistical analysis, and, if the following condition is not verified specific mitigation measures must be enforced (e.g. parachute, retention cable, etc.)

$$SO > PTE \quad (7)$$

Clearly, as stated before, the employment of mini-drone with a MTOW below 300g and all the features that make it inoffensive in a V70 airspace, both the probabilities related to ground impact and the midair collision are negligible, as discussed before, hence condition (7) is always satisfied and the corresponding risk can be considered null.

Explosion risk

Finally, when operating in industrial areas, particular attention must be paid to the issues related to explosion risk. It is hence mandatory that the drone is compliant with the Atex regulations, which ensures it does not constitute into a potential source of ignition in presence

of flammable gases. This is actually a substantial limitation since the RPAS currently available on the market generally are not ATEX compliant, except for some rare exceptions.

Results and Discussion

The objective of the study is to investigate the possibility of actually performing drone based inspections in high-risk industrial plants. This inspection system, in fact, can lead to a significant risk reduction in for the inspection workers, and a cost effective alternative compared to traditional inspection techniques. In order to meet such objectives, a first issue that must be investigated concerns the employment of an intrinsic inoffensive drone with MTOW less than 300g. which can easily be found in the market. The employment of such system drastically simplifies the risk assessment process, thus speeding up the authorization process from the Civil Aviation Authority (ENAC in Italy). Concerning the ground impact risk, it depends on the location where the inspection activities are carried out, and, specifically, on the density of population in the operations and buffer areas. Such risk is generally low, for industrial inspection activities, since the access to the operation area can be restricted, and the population density in the safety range is generally low. In particular, this risk can be realistically null if the plant is located in an isolated industrial area. Finally, the midair collision risk, is related to the presence of a manned aircraft in a potential collision trajectory with the drone. If the inspection activities are carried out by means of an inoffensive drone, this risk can be neglected, while in other cases the employment of a retention cable ensures operations are carried out in the established airspace volume. The last element to consider is the explosion risk, which requires the drone to be compliant with the Atex regulation. This condition, in fact, can hardly be met by an inoffensive drone. Some systems are actually present on the market, but their costs and operating features frequently make their operations impossible or non convenient. The conclusion, hence, is that the risks related to a drone based inspection can actually be negligible compared to traditional approaches, although the Atex regulation drastically limits the areas of operations for commercial drones. The employment of an Atex compliant inoffensive drone could however solve the problem.

Another important element to take into account is related to the capability of a drone inspection system of obtaining reliable information about the condition of the structures inspected, and the comparability of the results obtained by the different inspection methods. Traditional inspection method involve a team of skilled operators that examines the structure from a scaffold, generally performing a preliminary visual inspection of the surface. Subsequently, more advanced tools such as Phased Array Ultrasonic Technique or Low Frequency Electromagnetic Technique (LFET), can be applied if required. Information gathered from a visual inspection (which still is probably the most important of all non-destructive tests) may hence give a preliminary

indication of the condition of the structure and allow the formulation of a subsequent more detailed inspection program.

An inspection carried out by drone system, instead, is capable of providing a digital image of the structure inspected, but no additional information can be determined for example about the wall thickness. The digital image however can be multi-spectral thus allowing to analyze the heat distribution on the surface, or, for example, the presence of leaks. The digital information obtained by a drone inspection, in addition, can easily be archived for further reference, and it can post-processed into ortho-photos and digital 3D models with textured surfaces. Such information however can be effectively exploited within decision making processes related to the management of the structures.

The drone based inspection, hence, does not provide the same results, of traditional inspection techniques, and the quality of the information obtained is thus comparable only to a limited extent. In particular,, it must be highlighted that the accuracy and the quality of information obtained by a drone inspection is largely dependent upon flight-path and the features (e.g. resolution) of the camera employed. The flight-plan in fact should be designed with the aim of keeping the drone as close as possible to the structure, provided all the safety prescriptions are respected. For such reason the flight path must always be discussed by the service provider and the facilities manager. The imagery obtained by a drone based inspection can be finally post-processed in a typical photogrammetric workflow including setting ground control points, point cloud and digital surface model generation, and image ortho-rectification and mosaicking. An example of the results obtainable by such approach is given in the following figure 1, which has been obtained by post-processing the data gathered in an experimental inspection on the storage tanks of an abandoned industrial site. The system employed is a commercial DJI Spark mini drone, equipped with a weight reduction kit to achieve an extremely low (300g) maximum takeoff weight (MTOW), which makes it inoffensive. This drone comes equipped with a camera featuring a wide-angle lens with 25mm equivalent focal length allowing for stabilized video at 1080p/30 frames per second, and 12MP still images. Finally, The Spark mini drone has a Maximum Flight Time of approx. 16 minutes, a GPS satellite positioning system and is capable of reaching a maximum speed of 14 m/s. Another significant limitation of this system is represented by the environmental conditions, since the operating temperature range of 0-40°C and the maximum wind speed must not exceed 10 m/s. The minimal dimensions of this system also allow it to fly in small environments (e.g. into a tank or inside an indoor area) which would definitely be challenging task for bigger drones with less control sensitivity.



Figure 1 - 3D model of the site inspected

In order to highlight the presence of critical situations, for example related to corrosion, advanced post-processing methodologies can be employed. The topic of corrosion detection from images, in fact, has been recently investigated by several researchers and different image processing techniques have been proposed mainly based on Texture analysis and filtering, edge detection, image segmentation, etc.

Conclusions

Drones is an emerging technology with the potential of introducing disruptive innovation in a large number of industrial and civil applications. This paper in particular focuses on the safety issues related to drone based inspection services in industrial plants. For such purpose, the safety risks related to the traditional approaches and the drone based inspection have been compared. The results show that the new technology has the potential to drastically reduce the safety risks, but the achievement of such objective, significantly depends upon the specific features of the site inspected, and upon the technical features of the drone employed. In particular the employment of an inoffensive drone may significantly simplify the authorization process, thus speeding up the operations. The drawback is that the limited operating range of such systems may hamper the inspections due, for example, to the environmental conditions. In addition the video capturing devices which typically equip such systems are quite limited, due to the necessity of keeping the weight low. The most critical issue, however, concerns the compliance with the Atex regulations for explosion risks. In a critical industrial context such as oil and gas, for example, the drone could in fact ignite an explosion if it is not Atex compliant. Considering that the commercial offer of Atex compliant drones is very limited and expensive, this is probably the most significant element to take into consideration.

Another important issue is related to the quality of the information acquired by means of the drone based inspection service, which depends upon the capabilities of the sensing devices installed. The devices currently installed on commercial systems nowadays may easily allow for the generation of detailed 3d textured models, which can be stored and analyzed anytime. However, the identification of incipient failures or critical situations which are still in at an experimental stage, requires high quality images to provide precise and reliable results, and current commercial devices can be inadequate for such purposes. Generally speaking, the state of the art of commercial systems nowadays still lacks of adequate

software and hardware features to allow effective decision support.

Finally, additional problems that nowadays hamper a substantial market spread of drone based inspection services is related to the regulatory system, which, particularly in the EU, mainly relies on national regulations which do not benefit from mutual recognition.

Nevertheless drone technology is undergoing significant improvements, and we may expect in the near future that new aerial vehicles and sensing devices will benefit of enhanced capabilities to better support human operators in decision making. Current research trends are also focused on autonomous decision making and cooperative control strategies. Such features may turn common drones into highly efficient cyber-physical system (CPS) capable of operating autonomously or in swarms in dangerous situations (search, rescue, surveillance, fire prevention, anti-terrorism, etc.). This will also allow to raising the safety standards of many industrial operations.

Concerning the monitoring devices, the possibility of prototyping new advanced sensor systems would eventually lead to the possibilities of combining data sets, from different sources in a unified representation, exploiting the potential of modern data fusion methodologies. In year 2017, for example, the deployment of the world's first UT (Ultrasonic Thickness Testing) integrated UAV system has been announced (see for example <http://www.texodroneservices.co.uk/>) although no experimental evidences have been provided. The value of archiving the information obtained, however, should also be considered in terms of evidences to provide to third parties and local authorities when necessary.

In conclusion, the study proposed demonstrated that the drone technology can actually be the most economic and safe solution for monitoring industrial plants. However, there are still important shortcomings that limit the spread of such technologies and the market opportunities particularly in high-risk industrial contexts.

AUTHORS BIOGRAPHY

Prof. Giuseppe Aiello is an associate professor at the Department of Industrial and Digital Innovation of the University of Palermo in Italy. He is expert of Logistics and supply chain management and has a significant background in industrial engineering, including layout design, plant management and logistics in several industrial contexts including naval, chemical, power generation and Oil&Gas. The most relevant research topics concern the solution of complex optimization problems involving uncertain information by means of heuristic and meta-heuristic approaches. Recently, the research interests are mainly focused the development of decision support systems (DSS) and control rooms based on multisensor data fusion for industrial applications and on Cyber-Physical Systems supporting human operators in difficult or dangerous tasks. He has also been responsible of research projects granted by national and

international institutions. In cooperation with enterprises for the development of prototypal devices for industrial applications.

Dr. Fabrizio Hopps is a PhD in aeronautical engineering and an expert professional in the field of Occupational Health, Safety and Ergonomics. He is a consultant for the Italian National Institute for Insurance against Accidents at Work, with a specific interest towards research activities and new technology for safeguarding workers against physical injuries and occupational diseases. He has also a significant experience on industrial risk assessment in high risk industrial contexts. He has also a researchers and professor of industrial safety at the Department of Industrial and Digital Innovation of the University of Palermo in Italy. His research topics are mainly focused on risk assessment and evaluation as well as multi criteria decision making methods.

Dr. Mario Venticinque is an electronic engineer with a consolidated experience in the development of electronic systems and devices based on innovative technologies. He is a consultant for many national and international enterprises and a researcher Institute for Agriculture and Forestry Systems in the Mediterranean of the National Research Council of Italy (CNR-ISAFO). He is expert in the development of embedded industrial systems involving sensors and monitoring devices. Recently he has also cooperated with research institutions for the development of smart technologies and wireless sensor networks (WSN) for industrial applications. He has also been a team leader for several research projects granted by national and international institutions.

Dr. Domenico Santisi is a PhD in Aeronautics and Aerospace engineering with a substantial background of high risk industrial contexts, occupational safety, and plant management. He is also a former Navy officer, and a still active airline pilot and instructor with more than 40 years' experience in the civil and military aviation. He has also gained relevant skills in the development of manned and unmanned aerial vehicles by participating the development and test stages of prototypes of fixed and rotary wing vehicles. In his career he has cooperated with important national and international companies and research institutions including the Massachusetts Institute of Technology, and several Universities all over the world. More recently, his professional activity has focused on the field of Remote Piloted Aircrafts (RPAs), where he is currently operating as a pilot and instructor. He is also committed in the development of innovative services and technologies for the drone industry in cooperation with several international companies and institutions.

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