Application of Modern Technologies in Assessing Facade Condition of Building Structures

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SUMMARY

After many years of exploitation, the building structure itself in most cases still fulfills its intended purpose. However, its exterior, especially the facade, most often does not meet the quality requirements, whether as a result of the process of deterioration or changed requirements regarding the technical characteristics and appearance of the object. Exploring the possibility of restoration of the building exterior requires determining the technical condition of the facade. In the modern practice of facade inspection, there are several technologies of data acquisition and processing in order to optimize the process itself: to obtain the best possible knowledge about the degree of facade's deterioration and damage, with minimal time consuming. With the development of modern instruments and sensors, as well as the rapid growth of data processing capabilities in various software solutions, the approach to the realization of facade inspection projects has changed. This paper will review two modern technologies that are used in the facade inspection process – terrestrial laser scanning and UAV-based photogrammetry. The focus is given on how data is collected and processed and advantages and disadvantages of both methods.

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1. INTRODUCTION

Roads, bridges, buildings, towers, dams and similar structures over time lose their performance due to the action of various external and internal forces. Changes in the mechanical properties of structural elements due to aging; natural disasters such as earthquakes, landslides and floods; climate change - the influence of wind, changes in temperature and groundwater levels; as well as dynamic and static loads of the structure have the most common impact on deformation occurrence. The effects of these forces on structure result in: bending, slope, torsion and distortion (Marković et al., 2019), (Peltola et al., 2009). One of the most common and most obvious indicators of the effects of adverse impacts on a building is the appearance of cracks on the façade.

Like many other disciplines, imperatives in job include quality, cost-effectiveness, efficiency, minimal time consumption and automatization. With the development of modern surveying technologies, a precondition for fulfilling these requirements in the field of assessment of the technical condition of the facade has been created. Namely, the traditional approach to this process entailed visual inspection, which is expensive, time consuming and leads to data redundancy. Modern laser scanning and photogrammetry technologies are faster, more reliable, objective, accurate and, accordingly, their use is fully justified. The importance of inspecting the building's facade is confirmed by the fact that operational phase of a building is the main contributor to the building lifecycle cost (Bortolini & Forcada, 2018).

The paper will describe in detail technology of laser scanning and photogrammetry (UAV - *Unmanned Aerial Vehicle*), in terms of the principles of the technology itself, how data is collected, processed and the results that can be obtained. On this basis, a comparative analysis of these technologies will be given in terms of their advantages and disadvantages, as well as a recommendation on which technology is best to use depending on the environment and the building itself.

2. LITERATURE REVIEW

Numerous papers deal with this very topic - the use of modern technologies in the process of assessing the condition of the building's facade, as well as how these technologies can be further developed in order to increase their accuracy and performance.

(Choi, Yeum, Dyke, & Jahanshahi, 2018) developed a procedure for visual inspection of building façades using UAV images. Developed technique includes three major steps: image collection using UAV, orthophoto generation using a SfM (*Structure-from-Motion*) technique and regions-of-interest localization. They also gave guidelines for quality image collection of TBF (*Target Building Façades*). In order to demonstrate and validate developed method, they conducted case study on the damaged steel frame building covered with window panes and masonry cladding in West Lafayette, IN, USA. 3DR Solo Quadcopter UAV (Table 1) was used for data acquisition. UAV flied along a horizontal grid pattern, with the distance 4-5 m from the façade with flying speed suited for producing more than 60% overlap between images.

(Banaszek, Zarnowski, Cellmer, & Banaszek, 2017) investigated the possibility of using digital images obtained from the UAV platform to support the urban regeneration process where one of the goals was to determine the technical condition of buildings and structures. Case study was conducted in Olsztyn city in Poland. UAV DJI Inspire 1 (Table 1) was used for data acquisition, while software packages Pix4D and QGIS were used for data processing. In case of cubature objects (buildings) flights were carried out manually and resulted with orthofacade with an accuracy greater than 1 cm/pix (used parameters: longitudinal and transverse coverage - 90%, distance 5 to 10 m), point cloud allowing to perform measurements with an accuracy of less than 1 cm and 3D model.

(Russo, Carnevali, Russo, Savastano, & Taddia, 2019) performed close range photogrammetric survey using very small and ultra-lightweight drone (less than 300 g) equipped with a low-cost camera with aim to analyze a historical building façade in Bologna (Italy). The photogrammetric survey of the façade was performed with UAV DJI Spark (Table 1) with a distance of 13 m from the façade and parallel camera angle. The flight was manual (due to the low signal with the GNSS satellites (*Global Navigation Satellite System*), that was interrupted by tall buildings and narrow street) and resulted with an average *Ground Sample Distance* (GSD) of 4.5 mm. Image overlapping in the vertical direction was 80%, which was ensured with capturing of images at a distance of approximately 3 m along the single vertical paths, while vertical paths were distanced about 8 meters which ensured 60% of overlapping in horizontal direction. Moreover, total station was used to obtain points for identification of architectural features on building façade. Some of the surveyed points were used as a control points and others as check points for validation of a model. The case study resulted with dense point cloud and ortho-image of whole façade.

(Hallermann, Morgenthal, & Rodehorst, 2015) presented a method for visual inspection based on high quality UAV aerial photos. Within the case study, a façade of an office building was manually recorded with multirotor platform AscTec Falcon 8 (Table 1). West façade that was heavily damaged was recorded from distances of 5 m, 7.5 m and 10 m in several vertical lines, with adequate image overlapping in both directions. Façade damages were documented and measured in traditional way, while crack detection was also conducted manually by analyzing aerial images and results were compared. Selected cracks were measured with crack widths of 0.1 up to 1.0 mm. The analysis of aerial images has shown that high quality images allow visual identification of 0.3 mm cracks from a distance of 10 m to the surface. Authors stated that this is achievable only in case of sharp images, and images that have good exposure and the lowest possible image noise. Additionally, cracks with a crack width of 0.5 mm are clearly visible from a distance of approximately 7.5 m to building surface.

(Calantropio, Chiabrando, Rinaudo, & Teppati Losè, 2018) stated that in case of deteriorated facades in an historical building, the mapping of the deteriorations is one of the crucial preliminary operation to be achieved and image and range-based sensors and techniques can support the subsequent analysis that need to be conducted with the data collected on the field. Survey of Cultural heritage assets usually does not require high accuracies, except in case of structural monitoring or reverse engineering processes. In many cases (buildings or part of them, urban centres, natural landscapes), accuracies of about 2÷10 cm could be sufficient for each kind of intervention and support the generation of products at a scale of detail between 1:100 and 1:500.

Table 1 – Specification of drones used in reviewed studies

	DJI Spark	**DJI Inpire 1**	**3DR Solo**	**AscTec Falcon 8**
				
AIRCRAFT SPECIFICATION				
Take-off weight	0.3 kg	3.06 kg	1.5 kg	2.3 kg
Dimensions	143x143x55mm	438x451x301 mm	460x460x250 mm	770x820x125 mm
Max flight time	16 min	18 min	25 min	12–20 min
Operating temperature range	0°C to 40°C	0°C to 40°C	0°C to 45°C	-5°C to 35°C
Max wind force	~ 8 m/s	10 m/s	11 m/s	15 m/s
CAMERA SPECIFICATION				
			Canon PowerShot SX280 HS	Sony Alpha 7R
Sensor	1/2.3" CMOS Effective pixels: 12 MP	1/2.3" CMOS Effective pixels: 12.4 MP	1/2.3" CMOS Effective pixels: 12.1 MP	CMOS 26.3 MP
Lens	25 mm	20 mm		
Image resolution	3968x976 px	4000x3000 px	4000x2664 px	7360x4912
Focal length	4.49 mm	3.55 mm	4.5–90.0 mm	

Reviewing the literature, it became obvious that application of digital photogrammetry method (UAV) in assessment of building facades is still developing and there is a need to establish standardized procedures and methodologies for UAV-based visual inspections of building facades.

The use of *Terrestrial Laser Scanner* (TLS) technology as an inspection tool has been the subject of a number of recent studies. At present, TLS is used in multiple civil engineering applications, such as dam monitoring, landslide monitoring, bridge monitoring, motorway and tunnel monitoring, façade deformation analysis, assessing architectural heritage and other unusual fields like forestry inventory, environmental monitoring and crime scene reconstruction. For the purposes of this research, emphasis is placed on studies based on façade inspection, crack detection and heath monitoring.

A large number of scientists have focused only on TLS spatial data analysis to detect changes on a building's surface (Erdélyi, Kopáčik, & Kyrinovič, 2018), such as cracks and cavities (Valenca, Puente, Julio, Gonzalez-Jorge, & Arias-Sanchez, 2017), (Laefer, Truong-Hong, Carr, & Singh, 2014), (Law, Holden, & Silcock, 2015), whereas the intensity data recorded by TLS has been studied by multiple scientists over the last decade. This intensity can be effectively used to identify different changes in the surfaces of walls (Suchocki, Jagoda, Obuchovski, Šlikas, & Sužiedelytė-Visockienė, 2018), moisture (Tan, Cheng, Ju, & Wu, 2016) and biodeterioration (mosses and lichens) (Herrera, Le Borgne, & Videla, 2009). Currently, the use of the intensity value in diagnostic measurements is of special interest. It should also be noted that, apart from diagnostic measurements intensity data can also be used to identify various elements in point clouds, e.g., in 3D façades modelling (Faltynova, Matouškova, Šedina, & Pavelka, 2016) which can provide more accurate deformation, load response, and structural behaviour estimates.

(Erdélyi et al., 2018) performed construction control of the anchor blocks of the facade of the building complex of 110 m height using terrestrial laser scanning with uncertainty of position σ = 7 mm. (Valenca et al., 2017) presented method combining image processing and terrestrial laser scanning, aiming at assessing cracks in concrete. (Laefer et al., 2014) showed that TLS can consistently acquire data points for detecting cracks widther than 5 mm. (Law et al., 2015) have conducted the assessment of crack development in concrete using a TLS. Their study found that TLS technique could provide an indication of where and when cracking will occur in the future, but they also couldn't detect cracks 4 mm wide. (Suchocki et al., 2018) showed that the analysis of intensity distribution may be successfully used for detecting construction damages, such as cavities or cracks. (Giri & Kharkovsky, 2016) were able to develop a crack index or crack indicator using *Root Mean Square Deviations* (RMSD) from observations using a laser distance sensor. Their study found that these RMSD values supplied a reliable indication of crack presence and crack width for laboratory specimens. (S. W. Park, Park, Kim, & Adeli, 2015) presented health monitoring of structures using TLS and adopted a displacement measurement model to improve the accuracy of the measurements. (Yang, Xu, Xu, & Neumann, 2017) employed TLS to collect the deformation information of concrete composite structures.

Major players in the terrestrial laser scanning market include 3D Digital Corporation (US), Carl Zeiss Optotechnik (Germany), Creaform (Canada), FARO Technologies (US), Maptek (Australia), Trimble (US), RIEGL Laser Measurement Systems (Austria), Teledyne

Technologies (US), Topcon (Japan), Hexagon (Sweden) and Zoller + Fröhlich (Germany), among others. The terrestrial laser scanning market is estimated at USD 3.0 billion in 2018 and is projected to reach USD 4.4 billion by 2023, at a CAGR of 8.17% from 2018 to 2023 ("Markets and markets," 2019). In Table 2 are given technical specifications of some most commonly used Terrestrial Laser Scanners.

Table 2. Comparisons of latest Terrestrial Laser Scanners parameters (*Data Sheet, FARO Laser Scanner Focus 3D X 130 HDR*, 2018), (*Data Sheet, Laser Scanner Focus 3D*, 2015), (Leica Geosystems, 2011), (*Data Sheet, RIEGL VZ-400i*, 2019), (*Data Sheet, Z + F Imager ® 5006/5010*, 2016)

		RIEGL VZ 400i 	**Z+F IMAGER® 5016** 	**Leica ScanStation C10** 	**FARO® Focus3D X** 
Max. measurement range		800 m	360 m	300 m	330 m
Minimum range		0.5 m	0.3 m	0.1 m	0.6 m
Measurement rate (meas./sec)		42,000 - 500,000	1,100,000	50,000	976,000 - 2,000,000
Accuracy		5 mm	1 mm +10 ppm/m	4 mm	2 mm
Precision		3 mm		2 mm	
Measuring principle / Mode of operation		time of flight measurement/ single pulse ranging	phase-shift	time of flight measurement/ single pulse ranging	phase-shift
Angle measurement resolution	**Horizontal**	0,0005°	0,00018°	0,0012°	19 arcsec
	Vertical	0,0007°	0,00026°	0,0012°	19 arcsec

3. UAV-BASED PHOTOGRAMMETRY

In order to overcome the challenges related to the traditional building facades assessment approach, new assessment methods based on UAV data acquisition technologies have been developed. UAV, also known as drone, represents an unmanned aircraft vehicle controlled by a ground operator or computer located within the vehicle. UAV is a part of UAS (*Unmanned Aerial System*) that usually consists of an aircraft platform mounted with one or more sensors combined with a ground-based control station from where it is operated. The sensor typically comprises an inexpensive, nonmetric, consumer-grade digital camera, from which small-format overlapping images are acquired for photogrammetric purposes (Woodget, Austrums, Maddock, & Habit, 2017). A variety of UAV system has been developed and some of them includes the fixed-wing aircraft, chopper, multi-copter, motor parachute and glider, congregating ready-made parts and commercialized UAV. Based on landing, they can be divided into *Horizontal Takeoff and Landing* (HTOL) and *Vertical Takeoff and Landing* (VTOL) (Singhal, Bansod, & Mathew, 2018).

Within data acquisition, the object must be captured from a minimum of two camera positions in order to obtain information about the three spatial coordinates. The created imagery represents a stereo pair that allows creation of object's 3D model that provides information about its real dimensions (shape, position, size). Based on the analysis and measurement of UAV-collected two-dimensional images, automated digital photogrammetric method SfM is used for reconstruction of physical objects. The result of SfM image processing, beside 3D model, could be also a digital terrain model, point cloud, orthophoto image or orthophoto map. Quality and usability of images acquired by UAV depends on the number of parameters that should be defined within the mission planning phase. These parameters should be defined in relation to the mission goal.

Human vision also works on the principles of stereo visualization since human can create a spatial image of the environment by seeing it with two eyes. Information reaching the brain is automatically recognized as a three-dimensional space. The computer works in a slightly different way as automatism has been replaced by complex mathematical models that make it possible to determine the exact position of an object in any coordinate system (Stojaković, 2006).

2.1 UAV photogrammetric workflow

(Nex & Remondino, 2014) gave the general workflow for UAV data acquisition and image processing (Figure 1). Green fields represent input parameters, while single workflow steps are shown in the yellow fields.

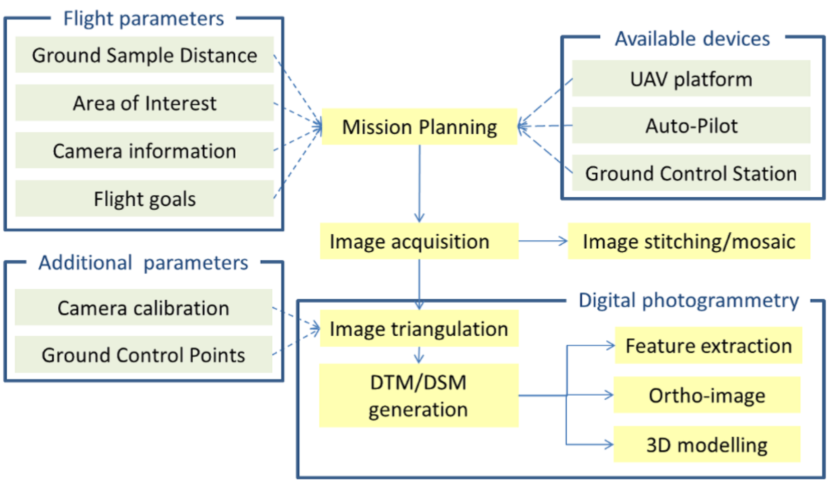

Figure 1 - General workflow for acquisition and processing of UAV images (Nex & Remondino, 2014)

Presented workflow is divided into three phases: mission planning, image acquisition and data processing.

Mission plan should be established based on the area of interest, the acquired GSD and camera specification. Parameters that should be defined in this stage are flight mode, path, speed, image overlaps, camera angle, flight altitude and distance from the target surface. The selection of optimal flight parameters depends on the mission goals, as well as on the available devices. Factors that should also be considered in the process of flight planning are limitations related to UAV battery life, legal regulations and weather conditions.

Within the *image acquisition* phase, flight is usually performed in manual or autonomous mode, based on the performances of available devices (platform, auto-pilot and GCS - *Ground Control Station*) affecting the quality of the collected data. In autonomous mode the flight path is set based on GNSS/INS (*Inertial Navigation System*) waypoints which UAV will follow using navigation system (auto-pilot). In this case, GCS observes UAV platform providing insight into real-time flight data such as drone position, flight speed, attitude and distances, battery level, etc. In manual mode, platform is remotely controlled by operator from the ground station and image acquisition process usually results with irregular image overlap and acquisition geometry. During the fully automated flight, limitations in GPS (*Global Positioning System*) positioning and relevant communication between drones and remote operating systems, obstacle interference with UAS and possible crashing, signal acquisition risks are some of the challenges that needs to be addressed (Rakha & Gorodetsky, 2018).

An additional step to the image acquisition process is placing and measuring of GCPs on site for scaling and geo-referencing purposes. This is done though a traditional surveying method of using a total station or GNSS positioning method.

The final phase represents processing of UAV acquired images. In order to successively generate a *Digital Surface Model* (DSM) or *Digital Terrain Model* (DTM) camera calibration and image triangulation should be initially performed. DSM and DTM can be finally used for the production of 3D models, ortho-images or for the extraction of further metric information.

4. TERRESTRIAL LASER SCANNING

TLS technology is a relatively new technique for quickly collecting three-dimensional spatial information. TLS can be used to obtain three-dimensional (3D) location information for a structural member or an entire building without being restricted to a particular location on the structure or affected significantly by the environmental conditions. It was hailed as another technological revolution in the field of surveying and mapping after GPS technology which accurately reconstructs the scanned objects and builds high-fidelity, high-precision 3D point clouds (Vosselman & Maas, 2010). TLS helps sample complex objects easily using 3D point clouds. The product of TLS measurements is a three-dimensional (XYZ) point cloud acquired with high-density and high-accuracy. This geometric dataset allows one to build 3D models, as well as detect building defects. However, the TLS can also receive the power of the laser beam backscattered from the observed object, which is called “intensity”.

In contrast to camera-based vision systems, using such laser signals to obtain 3D coordinate data does not require the additional computation for coordinate information upon image acquisition.

Modern TLS instruments measure target objects by observing either (a) TOF (*Time Of Flight*) or (b) change in phase of a reflected laser signal (Lemmens, 2011). The principle of 3D coordinate extraction using TLS is based on measuring the time it takes for the laser pulse to travel from its source to an object and return, and computing the distance based on the travel speed of the pulse (the same as the speed of the light) - Figure 2.

TLS is able to record dense point-clouds over an extremely short period of time by using the distance and laser pulse angle data at rates of tens of thousands per second. Moreover, the TLS can also record the intensity of the reflected pulsed laser and RGB color data of the target object. The intensity information can be very useful for façade inspection and detection of cracks.

TOF can measure over very large distances (e.g., 300 m) but is slower and less accurate than phase-based observations. Conversely, phase-based observations are rapid and accurate but presently limited to shorter ranges. Hybrid phase-pulse laser scanners combine the range and low noise sensitivity of the TOF technique, with the high accuracy at short range of phase shift technology (H. S. Park, Lee, Adeli, & Lee, 2007).

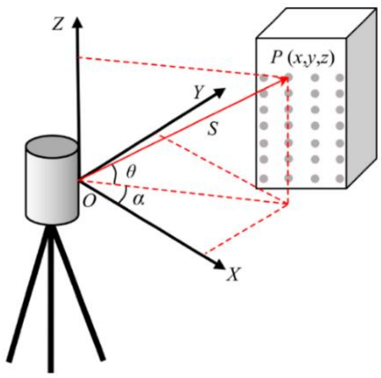

Figure 2 - Measuring principle of the terrestrial laser scanning (TLS) (Xu, Li, Yang, Qi, & Zhou, 2019)

TLS point clouds provide the benefit that each point is registered in the instruments reference frame upon measurement. This reference frame can be either arbitrary or a known coordinate system. As a result, dimensions can be extracted directly from the point cloud. The acquired information can be integrated into CAD systems for measurements or change detection studies. TLS technique, as a non-invasive surveying technique, can allow continuous monitoring without coming into physical contact with the interested object (especially useful in unreachable places).

For the purpose of health monitoring of structures accuracies in the order of 1 mm or less is required. Accuracy of spatial coordinates ranges from 2 mm to 3 mm from stationary measurements (Ninkov, Bulatović, Sušić, & Vasić, 2014).

5. DISCUSSION

A major advantage of using TLS is that it can provide rapid and very dense measurements in inaccessible regions. However, there are also some limitations, which may preclude its use in certain applications. For example, TLS use is weather dependent and expensive. Further, the accuracy of the measured point clouds degrades with distance (the most accurate measurements are acquired at close distances), and the equipment and software can be expensive. Surveying the exterior of tall objects is especially problematic because of the need for large distance from the object. In this case, it is even more of a problem if such a facility is located in the narrow streets of urban areas. The object properties are also an influencing factor on which the user has very little or no control - specular surfaces such as objects made of glass or mirror-like metal negatively affect reflection's diffusion when scanning with TLS. TLS, on the one hand, provides reliable geometrical information in terms of high resolution, high accuracy, and low uncertainty, and on the other hand it often lacks high quality radiometric data, due to the relatively low specs of the integrated RGB sensors (Calantropio et al., 2018), (Russo et al., 2019). TLS is also limited by the location of the acquisition point of view and the subsequent results are generally affected by lacks and non-homogeneous data.

Optical techniques such as close-range photogrammetry, is a cheaper option (relative to TLS) and can provide very accurate measurements at specified locations (e.g., control points and targets). However, this technique requires more careful setup of control points and coordinate space to ensure sufficient network geometry and datum definition. In contrast, using TLS, the coordinate system can be defined in the instrument axis. Close-range photogrammetry also requires much closer proximity to the target area for precise observations. Nonetheless, close-range photogrammetry has been applied for various crack detection studies (Nishiyama, Minakata, Kikuchi, & Yano, 2015), (Valença, Dias-Da-Costa, Júlio, Araújo, & Costa, 2013). Other laser technologies, such as laser displacement sensors, can also provide extremely precise distance and displacement/ deformation observations, but lack the spatial coverage of TLS. TLS allows measuring the 3D displacement of any particular point in a structure as well as the static deformed shape of the structure. However, in cases of small and medium objects it is possible to apply UAV technique without external framework or high-performance camera and obtain results comparable with the TLS corresponding ones, both in terms of accuracy and density. However, the architectonic or urban scale still requires the integration with a topographic survey and cannot always reach the same quality level of laser scanning results (Russo et al., 2019).

Advantages of using TLS in assessing facade condition are (1) no in situ instrumentation of sensors, (2) no difficulties to reach structures or structural members, (3) independence of natural light sources, and (4) no wiring costs. On the other hand, the main advantage of the photogrammetry stays is that images contain all the information required for 3D reconstruction of the scene as well as the photo-realistic documentation. An important point is also the equipment cost - cameras are generally cheap and easily portable (Faltynova et al., 2016).

6. CONCLUSION

Both methods presented in the paper - TLS and UAV have their advantages and disadvantages and one cannot generally tell which method is better and more applicable. It is always necessary to look at the requirements of the project - what is the subject of the surveying, what is the required accuracy, what level of detail is required and, of course, at what time interval it is necessary to collect the data and deliver product. Once these answers are defined, the choice of surveying method and the data collection process can begin. However, as in other areas, a more comprehensive approach is needed to obtain the best data and of highest quality. Based on what is presented in the paper, as a recommendation in documenting the condition of the facades, the integration of two modern methods - UAV and TLS can be adopted as the best solution. To obtain complete data coverage, TLS technology must be used, while UAV can be used to capture facades that are not in the scanner's field of view due to various obstacles in order to obtain complete data coverage.

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