The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2049-6427.htm

Received 18 May 2022
Revised 23 August 2022
Accepted 23 August 2022

Unmanned aerial vehicles in the construction industry - Towards a protocol for safe preparation and flight of drones

Mariusz Szóstak
Department of Building Engineering, Faculty of Civil Engineering, Wroclaw University of Science and Technology, Wroclaw, Poland
Tomasz Nowobilski
Department of Materials Engineering and Construction Processes, Faculty of Civil Engineering, Wroclaw University of Science and Technology, Wroclaw, Poland
Abdul-Majeed Mahamadu
The Bartlett School of Sustainable Construction, University College London, London, UK, and
David Caparrós Pérez
Department of Sustainable Construction and Architectural Heritage, Asociación Empresarial de Investigación Centro Tecnológico del Mármol, Piedra y Materiales, Cehegin, Spain

Abstract

Purpose – Unmanned aerial vehicles (UAV), colloquially called drones, are widely applied in many sectors of the economy, including the construction industry. They are used for building inspections, damage assessment, land measurements, safety inspections, monitoring the progress of works, and others.

Design/methodology/approach – The study notes that UAV pose new, and not yet present, risks in the construction industry. New threats arise, among others, from the development of new technologies, as well as from the continuous automation and robotization of the construction industry. Education regarding the safe use of UAV and the proper use of drones has a chance to improve the safety of work when using these devices.

Findings – The procedure (protocol) was developed for the correct and safe preparation and planning of an unmanned aerial vehicle flight during construction operations.

Originality/value – Based on the analysis of available sources, no such complete procedure has yet been developed for the correct, i.e. compliant with applicable legal regulations and occupational health and safety

The article is the result of the implementation by the authors of the research project Co-Funded by the Erasmus+ Programme of the European Union Reference: 2020-1-UK01-KA202-079176 "Virtual reality immersive safety training environment for robotized and automated construction sites". The participation of the following organizations in data collection is acknowledged: University of the West of England (UWE) Bristol, (United Kingdom); CTM - Centro Tecnologico del Marmol Piedra y Materiales (Spain); Bildungszentren des Baugewerbes e.V. (Germany); and Wrocław University of Science and Technology (Poland).

International Journal of Intelligent Unmanned Systems
Vol. 11 No. 2, 2023
pp. 296-316
Emerald Publishing Limited
2049-6427
DOI 10.1108/IJIUS-05-2022-0063

issues, preparation for flying UAV. The verification and validation of the developed flight protocol was performed on a sample of over 100 different flight operations.

Keywords Unmanned aerial vehicles, UAV, Safety, Construction industry, Flight preparation, Risk assessment

Paper type Research paper

1. Introduction

The era of using unmanned aerial vehicles (UAVs), so-called drones, for only military purposes is history (Skorupka *et al.,* 2020). Over the past decade, UAV have been used extensively in the civil and commercial sectors (Schach and Weller, 2017; Walczyński *et al.,* 2017). Currently, drones are widely used in many sectors of the economy, including: mining (Lee and Choi, 2016; Park and Choi, 2020), agriculture (Malinovska and Osadcuks, 2016; del Cerro *et al.,* 2021), medicine (Bhatt *et al.,* 2018), ecology (Cruzan *et al.,* 2016; Schaub *et al.,* 2018), and transport (Chung *et al.,* 2020; Macrina *et al.,* 2020). Unmanned aerial systems are also extensively used in the construction industry for, among others: construction inspections (Nowobilski *et al.,* 2020), damage assessment (failure, effects of catastrophes), area measurements (inventories, area mapping), safety inspections, monitoring of the progress of works (Rybka *et al.,* 2020), building maintenance, and thermal imaging tests (Noszczyk and Nowak, 2017).

It should be borne in mind that UAV pose new (not yet present) threats to the construction industry (Hussein *et al.,* 2021). These new threats are related to the development of new technologies, as well as to the continuous automation and robotization of the construction industry (Luo *et al.,* 2022). Although there has been research concerning the benefits of new technologies, including drones, to the construction industry, there is a lack of quantitative research that analyzes the impact of working with or near UAV on the health and safety of employees. The analysis of factors that influence the safety of UAV shows that the main causes of accidents are equipment problems and/or a lack of proper coordination (Ghasri and Maghrebi, 2021).

The use of unmanned aerial systems allows several important benefits in terms of safety in the construction industry to be achieved. First of all, drones can move faster than people, and they can also reach places that are inaccessible or difficult to reach for humans - e.g. located at height with no possibility of entry. The use of drones can significantly improve work safety, e.g. near moving vehicles on a construction site, within the working area of cranes, near unsecured edges and openings, and in the area of the so-called “blind spot” when using heavy construction equipment.

The main purpose of the research is to develop a procedure (protocol) for the correct and safe preparation and planning of an unmanned aerial vehicle flight for the purposes of construction operations in accordance with applicable legal regulations. For this reason, a systematic review of scientific articles, instructions, recommendations of device (drone) manufacturers, and applicable legal regulations in the field of flight preparation was performed.

Based on the analysis of the available sources, it appears that a complete procedure for the correct preparation to fly with UAV (i.e. compliant with applicable legal regulations and occupational health and safety issues) in the construction industry has not yet been developed. This article and the conducted research are intended to fill the identified gap. The development of such a protocol may contribute to the improvement of work safety at workplaces where UAV are used.

2. Systematic literature review

When starting the research, a systematic review of the available literature was carried out. Only Web of Science articles from the last decade (January 2011 to December 2021) have been included in the literature review in order to ensure that the information contained in the articles is up-to-date. The following keywords were selected for the literature review, which could appear in the title, abstract or keywords, namely "drone", "unmanned aerial vehicle" and "construction". In order to assess the relevance of selected works, a set of criteria that exclude irrelevant publications was established based on their content and type of publication. Firstly, those works that did not directly represent research or analysis concerning the use of UAV in the construction industry were identified and excluded. The type of paper was then verified in order to make sure that the publications came from peer-reviewed journals or conference materials. Finally, the manuscripts were also reviewed to ensure that at least one of the keywords of this study was covered in the body of the article. After an incremental evaluation, 40 publications were obtained. The thematic scope of the articles concerned 5 main areas:

(1) Review articles (12 articles),

(2) Drone classification (8 articles),

(3) Flight planning (4 articles),

(4) Work safety (8 articles),

(5) Case study analyzes (8 articles).

In a situation where the article dealt with several of the above-mentioned subject areas, it was qualified for only one leading area.

2.1 Review articles

This group of articles includes works that present the current state of knowledge in the field of the use of UAV in the construction industry, or describe the applicable legal regulations that regulate the principles of drone movement in the air (Herrmann, 2016; Łukasiewicz, 2020). These articles discuss the results of original scientific research to date, e.g. regarding the analysis of the current state of research concerning the use of drones in the USA (Zhou and Gheisari, 2018) and India (Rao *et al.*, 2019). The analyzed works present the possibilities of using UAV to manage a construction site, in particular to monitor the progress of works and to conduct construction inspections, to improve logistics at a workplace, and to assess work safety conditions and damage caused by disasters (Irizarry and Costa, 2016; Freeman *et al.*, 2021).

The second application of drones in the construction industry that can be found in literature (apart from managing a construction site) is the possibility of performing photogrammetric measurements using photos taken at the construction site. Pictures taken with the help of a drone allow for the development of, among others, orthophotomaps and numerical terrain models (Han *et al.*, 2021). The use of appropriate photogrammetric software allows for the integration of the collected and processed data with building information models that support BIM technology (Tatum and Liu, 2017). The development of a building information model can be used to assess the progress of a project (Julge *et al.*, 2019), as well as to check geometric compliances (Elghaish *et al.*, 2020). UAV, which are equipped with a thermal imaging camera, can also be used in construction thermography (Entrop and Vasenev, 2017), and after appropriate preparation, to inspect buildings in closed spaces (Eiris *et al.*, 2021).

2.2 Drone classification

Two types of UAV are commonly used in the construction industry: rotorcraft and fixed wing aircraft. Devices with rotary rotors (rotorcrafts) are characterized by their ability to hover, and to vertically take off and land (Yang *et al.*, 2017). Depending on the number of rotors, these may be helicopters or multi-rotor carriers (Li and Liu, 2018). The principle of rotor lift generation makes them a potentially better platform for small to medium sized projects or vertical types of structures. Remotely controlled devices in the form of a fixed airframe (resembling planes and flying wings) are characterized by their ability to stay in the air for a long time without the need to land. This translates directly into the possibility of covering large areas. Such possibilities make them a better platform for large projects, especially linear ones (Kim and Kim, 2018). The main limitations of fixed wing aircrafts, which are a result of their design, are their inability to hover and the need for a large take-off and landing space (Albeaino and Gheisari, 2021). In addition to the above-mentioned standard types of UAV, new and innovative solutions are being designed, which often combine the benefits of both types. Additionally, when designing and constructing new structures, the following options are taken into account: the use of materials that have not been used so far (Höche *et al.*, 2021), the possibility of adding additional devices (Sagrera *et al.*, 2015), or the possibility of modifying existing structures by adding additional rotors (Hu and Lanzon, 2018). Innovative materials and techniques, such as elements made with the use of 3D printing technology (Szywalski and Waindok, 2020), are used for their construction.

2.3 Flight planning

Regardless of the type of used equipment, it is important to properly plan the course of a flight before take-off. The aim of the research conducted in this area involves, among others, the optimization of the flight trajectory along which the drone moves during the monitoring of the progress of work (Keyvanfar *et al.*, 2021). An important issue is also the correct flight planning for a group of drones (the so-called "swarms") moving over urban areas, where there are obstacles of different heights. The aim of the research is to find the best trajectories while ensuring collision-free navigation (Bahabry *et al.*, 2019). Another goal of the research is to optimize flight speed, which will ensure that the drone will effectively spend most of its time monitoring the construction site, and also complete its route within the specified time and without the battery being drained (Yi and Sutrisna, 2021). However, it needs to be noted that when making photogrammetric measurements, the level of detail of the collected data is important. It allows for the recognition of structural elements and the internal consistency and precision of the conducted measurements (Siwiec, 2018).

2.4 Work safety

UAV are effectively used to improve occupational health and safety at workplaces. The use of UAV allows, among others, to eliminate the need for employees to stay in hazardous zones, to enter confined spaces, or to perform work at height. However, it should be remembered that UAV may pose new threats that have not yet been present at construction sites (Jeelani and Gheisari, 2021). Possible threats and potentially accidental situations should be identified, their risk should be assessed, and necessary preventive measures should be taken in order to prevent their occurrence (Izadi Moud *et al.*, 2021). This is necessary to ensure the safety of employees working where drones are used. The key role here is played by the identification of applied solutions, safety practices, and applicable technical requirements when using air systems (Gheisari and Esmaeili, 2016). Unstable flight conditions, operator errors, and equipment failures can pose a potential risk to nearby workers (Howard *et al.*, 2018). An incorrectly selected flight trajectory of an unmanned aerial vehicle may lead to a collision, which in turn may cause injuries to people or animals, significant damage to the equipment, or even loss of the device (Nguyen *et al.*, 2019). It should also be noted that UAV are devices that are powered by electricity, which in turn can be a potential source of ignition for flammable materials and combustible dust (Kas and Johnson, 2020). In addition, UAV on a construction site can be distracting for workers, and this can worsen their overall safety performance and increase the number of accidents at work that do not directly involve a drone (Namian *et al.*, 2021). Previous studies also show that stress and fatigue of the user/drone pilot are the main causes of accidents involving these devices (Sakib *et al.*, 2021).

2.5 Case study

The main purpose of the studies belonging to this group of articles is to present the practical application of UAV in real operating conditions and applications. For example, an unmanned aerial vehicle was used by stakeholders with varying degrees of experience to verify the quality of collected data and the obtained three-dimensional cloud of points for a part of the curtain wall of a large health care facility located in the south east of the United States (Liu *et al.*, 2016). Another interesting application of UAV concerned the examining of the possibility of monitoring surface deformation on the construction sites of expressways in Korea. An orthophotomap, a digital terrain model and a 3D topographic information model of the construction site were developed thanks to the use of low-altitude photogrammetry (Lee *et al.*, 2020). By using images and photogrammetry, it is possible, for example, to detect and determine the number of vehicles working on a construction site (Li *et al.*, 2019). An unusual example was the use of UAV for the assembly of electrical and grounding cables with optical fibers. The cited work describes the method of unwinding rope (wire) during the construction of the 400 kV high-voltage Ostrołęka-Olsztyn Matki line (Pawlak and Serek, 2017).

One of the most clearly described practical applications in literature of UAV is their use for building inspections for all types of buildings, including historical ones. For example, the purpose of the building inspection carried out in the historic Tan Swee Hoe residence was to assess the overall technical condition of the building. An innovative solution involved the performing of an inspection that was assisted by an image obtained with the use of an unmanned aerial vehicle (Yusof *et al.*, 2020). Similar techniques are also used in civil engineering, and in particular when inspecting bridge structures (Jung *et al.*, 2018), e.g. a three-span glued-laminated timber girder with a composite deck (located near Keystone, South Dakota) (Seo *et al.*, 2018), or the 140 m long bridge in Skodsberg, which is made of prestressed concrete (located in the district of Viken in eastern Norway) (Ayele *et al.*, 2020). As you know, bridges are a critical element of infrastructure in the road and rail transport system network. A large proportion of bridges in Europe are now reaching the end of their design life, and therefore regular inspection and maintenance is essential to ensure the safety of their further operation. Traditional inspection procedures and required resources are time consuming and costly. The use of UAV allows the time and the costs of inspecting this type of structure to be reduced, while at the same time the risk of carrying out work at height and in places difficult for human access to be minimalized.

2.6 Summary of the literature review

The number of analyzed publications concerning the use of UAV in the construction industry in the years 2015–2021 is presented in Figure 1. The first part of the analyzed period

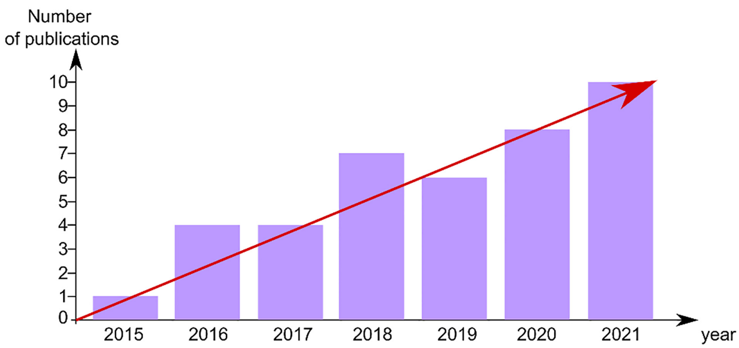

Figure 1.
Number of publications concerning the use of UAV in the construction industry in the years 2015–2021

(2015–2017) shows a small number of articles. In 2018, the number of publications almost doubled when compared to the previous year (7 publications). In the following years, the number of articles continued to increase, and in 2021 it had already reached the value of 10 publications. There is a noticeable upward trend and a growing interest in the use of UAV in the construction industry.

Figure 2 shows the percentage distribution of the analyzed articles with regards to the covered subject area. The largest number of articles were reviews, which accounted for 30% of all the analyzed publications. Often discussed issues, with the same number of occurrence (8 articles), were works presenting the classification of UAV, work safety issues, and case studies. The smallest number of articles, amounting to only 4 articles (10% of all publications), dealt with issues related to the proper planning of air operations and the safe operation/flight of a drone.

Additionally, Figure 3 shows the number of articles with regards to countries (with their location on the world map) in which research related to the use of UAV in the construction industry was conducted. Most of the research results come from the United States. These articles account for 45% of all the analyzed papers. Other countries that publish articles in this area are: South Korea, Great Britain, Poland, Australia and Malaysia (countries that have published at least 2 articles), which accounts for 45% of all the articles. The remaining 10% of articles are individual works from the rest of the world.

Based on the literature analysis, it can be concluded that the available literature (from the Web of Science database) lacks publications dealing with the safety and preparation of UAV for work. There are no papers presenting current, applicable legal regulations that regulate the movement of drones in the air in countries of the European Union. Importantly, no appropriate and safe procedure for the preparation of flying UAV in the construction industry has yet been proposed or developed, i.e. in accordance with applicable legal regulations and occupational health and safety issues. This article and the conducted research aim to fill the identified gap. A protocol for preparing an air operation with the use of a drone in the construction industry is also proposed.

3. Legal regulations related to the use of drones in European Union countries

3.1 Principles and categories of unmanned aerial vehicle operations

On December 31, 2020, uniform regulations related to the use of drones were introduced in European Union countries (excluding Iceland and Switzerland, which have their own rules for

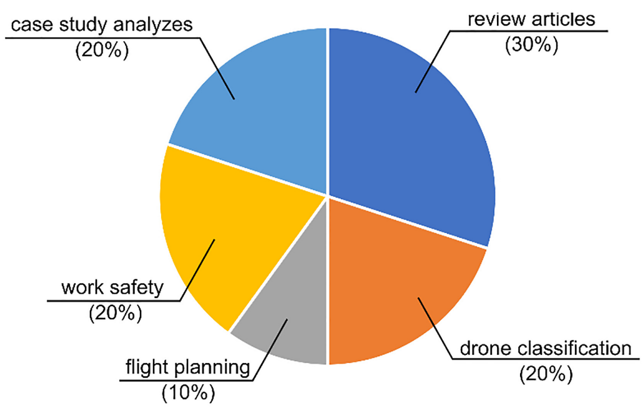

Figure 2.
Number of articles with regards to the thematic scope

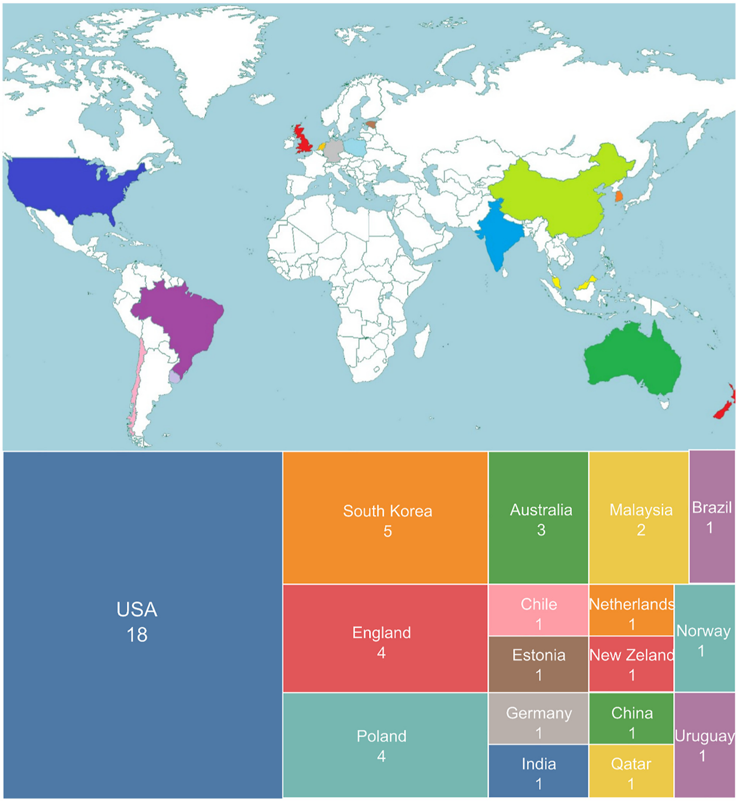

Figure 3.
Number of articles from individual countries of the world

UAV), as well as in Liechtenstein and Norway. They were determined on the basis of the *Commission Delegated Regulation (EU) 2019/945 of 12 March 2019 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems*, and also on the *Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft.*

European Union Aviation Safety Agency (EASA), in consultation with member countries, has developed common European rules for the use of UAV in order to ensure free movement of drones and equal operating conditions for all pilots of UAV in the European Union. Thanks to the new rules, users of UAV have more freedom to perform drone operations when traveling in the European Union or when expanding their drone business in Europe. The described principles are based on an assessment of the risk of exploitation, and they ensure a balance regarding the obligations of drone manufacturers and users in terms of safety, respect for privacy, the environment, and protection against noise and safety. They also introduce standardized document templates confirming the competences that are necessary to operate a drone in a given category. It should be noted, however, that despite the significant unification of regulations related to the use of drones in Europe, some member states still have internal regulations that may significantly limit the possibility of using a drone in a given situation. These provisions may be related to, among others, respect for personal privacy, or restrictions concerning the use and publication of material obtained from the air. In addition, some countries, including Poland and Croatia, require dedicated mobile applications that drone users are obliged to use.

Due to the above-mentioned differences related to the use of drones in individual Member States of the European Union, the following part of the article presents the implementation of EU regulations in the field of the use of drones in the construction industry, using Poland as an example. This does not mean, however, that the presented regulations apply only to the country in question, and they can, after appropriate adaptation to specific national regulations, be transferred to other European Union member states.

The regulations provided at the turn of 2020 and 2021 introduce a division of air operations that use drones into three basic categories:

(1) Open category – which is considered to be a low risk category. An unmanned aerial vehicle pilot, when performing an air operation in the "open" category, should pay particular attention to the class of the drone he is operating. This class depends on the technical parameters of a given device (including the take-off weight) and has a value from C0 to C4. The fact that a drone belongs to a given class has a direct impact on the rules of flying in the "open" category. It is worth noting that the "open" category distinguishes between three subcategories (from A1 to A3), which have certain restrictions concerning the drone class that can be used in them. The user of the device performing an aviation operation in a given subcategory should have the appropriate permission to use the drone. Additionally, in some cases, the user is subject to mandatory registration in the system of unmanned aerial vehicle operators. The rules of performing flights in individual subcategories of the "open" category differ slightly from each other, but they do have some common elements, which include, among others, the obligation to only fly within the sight of the pilot or with the help of an observer at a height of no more than 120 m from the nearest point of the Earth's surface - in some cases this altitude may be different,

(2) Special category - intended for medium risk operations, the flight parameters of which exceed those of the "open" category. Operations in the "special" category are performed according to the so-called "standard scenarios" (STS), in which the requirements for drones and the maximum flight parameters are presented - including heights and distances. In a situation where the planned flight parameters go beyond the situation described in the "standard scenario", the flight can only take place after obtaining the appropriate approval. An exception to the above rule applies to entities with an appropriate certificate issued by the Civil Aviation Authority. Additionally, the pilot of an unmanned aircraft performing an operation in the "special" category is required to have appropriate ratings, and should be registered in the system of operators of unmanned aircraft systems.

(3) Certified category - high risk category. This category includes operations with the use of drones that go beyond the requirements of the "open" and "special" categories - such operations include flights related to the transport of people and hazardous substances. Operations in the "certified" category require the certification of UAV under Regulation (EU) 2019/945. Certification of the operator and the obtaining of an additional license by the pilot of the unmanned aerial vehicle may also be required if the competent authority, based on a risk assessment, considers it to be necessary.

3.2 Registration of unmanned aerial vehicle system operators

One of the key elements that have been introduced as a result of the unification of the regulations related to the use of UAV in the European Union is the obligation for the operators of UAV to be registered. It is worth noting that the term operator is understood as an entity that provides services related to the use of drones. In the case of the recreational use of drones, the operator is the direct user of the drone. Unmanned aerial vehicle operators who perform operations in the “open” category using drones with a take-off mass (MTOM) from 250 g, or which, in the event of an impact, can generate kinetic energy of more than 80 joules, are subject to registration. An additional criterion due to which the operator is subject to the registration obligation is the use of a drone equipped with a sensor capable of collecting personal data (e.g. a camera). In the “special” category, all operators are subject to registration.

3.3 General rules for performing air operations with the use of drones

Each aviation operation related to the use of a drone in the construction industry is characterized by high variability, e.g. in terms of: weather conditions, local terrain conditions, legal regulations, as well as the type, scope and period in which the operation is performed. However, irrespective of the above-mentioned elements of the flight operation, the pilot of the drone should have:

(1) Manual skills that allow for the proper control of the drone in the airspace,

(2) Technical skills that allow the technical condition of the drone to be checked (especially before take-off and during the flight),

(3) Psychophysical abilities that allow the drone to be operated in a safe manner,

(4) Knowledge about the structure of the airspace and the rules of navigating in it, as well as possible restrictions in traffic that may occur in it,

(5) Knowledge of the impact of atmospheric conditions on the course of an air operation and possible related threats,

(6) Knowledge about the impact of terrain obstacles (including transmitters, transformers) and the shape of terrain on the course of an air operation - loss of range, interference, etc.

One of the most important elements, among the above-mentioned, which largely affects the possibility of performing an air operation and its safety, is the knowledge of the structure of the airspace. Airspace should be understood as the air area that extends over the land territory, internal waters and territorial sea area of a given state to a given height - in the case of Poland, the upper limit of the airspace is located at a height of FL 660 (Flight Level 660 = 66,000 ft. - about 20 km). The airspace includes several different air zones (Rozporządzenie Ministra Infrastruktury z dnia 27 grudnia 2018 r. w sprawie struktury polskiej przestrzeni powietrznej oraz szczegółowych warunków i sposobu korzystania z tej przestrzeni (Dz.U. 2019 poz. 619)). Figure 4 shows selected air zones that were active on February 13, 2022 in the Airspace Use Plan (AUP) for Poland.

In each air zone, there are detailed conditions and rules for performing air operations with the use of drones. In most of them, a drone flight can only take place after obtaining the appropriate consent from the manager of a given airspace to perform the flight operation, and after booking a given area for the duration of the flights. In most cases, communication in this regard is carried out through the PansaUTM system. In addition, in special cases (e.g. flights at an altitude above 120 m above sea level), the drone pilot, in addition to obtaining permission from the manager of a given zone to perform the flight, must also obtain a permit to perform an operation in the “special” category if this operation is not covered by the scenario standard STS and is not included in the “open” category. To apply for authorization to perform an operation in the “specific” category, the drone pilot must prepare a risk analysis carried out in accordance with either the specific operations risk assessment (SORA) methodology or predefined risk assessment (PDRA).

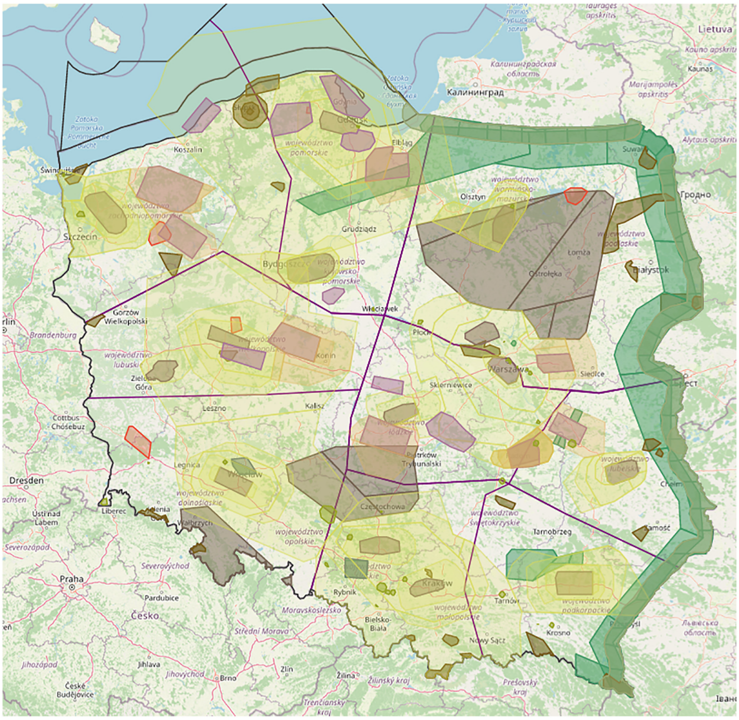

Figure 4.
Selected air zones that were active on February 13, 2022 in the Airspace use plan (AUP)

The drone pilot, after obtaining the necessary approvals and permits, immediately before the flight in the airspace (regardless of the type of air zone) informs the appropriate authority that manages the given airspace about the intention to perform the flight operation. In Poland, the air space management body is the Polish Air Navigation Services Agency (PANSA), and the contact is carried out via the ICT system using the DroneRadar application. During the flight operation, the drone pilot must exercise extreme caution and keep in constant contact with PANSA. During the flight, there may be sudden traffic restrictions in a given zone - for example, related to the flight of a rescue helicopter or the conducting of search and rescue operations. In such a situation, the drone pilot must immediately stop the operation and free up the air space he was occupying as quickly as possible. In addition, after completing each flight operation, the drone pilot immediately informs the above-mentioned authorities about the completion of the flight and the release of the airspace.

4. Procedure protocol - organization of a safe air operation with the use of a drone in the construction industry

On the basis of the analysis of the literature concerning the subject, the operating instructions for selected UAV, applicable regulations, as well as the knowledge and experience of the authors of the research (who are authorized to operate UAV and who have several years of practical experience), a typical scenario of safe conduct in the case of air operation with the use of a drone for the need of the construction industry was developed. The developed protocol takes into account all the phases related to the use of the drone, from the planning phase, through the stage of air operation, and ending with elements related to the end of the flight operation. For the purpose of this study, it was assumed that the drone pilot has the required competences and authorizations necessary to operate an unmanned aerial vehicle, has fulfilled all the requirements related to the operator's registration to the unmanned aerial vehicle system, and has his own profile in the PansaUTM system. This profile enables the conditions and consent for the execution of a mission to be obtained. All the above-mentioned elements must be met before starting the planning of an air operation with the use of a drone, and the developed protocol should be treated as a procedure to be followed when planning each new air operation.

The developed protocol consists of five main steps:

(1) *Stage I - Flight planning* (a few days before the planned flight):
   - Determination of the location and area over which the operation will be performed, as well as the maximum altitude at which flights will be carried out.
   - Preliminary planning of the flight course and its scope, e.g. facility inspection, work progress monitoring, thermal imaging tests, etc.
   - Defining the starting point of the device.
   - Learning national, regional and local regulations and rules for the use of UAV in a given area.
   - Identifying the category of operation and, in the case of a "specific" category, selecting the appropriate STS standard scenario.
   - Obtaining a permit to perform an operation in the "specific" category (if the operation is not covered by the STS standard scenario and is not included in the "open" category), and other local approvals (e.g. an operating permit from the owner of the facility over which the flight will be performed).
   - Detailed mission planning and sending the flight plan to the Polish Air Navigation Services Agency in order to gain permission for ascent (communication is most often carried out using the PansaUTM system).
   - Obtaining approval and flight conditions from the Polish Air Navigation Services Agency.

(2) *Stage II - Initial preparation of the device for flight* (one day before the planned flight):
   - Charging the drone's batteries.
   - Charging the batteries of the controller and auxiliary devices - e.g. tablet, computer.
   - Initial checking of the technical condition of the device and its components.
   - Preliminary checking of the weather conditions, in particular: wind speed, humidity, temperature, the level of solar radiation (Kp index), and the occurrence of precipitation, which may prevent the safe performance of the operation.
   - Preliminary flight path planning, taking into account the drone's flight dynamics and possible terrain obstacles, as well as the capabilities of the equipment.

(3) *Stage III - Preparation for an air operation* (directly before take-off):
   - Final verification of the weather conditions.

- Final verification of the permits held for the execution of operations in a given place and time, and checking NOTAM messages in the vicinity of the place of the air operations.
- Preparation of a safe take-off and landing site, and a plan for an emergency landing site.
- Preparation of the object over which the flights will be carried out (e.g. the location of measurement points).
- Preparation of the drone for the flight (e.g. device calibration, synchronization with the controller, checking for updates).
- Final inspection of the technical condition of the drone (in particular checking the drive system and power supply of the device).
- Launching the DroneRadar application, selecting a complex flight plan (if applicable), verifying flight settings, and performing a "check-in" in the application.
- Awaiting for feedback from the controller, who clears the commencement of the flight in accordance with the flight plan.

(4) *Stage IV - Commencement and course of the air operation* (from take-off to landing):

- Checking that there are no people or other obstacles in the area of the take-off site and scheduled flight.
- Turning on the device and controller.
- Starting the engines.
- Ensuring that the device is operational - performing a test flight.
- Performing the proper flight - incl. Flight mode selection (e.g. planned path flight, manual control).
- Controlling the device while also controlling the flight parameters, technical condition of the device, surroundings, and messages sent by the controller using the DroneRadar application.
- In the event of an emergency (e.g. device failure or a sudden restriction in traffic in a given zone), immediate termination of the operation in progress and quick landing in a safe place.
- Inspection of the landing site.
- Landing.
- Turning off the engines.

(5) *Stage V - End of the flight operation* (after landing and turning off the engines)

- Turning off the device.
- Sending a mission completion confirmation using the DroneRadar application (see Figure 5).

The developed protocol was verified in test flights, during which all its elements were checked. The course of an exemplary attempt to validate the developed protocol is presented in Chapter 5.

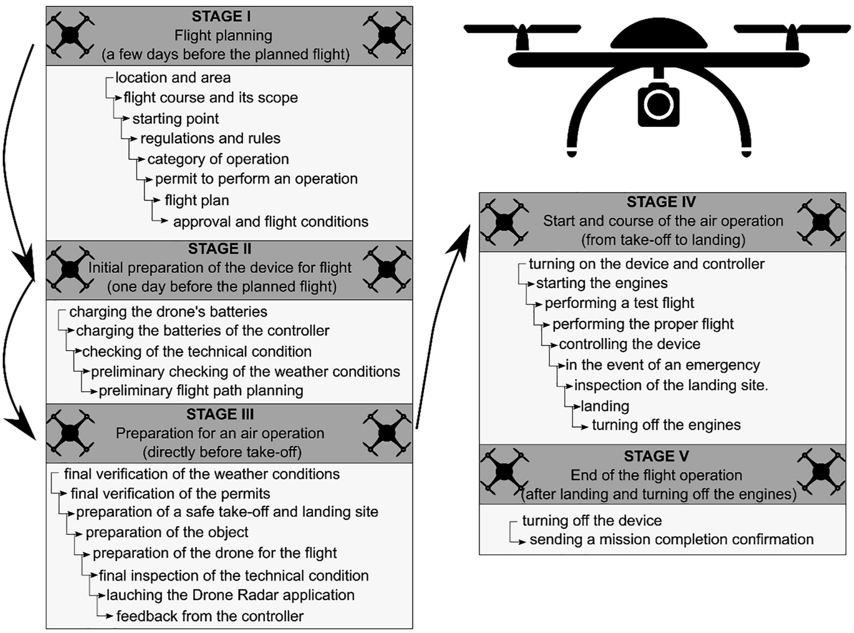

Figure 5.
Procedure protocol - scheme

5. Verification and validation of the developed procedure protocol - case study

The verification and validation of the developed flight protocol was performed on a sample of over 100 different flight operations. The analyzed air operations concerned, among others, the monitoring of the progress of the works and inspection of construction facilities, such as: cubature facilities (public buildings, e.g. kindergartens, schools and academic buildings, religious buildings, residential buildings, industrial facilities), engineering facilities (bridges, road structures), and health and safety inspections (scaffolding inspections, excavation inspections).

During the implementation of the analyzed air operations, a DJI device - the Phantom 4 PRO V2.0 model - was used as shown in Plate 1.

Plate 1.
DJI Phantom 4 PRO V2.0 drone

The drone shown in the above photo is one of the most popular devices used during construction and surveying works. This drone is equipped with a three-axis stabilized 4 K camera (maximum photo resolution of 20 Mpix), with the possibility of transmitting FullHD image resolution in real time. Its take-off weight is about 1.5 kg, and its maximum flight speed is up to 72 km/h. The drone also has obstacle avoidance sensors located on the front, back and sides of the device, as well as on its the bottom. The maximum real flight time with a fully charged battery is about 20–25 min.

The purpose of the described exemplary air operation with the use of a drone was to inspect the technical condition and inventory of the roofing of the building of Primary School No. 1 named after Maria Dąbrowska, which is located at Nowowiejska Street 78 in Wroclaw (facility coordinates: 51° 07'14.5 "N 17° 03'20.2" E) - Plate 2.

A few days before the flight, a local inspection of the planned air operation site was conducted. It was verified if there are any terrain obstacles in the vicinity of the building that could pose a threat during the drone flight (e.g. telecommunication transmitters). After verifying the technical feasibility of the operation in the assumed location, its parameters were initially planned - i.e. the place of take-off and landing, the area of flight performance, the planned maximum altitude of the flights, and the time of their execution. On the basis of the applicable regulations, as well as the type of drone to be used during the operation, it was assumed that the operation would be performed in the “special” category according to the national standard scenario NSTS-01. Due to the fact that the area of the planned flights is in the city center near the airport, it was necessary to submit the flight plan to the Polish Air Navigation Services Agency (PANSA) in order to obtain the necessary approval for ascent as shown in Figure 6.

The day before the planned flight, the technical condition of the drone was checked, as well as its battery charge level. The weather forecast and the predicted level of solar radiation (Kp index) for the next day were also verified. On the day of the flight, directly before the take-off, the prevailing weather conditions and the permits for the operation were re-verified. The take-off and landing site was then prepared, measurement points were distributed, and the device was calibrated with a final inspection of its technical condition. After successful completion of the above activities, the “DroneRadar” application was launched, with the use of which the previously created mission (approved by PANSA) was selected, and the so-called “Check-in”, which notified the air traffic controller at the nearest airport (CTR EPWR) about the intention to proceed with the implementation of the flight plan, was carried out. After a few minutes of

Plate 2.
View of the analyzed object

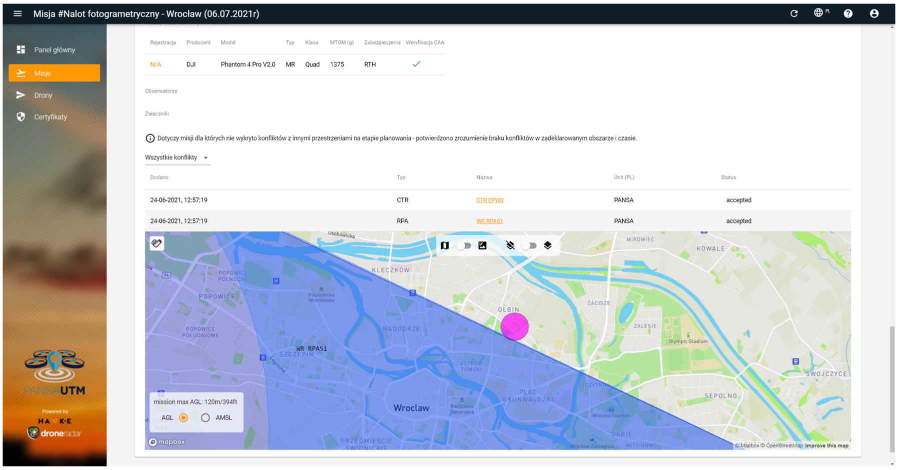

Figure 6.
View of a fragment of the approved flight plan for the analyzed case - PansaUTM system

waiting for approval, the operation was started. Before the take-off, the pilot was assured that there are no bystanders and obstacles in the vicinity. After the test flight, the proper task was started, which involved a flight over the analyzed object at an altitude of about 45 m lasting for about 13 min - Figure 7. During the flight, its parameters were monitored, in particular the battery charge status, as well as messages displayed by the DroneRadar application.

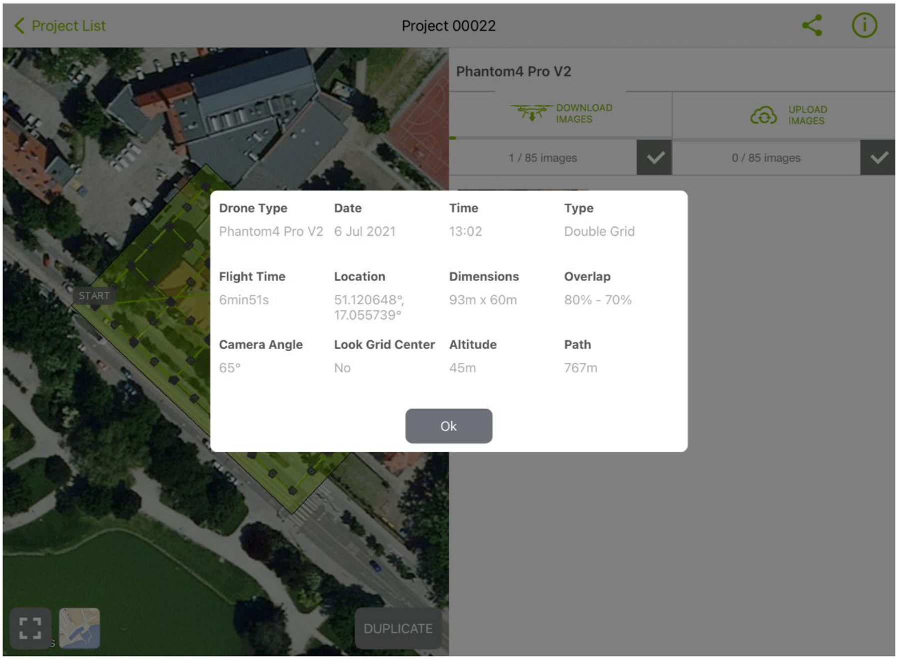

Figure 7.
The view of the flight parameters

After completing the mission, the device safely landed in the previously planned place and was turned off. Information concerning the safe completion of the mission was then transferred to the air traffic controller at the nearest airport (EPWR CTR) using the "DroneRadar" application.

6. Discussion

The literature analysis presented in the article indicates a growing interest in the technology of UAV for industrial applications. The confirmation of this is the increasing number of initiatives that aim to use drones in practical activities, which come from private enterprises, public and local government institutions, and various types of organizations. This state of affairs enables this sector of the economy to significantly and dynamically develop. It is estimated that the drone market in the world will reach a value of UDS 58.4 billion by 2026. Such a significant and dynamic development of the software development sector, and the provision of services with the use of drones, generates new previously unknown threats. Therefore, it is very important to carry out preventive actions that aim to reduce the risk of conducting operations with the use of drones. The methodology of conduct that was proposed in the article is a universal method of dealing with safe planning and operations with the use of UAV. This methodology is fully compliant with the current legal regulations, industry standards (ISO 21384-3:2019 Unmanned aircraft systems – Part 3: Operational procedures, 2019), and ICT solutions. Its practical implementation significantly reduces the level of risk of air operations with the use of drones in the construction industry, and thus increases the level of safety in society.

It can be undeniably stated that UAV are very useful devices that support the implementation of a construction project. However, it should be remembered that in some situations there are certain limitations in their use, such as (Nowobilski, 2020):

(1) The need to have appropriate permissions to control a drone,

(2) The impact of weather conditions on the proper course of an air operation,

(3) The need to adapt to airspace restrictions,

(4) The need for approval to conduct an air operation in some cases.

Additionally, the use of drones during construction investments may generate the following problems:

(1) In a situation where a drone flight operation is not performed by a trained specialist, the obtained results may be inaccurate, incomplete, or even erroneous. In addition, a drone controlled by a person without appropriate competences causes a real threat to the health and life of people in its vicinity, as well as a significant threat to the environment in which it moves.

(2) UAVs have a limited flight time. If an operation needs to be completed urgently, but needs to cover a large area, it may be necessary to use multiple drones or batteries in order to ensure full coverage.

(3) Operating a drone in an environment with telecommunication transmitters, antenna masts, and other transmitting and receiving devices may cause disturbances that are dangerous for the proper course of the flight.

(4) The rules governing the use of drones are constantly changing. The rapidly changing regulations may make it necessary to obtain additional permits that were not previously required.

7. Summary

An unmanned aerial vehicle, commonly known as a drone, is not only a popular gadget that is increasingly used by amateurs and hobbyists for private purposes, but also a modern system that can be used in many areas of life, including construction and research. The use of drones in construction has a wide spectrum of activity, e.g. construction inspections, damage assessment, land measurements, monitoring of work progress, and safety inspections. UAV not only allow for photos from the air to be taken, but also provide three-dimensional models or orthophotos.

Documentation obtained in this way allows the topography of the area intended for the investment to be precisely examined, as well as the scope of the planned earthworks to be verified, e.g. to estimate the volume of excavations, the dimensions of foundations, or the depth of embedding a pipeline. This contributes to a more precise planning of the pace of work and the duration of the investment and construction project, makes it easier to control progress, and, as a result, prevents delays on the construction site.

The use of drones in the construction industry may increase the level of safety at construction sites, but it should be remembered that UAV may also pose new threats that were previously not present. Unstable flight conditions, operator errors, and equipment failure can potentially put people working next to the areas where drones are used at risk. A poorly chosen flight trajectory of an unmanned aerial vehicle may lead to a collision that may cause injury to people or animals, significant damage to equipment, or even to the loss of the device.

The aim of the research was to develop a procedure (protocol) for the correct and safe preparation and planning of an unmanned aerial vehicle flight for the purposes of construction operations in accordance with applicable legal regulations. For this purpose, a systematic review of literature, scientific articles, manuals, recommendations of device manufacturers, and the applicable legal regulations in the field of flight preparation was performed. According to the authors, the application of the developed protocol in practice may contribute to the improvement of work safety at workplaces where UAV are used.

Education regarding the safe use of UAV, as well as the proper use of drones, has a chance to improve the safety of people that work using these devices. This is especially important because the use of drones in the construction industry, as mentioned earlier, brings many benefits. The academia environment is also aware of the fact that UAV are rapidly expanding their range of applications.

In order to meet the latest trends, the international project "Virtual reality immersive safety training environment for robotized and automated construction sites" is being implemented by the consortium: University of the West of England (UWE) Bristol, (United Kingdom); CTM -Centro Tecnologico del Marmol Piedra y Materiales (Spain); Bildungszentren des Baugewerbes e.V. (Germany); and Wroclaw University of Science and Technology (Poland). The main goal of the project is to develop a very innovative, safe and interactive training environment based on virtual reality (VR) technology. The main aim of the project was to create a very innovative, immersive and interactive training environment based on Virtual Reality (VR) technology in order to provide construction workers with the essential skills and education required to interact with machinery and materials.

References

Albeaino, G. and Gheisari, M. (2021), "Trends, benefits, and barriers of unmanned aerial systems in the construction industry: a survey study in the United States", *Journal of Information Technology in Construction*, Vol. 26, pp. 84-111, doi: 10.36680/J.ITCON.2021.006.

Ayele, Y.Z., Aliyari, M., Griffths, D. and Droguett, E.L. (2020), "Automatic crack segmentation for uav-assisted bridge inspection", *Energies*, Vol. 13 No. 23, doi: 10.3390/EN13236250.

Bahabry, A., Wan, X., Ghazzai, H., Menouar, H., Vesonder, G. and Massoud, Y. (2019), "Low-altitude navigation for multi-rotor drones in urban areas", *IEEE Access*, Vol. 7, pp. 87716-87731, doi: 10.1109/ACCESS.2019.2925531.

Bhatt, K., Pourmand, A. and Sikka, N. (2018), "Targeted applications of unmanned aerial vehicles (drones) in telemedicine", *Telemedicine and e-Health*, Vol. 24 No. 11, pp. 833-838, doi: 10.1089/TMJ.2017.0289.

Chung, S.H., Sah, B. and Lee, J. (2020), "Optimization for drone and drone-truck combined operations: a review of the state of the art and future directions", *Computers and Operations Research*, Vol. 123, doi: 10.1016/J.COR.2020.105004.

Commission Delegated Regulation (EU) (2019), 2019/945 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems, 2019; Commission Implementing Regulation, 2019; ISO 21384-3:2019 Unmanned aircraft systems – Part 3: Operational procedures, 2019.

Commission Implementing Regulation (EU) (2019), "2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft".

Cruzan, M.B., Weinstein, B.G., Grasty, M.R., Kohrn, B.F., Hendrickson, E.C., Arredondo, T.M. and Thompson, P.G. (2016), "Small unmanned aerial vehicles (Micro-Uavs, drones) in plant ecology", *Applications in Plant Sciences*, Vol. 4 No. 9, 1600041, doi: 10.3732/APPS.1600041.

del Cerro, J., Ulloa, C.C., Barrientos, A. and de León Rivas, J. (2021), "Unmanned aerial vehicles in agriculture: a survey", *Agronomy*, Vol. 11 No. 2, doi: 10.3390/AGRONOMY11020203.

Eiris, R., Albeaino, G., Gheisari, M., Benda, W. and Faris, R. (2021), "InDrone: a 2D-based drone flight behavior visualization platform for indoor building inspection", *Smart and Sustainable Built Environment*, Vol. 10 No. 3, doi: 10.1108/SASBE-03-2021-0036.

Elghaish, F., Matarneh, S., Talebi, S., Kagioglou, M., Hosseini, M.R. and Abrishami, S. (2020), "Toward digitalization in the construction industry with immersive and drones technologies: a critical literature review", *Smart and Sustainable Built Environment*, Vol. 10 No. 3, doi: 10.1108/SASBE-06-2020-0077.

Entrop, A.G. and Vasenev, A. (2017), "Infrared drones in the construction industry: designing a protocol for building thermography procedures", *Energy Procedia*, Vol. 132, pp. 63-68, doi: 10.1016/J.EGYPRO.2017.09.636.

Freeman, M., Kashani, M. and Vardanega, P. (2021), "Aerial robotic technologies for civil engineering: established and emerging practice", *Journal of Unmanned Vehicle System*, Vol. 9 No. 2, pp. 75-91.

Ghasri, M. and Maghrebi, M. (2021), "Factors affecting unmanned aerial vehicles' safety: a post-occurrence exploratory data analysis of drones' accidents and incidents in Australia", *Safety Science*, Vol. 139, doi: 10.1016/j.ssci.2021.105273.

Gheisari, M. and Esmaeili, B. (2016), "Unmanned aerial systems (UAS) for construction safety applications", *Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan - Proceedings of the 2016 Construction Research Congress*, CRC, 2016, pp. 2642-2650, doi: 10.1061/9780784479827.263.

Han, D., Lee, S.B., Song, M. and Cho, J.S. (2021), "Change detection in unmanned aerial vehicle images for progress monitoring of road construction", *Buildings 2021*, Vol. 11 No. 4, p. 150, available at: https://doi.org/10.3390/BUILDINGS11040150 (accessed 15 October 2021).

Herrmann, M. (2016), "Unmanned aerial vehicles in construction: an overview of current and proposed rules", *Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan - Proceedings of the 2016 Construction Research Congress*, CRC, 2016, pp. 588-596, doi: 10.1061/9780784479827.060.

Höche, D., Weber, W.E., Gazenbiller, E., Gavras, S., Hort, N. and Dieringa, H. (2021), "Novel magnesium based materials: are they reliable drone construction materials? A mini review", *Frontiers in Materials*, Vol. 8, doi: 10.3389/FMATS.2021.575530.

Howard, J., Murashov, V. and Branche, C.M. (2018), "Unmanned aerial vehicles in construction and worker safety", *American Journal of Industrial Medicine*, Vol. 61 No. 1, pp. 3-10, available at: https://doi.org/10.1002/AJIM.22782 (accessed 15 October 2021).

Hu, J. and Lanzon, A. (2018), "An innovative tri-rotor drone and associated distributed aerial drone swarm control", *Robotics and Autonomous Systems*, Vol. 103, pp. 162-174, doi: 10.1016/J.ROBOT.2018.02.019.

Hussein, M., Nouacer, R., Corradi, F., Ouhammou, Y., Villar, E., Tieri, C. and Castiñeira, R. (2021), "Key technologies for safe and autonomous drones", *Microprocessors and Microsystems*, Vol. 87, doi: 10.1016/j.micpro.2021.104348.

Irizarry, J. and Costa, D.B. (2016), "Exploratory study of potential applications of unmanned aerial systems for construction management tasks", *Journal of Management in Engineering*, Vol. 32 No. 3, 05016001, doi: 10.1061/(ASCE)ME.1943-5479.0000422.

ISO 21384-3:2019 Unmanned aircraft systems – Part 3: Operational procedures (2019).

Izadi Moud, H., Flood, I., Zhang, X., Abbasnejad, B., Rahgozar, P. and McIntyre, M. (2021), "Quantitative assessment of proximity risks associated with unmanned aerial vehicles in construction", *Journal of Management in Engineering*, Vol. 37 No. 1, 04020095, doi: 10.1061/(ASCE)ME.1943-5479.0000852.

Jeelani, I. and Gheisari, M. (2021), "Safety challenges of UAV integration in construction: conceptual analysis and future research roadmap", *Safety Science*, Vol. 144, 105473, doi: 10.1016/J.SSCI.2021.105473.

Julge, K., Ellmann, A. and Köök, R. (2019), "Unmanned aerial vehicle surveying for monitoring road construction earthworks", *Baltic Journal of Road and Bridge Engineering*, Vol. 14 No. 1, pp. 1-17, doi: 10.7250/BJRBE.2019-14.430.

Jung, H.J., Lee, J.H. and Kim, I.H. (2018), "Challenging issues and solutions of bridge inspection technology using unmanned aerial vehicles", *Proceedings Volume 10598, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*, doi: 10.1117/12.2300957.

Kas, K.A. and Johnson, G.K. (2020), "Using unmanned aerial vehicles and robotics in hazardous locations safely", *Process Safety Progress*, Vol. 39 No. 1, e12066, doi: 10.1002/PRS.12066.

Keyvanfar, A., Shafaghat, A. and Awanghamat, M.A. (2021), "Optimization and trajectory analysis of drone's flying and environmental variables for 3D modelling the construction progress monitoring", *International Journal of Civil Engineering*, Vol. 20, doi: 10.1007/S40999-021-00665-1.

Kim, S. and Kim, S. (2018), "Opportunities for site monitoring by adopting first personal view (FPV) of a drone", *Smart Structures and Systems*, Vol. 21 No. 2, pp. 139-149, doi: 10.12989/SSS.2018.21.2.139.

Lee, S. and Choi, Y. (2016), "Reviews of unmanned aerial vehicle (drone) technology trends and its applications in the mining industry", *Geosystem Engineering*, Vol. 19 No. 4, pp. 197-204, doi: 10.1080/12269328.2016.1162115.

Lee, S.B., Song, M., Kim, S. and Won, J.H. (2020), "Change monitoring at expressway infrastructure construction sites using drone", *Sensors and Materials*, Vol. 32 No. 11, pp. 3923-3933, doi: 10.18494/SAM.2020.2971.

Li, Y. and Liu, C. (2018), "Applications of multirotor drone technologies in construction management", *International Journal of Construction Management*, Vol. 19 No. 5, pp. 401-412, doi: 10.1080/15623599.2018.1452101.

Li, W., Li, H., Wu, Q., Chen, X. and Ngan, K.N. (2019), "Simultaneously detecting and counting dense vehicles from drone images", *IEEE Transactions on Industrial Electronics*, Vol. 66 No. 12, pp. 9651-9662, doi: 10.1109/TIE.2019.2899548.

Liu, J., Jennesse, M. and Holley, P. (2016), "Utilizing light unmanned aerial vehicles for the inspection of curtain walls: a case study", *Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan - Proceedings of the 2016 Construction Research Congress*, CRC 2016, pp. 2651-2659, doi: 10.1061/9780784479827.264.

Łukasiewicz, J. (2020), "Unmanned aerial vehicle as a device supporting the physical protection system of critical infrastructure facilities: nuclear power plant as a case in point", *Scientific Journal of Silesian University of Technology Series Transport*, Vol. 108, pp. 121-131, doi: 10.20858/SJSUTST.2020.108.11.

Luo, F., Li, R.Y.M., Crabbe, M.J.C. and Pu, R. (2022), "Economic development and construction safety research: a bibliometrics approach", *Safety Science*, Vol. 145, doi: 10.1016/j.ssci.2021.105519.

Macrina, G., di Puglia Pugliese, L., Guerriero, F. and Laporte, G. (2020), "Drone-aided routing: a literature review", *Transportation Research Part C: Emerging Technologies*, Vol. 120, doi: 10.1016/J.TRC.2020.102762.

Malinovska, L. and Osadcuks, V. (2016), "Technical analysis of unmaned aerial vehicles (drones) for agricultural applications", *15th International Scientific Conference: Engineering for Rural Development Jelgava*, Latvia, pp. 870-875, available at: https://www.webofscience.com/wos/woscc/full-record/WOS:000390059500135.

Minister Infrastruktury (2018), "Rozporządzenie Ministra Infrastruktury z dnia 27 grudnia 2018 r. w sprawie struktury polskiej przestrzeni powietrznej oraz szczegółowych warunków i sposobu korzystania z tej przestrzeni", Dz.U. 2019 poz. 619 (in Polish).

Namian, M., Khalid, M., Wang, G. and Turkan, Y. (2021), "Revealing safety risks of unmanned aerial vehicles in construction", Vol. 2675 No. 1, doi: 10.1177/03611981211017134.

Nguyen, V.T., Jung, K. and Dang, T. (2019), "DroneVR: a web virtual reality simulator for drone operator", *Proceedings - 2019 IEEE International Conference on Artificial Intelligence and Virtual Reality*, AIVR 2019, pp. 257-262, doi: 10.1109/AIVR46125.2019.00060.

Noszczyk, P. and Nowak, H. (2017), "Zastosowanie dronów do termowizyjnych badań obiektów budowlanych", *Materiały Budowlane*, Vol. 11, pp. 27-28, (in Polish), doi: 10.15199/33.2017.11.11.

Nowobilski, T. (2020), "Bezzałogowe statki powietrzne w kontroli obiektów budowlanych", *Builder*, Vol. 24 No. 2, pp. 18-20, (in Polish), doi: 10.5604/01.3001.0013.7500.

Nowobilski, T., Sawicki, M. and Szóstak, M. (2020), "Drony w ocenie stanu rusztowań", *Builder*, Vol. 24 No. 1, pp. 40-41, (in Polish), doi: 10.5604/01.3001.0013.6481.

Park, S. and Choi, Y. (2020), "Applications of unmanned aerial vehicles in mining from exploration to reclamation: a review", *Minerals*, Vol. 10 No. 8, pp. 1-32, doi: 10.3390/MIN10080663.

Pawlak, K. and Serek, D. (2017), "High voltage transmission line stringing operation. Usage of unmanned aerial vehicles for installation of conductor and grounding wires with optical fibers", *In: 15th International Conference On Electrical Machines, Drives And Power Systems (Elma)*, Tech Univ Sofia, Sofia, pp. 32-37.

Rao, C., Krishna, K., Rachananjali, K. and Sravani, V. (2019), "Unmanned flying vehicles for various applications and their future scope in India", *Journal of Mechanics of Continua and Mathematical Sciences*, Vol. 14 No. 6, pp. 747-760, doi: 10.26782/JMCMS.2019.12.00055.

Rybka, I., Stolarz, M. and Nowobilski, T. (2020), "Nowoczesne technologie monitorowania robót ziemnych. Praktyczne wdrożenie na przykładzie budowy Kwatery Południowej OUOW Żelazny Most", *Builder*, Vol. 24 No. 5, pp. 44-47, (in Polish), doi: 10.5604/01.3001.0014.0810.

Sagrera, M., Tuyare, V., Compagnone, G. and Sotelo, R. (2015), "Design, construction and manually or autonomously control of an unmanned aerial vehicle", *Memoria-Investigaciones en Ingenieria*, No. 14, pp. 95-105, available at: https://www-1webofscience-1com-1wvxxxm9d083f.han.bg.pwr.edu.pl/wos/woscc/full-record/WOS:000376491800007.

Sakib, M.N., Chaspari, T. and Behzadan, A.H. (2021), "A feedforward neural network for drone accident prediction from physiological signals", *Smart and Sustainable Built Environment*. doi: 10.1108/SASBE-12-2020-0181.

Schach, R. and Weller, C. (2017), "Construction inspection with unmanned aerial vehicle", *Bauingenieur*, Vol. 92, pp. 271-279, available at: https://www.webofscience.com/wos/woscc/full-record/WOS:000404948600007.

Schaub, J., Hunt, B.P.V., Pakhomov, E.A., Holmes, K., Lu, Y. and Quayle, L. (2018), "Using unmanned aerial vehicles (UAVs) to measure jellyfish aggregations", *Marine Ecology Progress Series*, Vol. 591, pp. 29-36, doi: 10.3354/MEPS12414.

Seo, J., Duque, L. and Wacker, J. (2018), "Drone-enabled bridge inspection methodology and application", *Automation in Construction*, Vol. 94, pp. 112-126, doi: 10.1016/J.AUTCON.2018.06.006.

Siwiec, J. (2018), "Comparison of airborne laser scanning of low and high above ground level for selected infrastructure objects", *Journal of Applied Engineering Sciences*, Vol. 8 No. 2, pp. 89-96, doi: 10.2478/JAES-2018-0023.

Skorupka, D., Duchaczek, A., Waniewska, A., Kowacka, M. and Debita, G. (2020), "Identifying the possibility of using unmanned aerial vehicles in the process of construction projects implementation", *In: XV International Conference on Durability of Building Materials and Components (DBMC 2020) Scipedia, S.L.* doi: 10.23967/DBMC.2020.221.

Szywalski, P. and Waindok, A. (2020), "Practical aspects of design and testing unmanned aerial vehicles", *Acta Mechanica et Automatica*, Vol. 14 No. 1, pp. 50-58, doi: 10.2478/AMA-2020-0008.

Tatum, M.C. and Liu, J. (2017), "Unmanned aircraft system Applications in construction", *Procedia Engineering*, Vol. 196, pp. 167-175, doi: 10.1016/J.PROENG.2017.07.187.

Walczyński, M., Bożejko, W. and Skorupka, D. (2017), "Parallel optimization algorithm for drone inspection in the building industry", *In: AIP Conference Proceedings [Internet]*, Vol. 1863, p. 1863, doi: 10.1063/1.4992399.

Yang, H., Lee, Y., Jeon, S.Y. and Lee, D. (2017), "Multi-rotor drone tutorial: systems, mechanics, control and state estimation", *Intelligent Service Robotics*, Vol. 10 No. 2, pp. 79-93, doi: 10.1007/S11370-017-0224-Y.

Yi, W. and Sutrisna, M. (2021), "Drone scheduling for construction site surveillance", *Computer-Aided Civil and Infrastructure Engineering*, Vol. 36 No. 1, pp. 3-13, doi: 10.1111/MICE.12593.

Yusof, H., Ahmad, M.A. and Abdullah, A.M.T. (2020), "Historical building inspection using the unmanned aerial vehicle (UAV)", *International Journal of Sustainable Construction Engineering and Technology*, Vol. 11 No. 3, pp. 12-20, doi: 10.30880/IJSCET.2020.11.03.002.

Zhou, S. and Gheisari, M. (2018), "Unmanned aerial system applications in construction: a systematic review", *Construction Innovation*, Vol. 18 No. 4, pp. 453-468, doi: 10.1108/CI-02-2018-0010.

Corresponding author
Mariusz Szóstak can be contacted at: mariusz.szostak@pwr.edu.pl