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Table of contents

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7. A UAV-based 3D model for building condition monitoring

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Abstract: The aim of the paper is to introduce a tool for the accurate assessment of the technical condition of buildings. The proposed methodology is becoming an efficient strategy for the massive inspection of building stocks, in big residential areas. The authors have developed an utility based on high-performance images captured by Unmanned Aerial Vehicles (UAVs). The flights of the UAVs have been technically protocolized in order to get the proper high-quality information about the real condition of the building. After collecting the images a 3D model is generated and orthophotos of building facades are created. The graphical information is connected with tables of attributes which allow the interactive geo-referenced management and assessment. Main requirements and advantages of this visualization technique will be presented by analyzing a particular case study. The selected example will allow the illustration of the methodology. Ongoing developments and technical details about the information system and the analysis platform connected with the visualization tool will be also reported.

Keywords: Condition monitoring, Unmanned aerial vehicles, inspection methodology, building facades

7.1. Introduction, motivation and background

"*Przybilla and Wester-Ebbinghaus (1979) did the first experiments with UAVs (Unmanned Aerial Vehicles) in photogrammetric applications. At that time, results were not sufficient because of the vibrations caused by the rotor which resulted in image motion. …With this system, it was possible to acquire images of an archaeological area, architecture and building sites…*" (Eisenbeiss, 2004). Twenty years later, Zischinsky, Dorfner and Rottensteiner (2000) used images taken from a model helicopter partly for the generation of a 3D-model of an historical mill. In the last two decades, there has been a growing demand in using UAVs for monitoring, surveillance and information collection tasks. The application contexts and the objectives are different and diverse: marine-oceanic missions (Rubio, Vagners and Rysdyk, 2004), (Reineman, Lenain and Melville, 2016), (Schaub *et al.*, 2018), natural disasters detection and monitoring (Alexis *et al.*, 2009), (Neto *et al.*, 2012), (Popescu, Ichim and Caramihale, 2015), surveillance of complex urban environments (Semsch *et al.*, 2009), among others. In some cases, also the use of multiple UAVs for a persistant surveillance aim has been also considered, and specific optimized algorithms have been studied (Nigam *et al.*, 2012).

Despite the above-mentioned applications and research, the use of UAVs for collecting accurate information in a building, aiming to asses and monitor its technical condition, has not been too much considered. Seminal studies have been developed by Eschmann *et al.* (2012), Hallermann, Morgenthal and Rodehorst (2015), Banaszek, Banaszek and Cellmer (2017) and by Serrat *et al.* (2018, 2019a, 2019b). Within this background, the main aim of this paper is to introduce the preliminary steps for a tool for the accurate assessment of the technical condition of buildings, as an efficient strategy for the massive inspection of building stocks, in big residential areas. The methodology is based on high-performance images captured by UAVs, and it is motivated by authors' previous works in the context of the Building Research Analysis and Information Network (Serrat and Gibert, 2011), (Serrat *et al.*, 2017).

The paper is organized as follows. In Section 7.2 the methodology will be introduced, in particular details on the flights mission and the 3D model will be given. Description of the case study, results and discussion will compose Section 7.3. The paper ends with a summary of the main conclusions.

7.2. Methodology

In recent years, research has developed following use of digital images obtained from the UAVs to monitor the technical condition of buildings and inventories of technical infrastructure. Conventional state-of-the-art inspections are primarily based on visual research methods. New UAV data acquisition technologies offer new opportunities in this field. The method of visual building inspection using UAV is generally divided into two stages: data acquisition (in-flight) and digital post-processing (post-flight) (Eschmann *et al.,* 2012). The type and quality of the data obtained using UAVs depends largely on installed on them sensor, the technical capabilities and planning of photogrammetric flights. The flight mission of the UAVs has been technically protocolized in order to get the proper high-quality information about the real condition of the building.

Based on that, the following methodology of a fully interactive visualization is proposed which is used for building condition assessment.

7.2.1. Data acquisition

7.2.1.1. Assessment of flight conditions (preparation for the flight mission).

Based on the available data sources including project documentation, maps, digital images, video, field vision, etc., the flight area is assessed: density of buildings, overhead lines, directional antennas and masts, height of chimneys, density of the stand, interference (WiFi networks, directional antennas), height of buildings.

For the assessment of meteorological conditions (see Fig. 7.1), the following is checked: a) temperature: average temperature, perceptible temperature, dew point temperature, b) precipitation: relative humidity, rainfall, snowfall, convective precipitation occurrence, sea level pressure, c) wind: average wind speed, maximum gusts of wind, wind direction, d) cloudiness: cloud base, cloud cover, fog.

Evaluation of the possibility of occurrence of undesirable phenomena such as a) downslope winds - arising at the edges of roofs, air collapse, b) turbulence - caused by dense buildings with objects of irregular shapes and a large number of other altitude objects and trees, c) strong wind gusts occurring in the urban canyons, significantly exceeding gusts indicated in local weather forecasts. Analysis based on available sources of national and international data: maps, weather forecasts, field vision.

The last step is checking the legal status of the property and the nearest neighbourhood based on available data sources including project documentation, geoportals, maps, land and mortgage registers, field vision. At this stage, it should be checked whether the building subject to inspection is not located on or near the statutory prohibition of UAV flying.

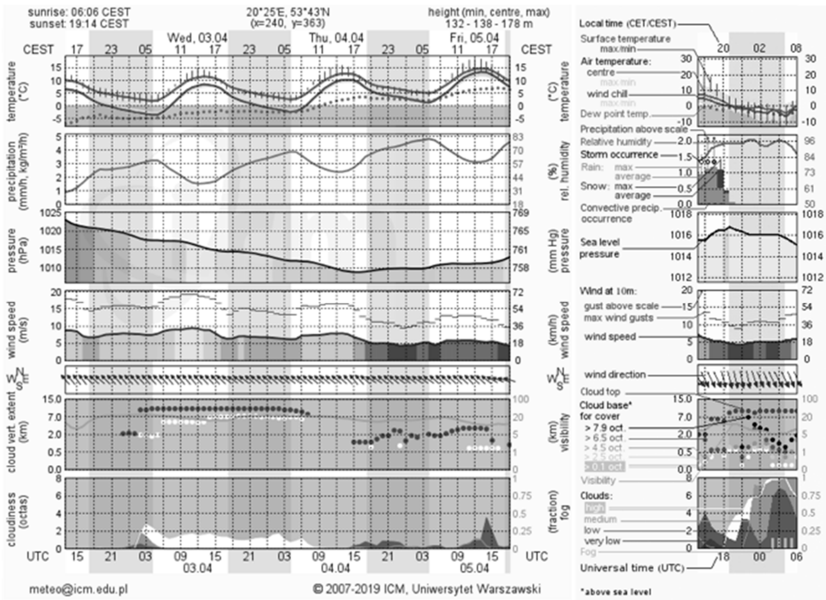


Fig. 7.1. Model UM – meteorogram

7.2.1.2. Law and airspace control (preparation for the flight mission).

The flight mission should be performed in accordance with national law. For example, in this research case study, using UAV for commercial and scientific purposes requires in Poland a qualification certificate of UAVO unmanned aircraft operator (a pilot certificate). This requires Art. 95 of the Law of July 3, 2002, Aviation Law, and the detailed rules for obtaining the certificate are contained in the Regulation of the Minister of Transport, Construction and Maritime Economy of 3 June 2013 on certificates of qualification. It is received by the operator after the completion of theoretical and practical training and passes the state examination, which is conducted by an examiner appointed by the Polish Civil Aviation Office. Civil air traffic in Poland is organized in accordance with international regulations provided by International Civil Aviation Organization (ICAO). Flight operations are performed in controlled airspace (CAS) or uncontrolled airspace. The division contains different approach to flight planning (FP) and group specific types of airspace users (AUs) and aircrafts types (Lichoń, 2017).

7.2.1.3. Selection of a suitable UAV and sensors.

The selection of an appropriate UAV is of key importance to the implementation of the flight mission. Due to the specificity of flights for the purpose of assessing the condition of buildings, the best results are achieved by multirotor (Eschmann *et al.*, 2012), (Nex and Remondino, 2014), (Zhou and Gheisari, 2018). Types of multirotors:

- Super light - weighing up to 0.6 kg (e.g. DJI MAVIC) - the biggest advantage is the weight, such UAVs are subject to simplified legal regulations, the biggest disadvantage is susceptibility to wind and turbulence.
- Lightweight - weighing up to 1.5 kg (e.g. DJI Phantom 4) - the biggest advantage is versatility, it can be used for most applications; the biggest disadvantage is the lack of an interchangeable sensor.
- Medium heavy - weighing up to 5 kg (e.g. DJI Inspire One, Yuneec Typhoon H520) - the biggest advantage is the replaceable sensor, it can be used for most applications; the biggest disadvantage is the short flight time.
- Heavy - over 5 kg (eg DJI MATRICE 600) - the biggest advantage is the possibility of using specialized heavy sensors, they can be used for most applications; the biggest disadvantage is inertia in flight.

The use of light and medium heavy Unmanned Aerial Vehicles is optimal for this type of flight mission. In the case of selecting a UAV with a non-replaceable sensor, a multirotor should be selected in such a way that the sensor RGB parameters allow to get the high-quality information about the real condition of the building. In the case of removable sensor, it should be noted how the installation of the sensor changes the parameters of the UAV which decided on its choice. Examples of technical parameters of sensors RGB according to the price range: a) low - 12 megapixel 1/2.3 inch, fixed lens; b) medium - 20 megapixels 1 inch, fixed lens; c) high - 24 megapixels, 4/3 inch, interchangeable lens.

For data recording, the digital camera is controlled by an automatic photo-firing sequence. Depending on the sensor and distance from the object, you can obtain the resolution of the BRD (Building Resolved Distance) at 0.3 mm BSD (Building Sampling Distance) at the level of 0.1-1.0 cm/pix.

$$BRD = d \cdot \frac{\Delta x_i}{f} \tag{7.1}$$

where *BRD*: Building Resolved Distance,

d: distance of the sensor from the facade/roof of the building,

Δx_i: the size of the smallest detail of the facade/roof depicted in the picture,

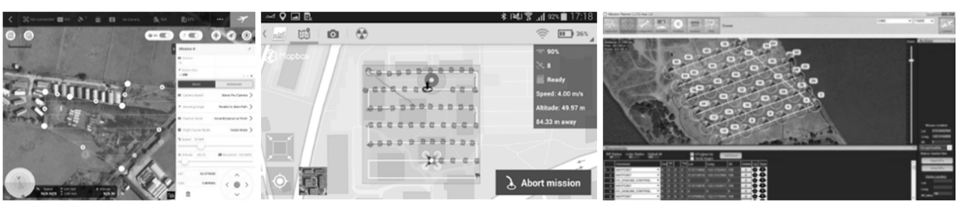
f: focal length of the sensor.

7.2.1.4. Flight mission.

The types of flight operations are: VLOS (Visual Line of Sight) operations in which the pilot or observer maintains direct eye contact with the UAV; FPV (First Person View) operations in which the operator pilots the UAV, not maintaining direct eye contact with him, determining its location in the airspace by the image transmitted in real time to the ground by devices mounted on its board; BVLOS (Beyond Visual Line of Sight) operations in which the UAV pilot does not maintain direct eye contact with unmanned aircraft, including automatic flights.

Due to the specificity of flight mission, VLOS operation flights are preferred. A detailed planning of a flight mission is a fundamental prerequisite for a successful acquisition of UAV data sets. VLOS flights for the purpose of visual building inventory and the creation of 3D model are performed according to standard rules.

The mission is normally planned with dedicated software. Hence manual flight control is currently still the only option to perform when flying close to a building and require from the UAV's operator to be highly skilled in piloting, assessing flight conditions and predicting in-flight abnormalities. According to Eschmann *et al.* (2012) there are two options of flight patterns available when using an UAV for the building inspection in order to have a images allocated to the real object in a structured way: on the one hand, the flight path can be allocated horizontally as a storey-wise scanning of the building, and on the other it can follow vertically aligned slices. Due to the technical aspects of UAV control and legal regulations, the flight close to a building should not be in circular patterns to capture information to ensure consistent overlap. Of course, there are professional photogrammetry and UAV mapping software that facilitate horizontal flight, for example, useful for roof inventory: https://www.pix4d.com/ Dedicated, Universal, and Open source (see Fig. 7.2).



a) b) c)

Fig. 7.2. UAV mapping software: a) Dedicated (DJI GS Pro app), b) Universal Pix4Dmapper, and c) Open source APM (ArduPilot Multiplatform) Pilot

In Fig. 7.3 the red line presents the vertical flight plan, made for the purpose of generating the orthophoto facade (the flight is usually performed in manual mode). The green line presents a horizontal flight plan, made for the purpose of generating the orthophoto roofs. This type of flight can be implemented using professional photogrammetry and UAV mapping software.

According to Nex and Remondino (2014) three primary flight modes have been identified. These are manual, assisted, or autonomous. In connection with the

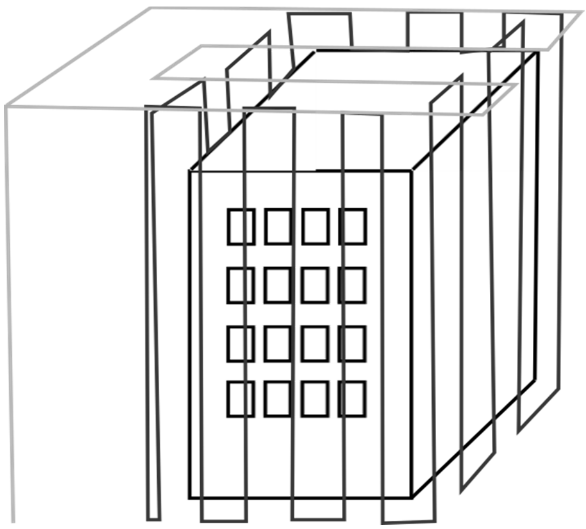


Fig. 7.3. Schematic UAV flight plan

above the flight should be implemented in a mode that provides control in any phase of the flight (GPS mode), however, due to interference near the buildings often should be selected the ATTI mode or manual (excluding some or all electronic flight assistance systems).

7.2.2. Digital Post-processing

7.2.2.1. Control of the data obtained from Unmanned Aerial Vehicles

In the manual flight mode, special attention should be paid to the quality control of the data obtained. During the inspection, the following is checked:

- Geometric accuracy of the flight line. Keeping on the designed flight's line is difficult due to variable wind conditions (including turbulence), interferences in the operation of UAV positioning systems and manual control mode.
- Minimum longitudinal and transverse overlap of digital images. Camera can be controlled manually to set zoom, focus and shutter release if necessary or controlled by an automatic photo-firing sequence and the short distance from the object makes it necessary to maintain a small flight speed. These factors have a negative effect on maintaining the correct parameters.

- Image quality. Better image quality is achieved more easily with larger pixels on sensors. High resolution sensors are required to provide the level of detail needed from an aerial digital image. Factors such as low fixed flight speed in manual mode, small distance to the object and variable lighting conditions have a negative impact on the quality of digital images acquired by UAV.
- Image exposure correctness. Obtaining homogeneous effects in terms of exposure is very difficult to achieve, due to weather conditions (clouds), terrain conditions (high objects casting a shadow), geometry of the object (complex shape), lens parameters (maximum aperture size), time of flight mission (changes in flight altitude and angle of sunlight), a large number of acquired images. Usually aerial images require a radiometric correction in the post-process.

UAV flight mission generates a large amount of data due to the automatic triggering of the camera. The number of photos is much greater than the amount needed for the next visual inspection. In addition, there is often a very large overlap of the area captured on each image, which varies depending on the speed of the hinge parallel to the facade of the building. Therefore, unnecessary records are eliminated if the overlap is too large to avoid double or multiple information in the images and to keep the image database as small as possible without losing quality (Eschmann *et al.*, 2012).

7.2.2.2 Generation of elevation and roof orthophotos

The standard process of generating the orthophoto map is shown in Fig. 7.4. Currently, highly specialized software is used for the generation of orthophoto. This allows the entire process to be performed in automatic mode, using standard processing settings or in supervised mode (supervised images classification) with the possibility of influence on selected processing parameters.

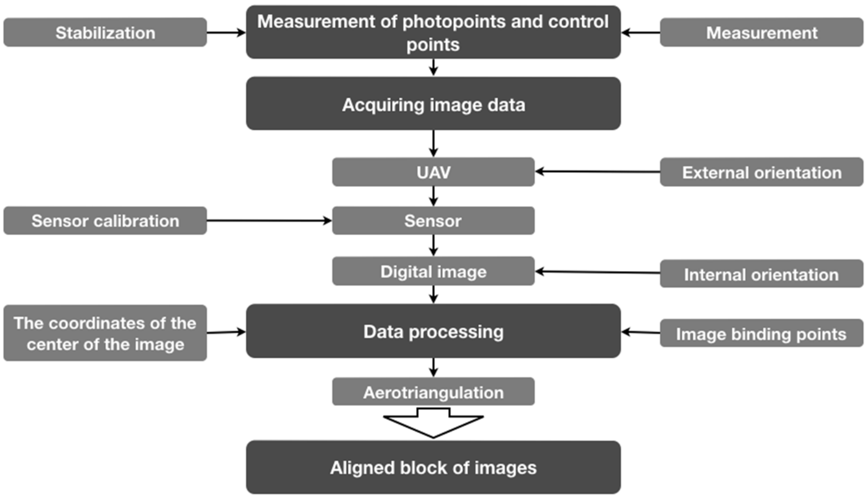


Fig. 7.4. The process of generating an orthophoto map based on UAV images

Regardless of the type of software used, generating a good quality orthophoto of the facade (see Fig. 7.5) is more difficult than generating a good quality orthophoto map or roof plan.

Fig. 7.5. Example of elevation orthophoto generated on UAV images, and enlargements

7.2.2.3. Generating a 3D model

Cleaning the point cloud and recalculating for the purpose of generating orthophotos also has a positive effect on improving the geometry and aesthetics of the generated 3D model. Originally, on the model generated automatically, there are numerous artifacts, especially in the area of roofs, antennas, chimneys, pillars, overhead lines and facade decorative elements. Not all of them can be eliminated by cleaning the point cloud or selecting the appropriate processing parameters. Other artifacts should either be accepted or corrected in a 3D graphics program. Nevertheless, from the authors' point of view, such interference in the material obtained is unacceptable.

7.2.2.4. Vectorization

The next step is vectorization and creation of attributes tables. Among the vector layers, the most commonly used are:

- Image layer (a point layer). A layer indicating the place of release of the shutter, enabling the preview of images taken directly in the analyzed part of the object, without the need to know their location in the catalog or name.
- Grid layer (a polygon layer). A layer containing a grid of squares of the selected size that allows linking the results of the inspections to a specific part of the object. It allows for qualitative and quantitative analysis of the phenomena studied, taking into account spatial and localization attributes.
- Analytical layer (a layer of polygonal most common). Comprising a vectorized content according to the analytical needs.
- Layer of forms (a point layer). A layer containing links to documents referring directly to a selected part of the space, enabling the preview of documents, including forms made during the field vision, without the need to know their location in the catalog or name

The most frequently used software at this stage is the open source QGIS solution; a commercial alternative can be, for example, ArcGIS software.

7.2.2.5. Interactive 3D model

Combination of previously developed elements:

- digital images - in the form of graphic files,
- orthophoto plans - in the form of raster files,
- information and analytical layers - in the form of vector files,
- text documents - in the form of * .pdf files,
- 3D model - in the form of files, e.g. * .obj

on one platform it allows intuitive use and easy access to data of interest to the user without the need to know the structure of names, file directories, databases or the ability to use specialized software.

7.3. Results and discussion

As a research case study, the building was selected taking into account the visible technical wear of the facade, the complicated shape and roof, and its location in a dense urban surrounding. The complex shape of the building caused the need to adjust the flight plan accordingly. The flight plan was developed separately for each of the 6 facades (see Fig. 7.6) and one for the whole roof, and 7 flights were planned and carried out in total. The location in dense urban buildings required great caution during the flight. The location of the sidewalks and the roadway next to the building caused the necessity of interrupting the flight when pedestrians or cars appeared, in particular buses. Despite considerable difficulties, the flight was carried out, which finally confirmed that the proposed solution can be used for the majority of buildings requiring a technical condition assessment.

The experiment uses the DJI Inspire One lightweight quadcopter with the following specifications: weight: 2935g, vertical GPS accuracy: 0,5 m (accuracy determination), horizontal GPS accuracy: 2,5 m (accuracy of X, Y coordinates), Climb speed: 5 m/s, max. drop speed: 4 m s, max. cruising speed: 22m/s (ATTI mode, no wind), maximum flight height: 4500 m ASL (Above Sea Level), max. wind force:10 m/s, flight time: 18 minutes, operating temperature: -10 ° to 40 ° C, size: 438x451x301 mm. Digital camera (RGB sensor) has been used to obtain digital images with the following specifications: 12Mpix resolution (4000x3000), physical size 6.170mm x 4.628mm, focal length: 3.55mm. The flight was carried out at high humidity and transient slight rainfall, the temperature was about +5 degrees, wind at about 5 m/s (in gusts up to 10 m/s).

As can be seen in Fig. 7.6, despite the difficult weather conditions, vertical flight lines, including the assumed longitudinal and transverse overlap, have been preserved.

During the flight, 818 photos with a volume of 4.06 GB were made. As part of the inspection, no blurry photos were found and all of them were included in the processing process performed in the Pix4D software.

A desktop computer with the following parameters was used for processing: CPU: Intel (R) Core (TM) i7-2600 CPU @ 3.40GHz; RAM: 16GB; GPU: NVIDIA GeForce GTX 750 (Driver: 25.21.14.1694). The total processing time in the first iteration with standard processing settings was almost 7 hours:

- Time for Point Cloud Densification - 3 hours. 44 min.
- Time for 3D Textured Mesh Generation - 28 min.
- Time for DSM Generation - 42 min.
- Time for Orthomosaic Generation - 1 hour. 42 min.

The following results of processing have been achieved:

- GSD at the level of 0.36 cm / pix.
- 817 out of 817 images calibrated (100%), 1 images disabled.

- 1.93% relative difference between initial and optimized internal camera parameters.
- Median of 13924.4 matches per calibrated image.

At this stage, it can be confirmed that the coating, despite the difficulties, was made correctly and the material can be used to generate the facade and roof elevation for the purpose of assessing the technical condition of the building. The final effect in the form of a 3D model generated in the 3rd iteration after cleaning the point cloud and recalculating the design is shown in Fig. 7.7.

7.4. Conclusions

In summary, according to the aim of the paper introduced in Section 7.1, in the context of a smart city where the monitoring and prediction on building condition is permanently assessed, a) a comprehensive protocol of flight missions has been established and, b) a full interactive visualization method based on high-quality images from UAVs has been developed.

Specifically, the proposed methodology is an efficient strategy for the massive inspection of building stocks, in big residential areas. The graphical information, collected and processed by the platform, is connected with tables of attributes which allow the interactive geo-referenced management and assessment.

Ongoing developments include the link of the inspection tables as well as the Followup-and-Decision QGIS analysis platform described in Serrat *et al.* (2017) in information and analytical layers, in order to prepare the corresponding monitoring and prediction assessment documents.

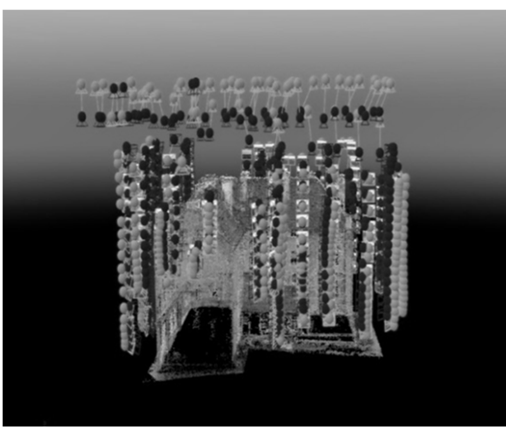


Fig. 7.6. Location of images (view of the west facade)

Fig. 7.7. 3D model generated after three iterations

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