BIM AND UAV PHOTOGRAMMETRY FOR SPATIAL STRUCTURES SUSTAINABILITY INVENTORY

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ABSTRACT:

The paper describes the basic concept of the integration between UAV surveying results and BIM. As a case study, it was considered the large spatial shell that served as a hangar for the Antonov An-225 Mriya, the largest in the world strategic cargo aircraft with a maximum take-off weight of 640 tons. Due to an explosion inside, the hangar and aircraft were significantly damaged. The key point of the study is the damage estimation by analysis and modeling of this unique engineering structure. The study has included several steps: hangar structure documentation (before damage), UAV surveying of the hangar (for ongoing condition estimation), terrestrial measurements for the control, and integration of 3D models inside BIM for structural analysis. Deploying the UAV allowed us to generate detailed 3D models of the hangar by means of photogrammetry and computer vision methods. The inclusion of the field geodetic measurements into the processing made it possible to increase significantly positioning accuracy of the results to the sub-centimeter level and served as a ground truth for the models obtained based on UAV sensors data. The results proved the feasibility of BIM and UAV photogrammetry for the hangar stability model development and practical verification based on geospatial and structural engineering data.

1. INTRODUCTION

The variety of UAV data applications has increased significantly in recent decades. Thanks to the new developments in drone production, it has become possible to carry out surveying using intelligent planning apps under various conditions, sometimes adverse, and gather the data with a bunch of sensors that modern UAVs equipped (Colomina and Molina, 2014). Those advances open the way for precise UAV photogrammetry (Mostafa, 2017). That kind of surveying is required for civil engineering applications. On the other hand, civil engineering management has made progress as well. The core transformation is a transfer from the standard management of building processes to building information modeling (BIM). Today, BIM is on the way to transforming into digital twins and, shortly, to smart cities. UAV data could be a reliable and real-time data source to supplement the BIM operation (Ciotta et al., 2021). However, one needs definitely knows which data UAV can provide and how it can be used. Especially concerning BIM, we must remember that this technology supposes deep data fusion. In other words, more than the simple coordinate set of the particular points of the structure is required. The data have to be provided in such a way that ensures their easy and quick integration into BIM software for further processing.

A number of scholars have conducted research on various UAV applications in civil engineering. Recent studies have shown the usefulness of the UAV data for structure monitoring and condition assessment (Henriques et al., 2015, Carroll et al., 2021), crack detection (Lei et al., 2020, Choi et al., 2021), surveying engineering (Hoskere et al., 2019), construction process monitoring (Shults et al. 2020), and many else. The paper aimed to familiarize the audience with one of the UAV applications that combine high-precision surveying for monitoring with further integration of surveying results into engineering software for structural analysis as a part of BIM.

2. STUDY OBJECT

2.1 Object description

The study object is an airplane hangar that hosts Antonov An-225 Mriya, the largest in the world strategic cargo aircraft with a maximum take-off weight of 640 tons (length 84 m, height 18 m, wingspan 88.4 m). The hangar is emplaced in Kyiv’s outskirt city Hostomel at the airport that serves as a testing center for airplane building company Antonov (Figure 1).

Figure 1. Geography of the studied object.

The hangar position according to the runway is shown in Figure 2.

Figure 2. The hangar position.

The hangar was built in 2002. To fulfill the requirements, the construction was built from steel trusses connected to span a large arch with a height in the middle of 33 m (Figure 3). The structure is intended for temporal parking and repairs of various aircraft. It was built assuming that heavy snow and strong wind gusts are possible.

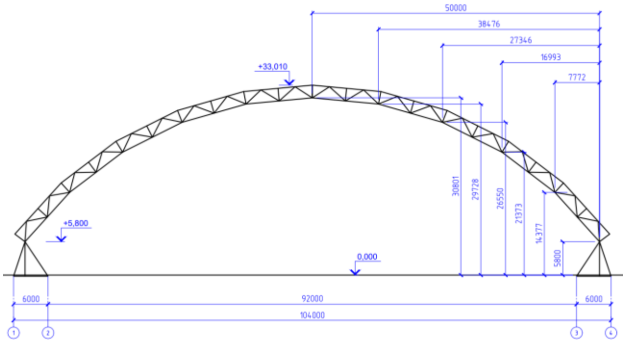


Figure 3. Vertical cross-section of the structure.

The horizontal sizes of the hangar are 116 x 96 m. The roof is covered by metal sheets.

2.2 Hangar's current state

During the war activities after the Russian invasion, the hangar underwent severe damage as a result of shelling and an explosion inside in March 2022 (Figure 4).

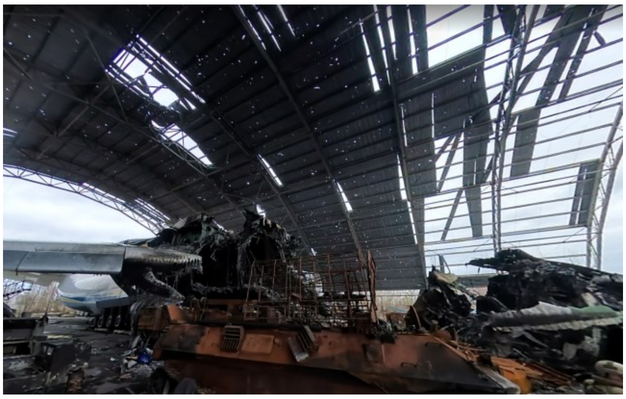


Figure 4. The damaged hangar and the fragments of the destroyed An-225 Mriya.

Different parts of the hangar coverage have different types of damage (Figures 5, 6, and 7).

Figure 5. Truss rupture.

Figure 6. Truss deformation.

The roof was almost destroyed. Many elements of the frame have ruptures, deformed parts, holes, and failures due to fire burning effect.

Figure 7. A bullet hole inside the bar.

When the situation settled down, it was decided to make the study of the structure aimed at determining its possibilities for further exploitation. In the summer of 2022, the complex observation by a team of scientists from Kyiv National University of Construction and Architecture was accomplished. This observation included geodetic surveying, detailed UAV surveying, and further structural analysis in BIM. The critical role was laid on the UAV surveying insofar as it must provide the complex 3D model of the hangar and provide a detailed screening of the structure condition, especially for the parts that are hard to reach out to.

3. GEODETIC SURVEYING

3.1 Network

The geometry of the object is pretty simple. Therefore, the ordinary geodetic network has been created. The geometry of the network is a geodetic quadrangle with diagonals. The aim of this network was twofold. The first is to provide the coordinates of ground control points for UAV surveying, and the second is to ensure control measurements of the structure by total station. The points were mounted into the concrete ground coverage of the airport and marked appropriately to facilitate their recognition in the UAV images. The size and form of the ground control points were calculated using the appropriate camera parameters and flight mission parameters. Before, it was mentioned that such a kind of surveying needs pretty high accuracy. That is why the precise total station has been used. Finally, the network points were determined with RMS errors equal to m_X = 1.8 mm, m_Y = 3.5 m, and m_X = 1.6 mm, which is good enough for the declared purpose.

3.2 Control surveying

The control surveying was accomplished from the network points. The goal of the control surveying was to determine the construction deformation across the preliminary assigned vertical cross-sections. Five cross-sections were surveyed in total. The surveying was carried out in reflectorless mode. The spatial coordinates of the nine joints of the arch were determined in each cross-section. Since the initial geometry of the structure was known, the differences between determined coordinates and actual coordinates determine the structure deformation. The sample of the surveying results is given in Figure 8.

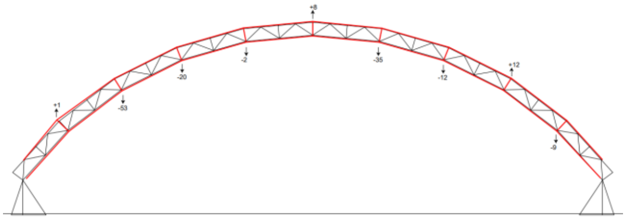


Figure 8. Control surveying results.

In Figure 8, the red line presents the actual structure position while the figures portray the deformation values in vertical directions. Obviously, this method is time-consuming and laborious. Moreover, it is not ensured the control of the structure from above. Detailed surveying needs a considerably larger number of network points, but even then, the incidence angle would have been too large, which might seriously distort the surveying results. Despite the insufficient data from traditional control surveying, it was confirmed that the structure is seriously deformed in many places. These deformations may lead to the hangar failure under dead weight, not to mention other loads, e.g., snow or wind gusts. Therefore, detailed surveying using UAV photogrammetry was necessary. In what follows, the geodetic surveying data were used only to control the UAV surveying.

4. UAV SURVEYING

4.1 Data collection

UAV surveying aimed to provide a comprehensive overview of the structure condition and reveal the places of significant damage. For that purpose, DJI Phantom 4 UAV was used. The surveying design was developed using Drone Deploy and QGroundControl software. The coverage of the surveying area with a number of overlapped images is presented in Figure 9.

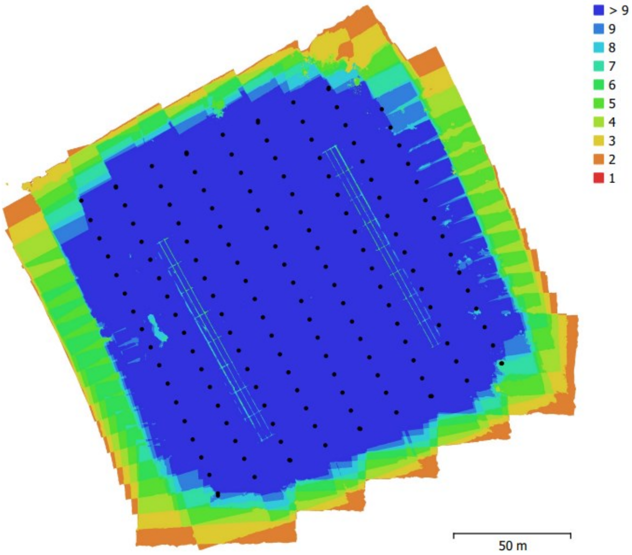


Figure 9. Coverage of the surveying area with several images.

The flying height was 40 m for the whole object, and the height difference for the hangar points was about 34 m. It was not impossible to assign the changing height due to obstacles and various hangar elements that protrude outside. The standard camera was used with a principal distance of 8.8 mm and a resolution of 5472x3648 (pixel size 2.41x2.41 μm). In total, 160 images were captured. The weather conditions allowed us to collect the images with very stable overlaps. That made further processing more reliable. Thus, we dealt with precise surveying but, with significant scale variability from 1:5700 at the ground up to 1:1900. Such scale variation makes image processing challenging. However, the preliminary accuracy calculations have shown that the required accuracy is achievable even in the given circumstances; the following expressions were used (Shults et al. 2017),

$$m_X = \frac{H^2 \cdot x \cdot m_p}{B \cdot f^2 \sqrt{r}}; m_Y = \frac{H^2 \cdot y \cdot m_p}{B \cdot f^2 \sqrt{r}}; m_Z = \frac{H^2 \cdot m_p}{B \cdot f \sqrt{r}}, \qquad (1)$$

where f = principal distance
H = surveying height
$m_p = \sqrt{2m_{dist}^2 + 0.5 l_{pix}^2}$ = parallax error
l_{pix} = pixel size
m_{dist} = distortion error
B = distance between projection centers
x, y = matrix half sizes
r = mean number of images

Having the listed above values, we may calculate the expected errors for the extreme height values. For 34 m, was obtained m_X = 6.4 mm, m_Y = 6.8 mm, m_Z = 10.4 mm, and for the mean height, we have m_X = 2.2 mm, m_Y = 2.3 mm, m_Z = 3.6 mm. Even the extreme values correspond to the requirements.
To fulfill the quality camera must be calibrated. The camera was calibrated thru the self-calibration approach. The well-known Brown’s calibration model was employed. The calibration results are given in Table 1.

Parameter	Value	Accuracy
f	3648	
cx	-9.268	0.075
cy	-12.147	0.037
K1	-0.00837	0.00016
K2	-0.00358	0.00012
K3	0.00988	0.00011
P1	-0.00084	3.4e-06
P2	-0.00120	2.8e-06

Table 1. Camera calibration parameters.

Despite the low accuracy of the principal point coordinates, it does not affect the overall accuracy essentially. These parameters were used for image orientation, point cloud, and orthophoto generation.

4.2 Data processing

The final goal of the data processing is the precise 3D model that should be easily integrated into the BIM system for structural analysis and further decision process. However, the orthophoto and point cloud is also badly needed to inspect the probable damages that have non-geometrical nature.

Firstly, the images were oriented. The ellipses of the orientation accuracy overlaid above the orthophoto are presented in Figure 10.

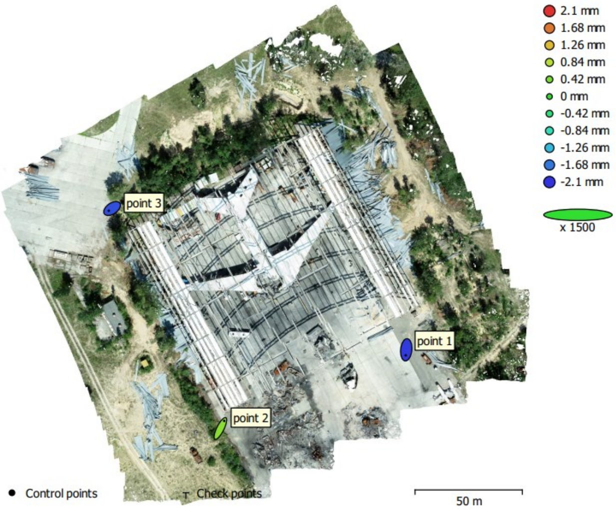


Figure 10. Orientation accuracy.

The total orientation error equals 4.2 mm, which satisfies the necessary requirements. The high redundancy of images allowed us to build a dense point cloud of over 500K points. The unfiltered point cloud is given in Figure 11.

Figure 11. Point cloud.

After the processing, the point cloud was converted to a 3D model suitable for BIM software (Figure 12). The precise coordinate determination of the particular points (truss joints, bar corners, etc.) was carried out manually during the image orientation process. Therefore, the identified failures were measured and compared with project drawings. In what follows, these measurements were exported to Autodesk Revit software with the point cloud. The processing results are presented in Figure 12.

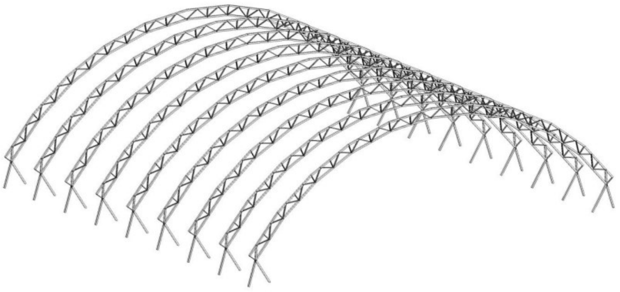


Figure 12. 3D BIM model.

The model in Figure 12 is obtained in one of the BIM formats and has all the necessary information about the types and qualities of the material that the structure is made up of, referenced images of each element of the structure, and a detailed description of the damage. A complex 3D model is ready to export and process in any BIM software for in-depth analysis.

5. BIM STRUCTURAL ANALYSIS

5.1 Damage inspection

Damage inspection is an indispensable step of structure study. Thanks to UAV data, the research engineer is able to move around, outside, and inside of the structure and estimate the type and degree of damage. As a result, the damage diagrams for trusses, coverage bars, and supports were created (Figure 13).

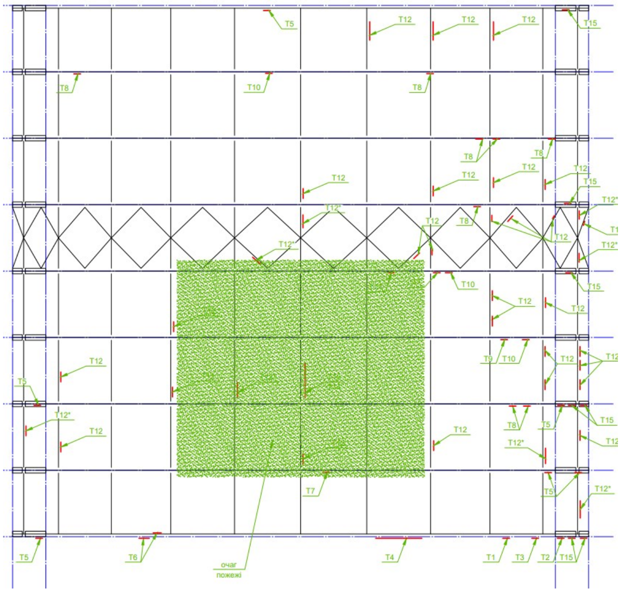


Figure 13. Damage diagram for trusses.

In Figure 13, the green square defines the region of intensive fire after the explosion. Red lines designate the damage. The user immediately obtains the complete description, coordinates, and referenced image by clicking on any of them. In this way, we may study the faults that are not discernible and hard or impossible to measure from the ground. A couple of these examples are given below (Figures 14, 15, and 16).

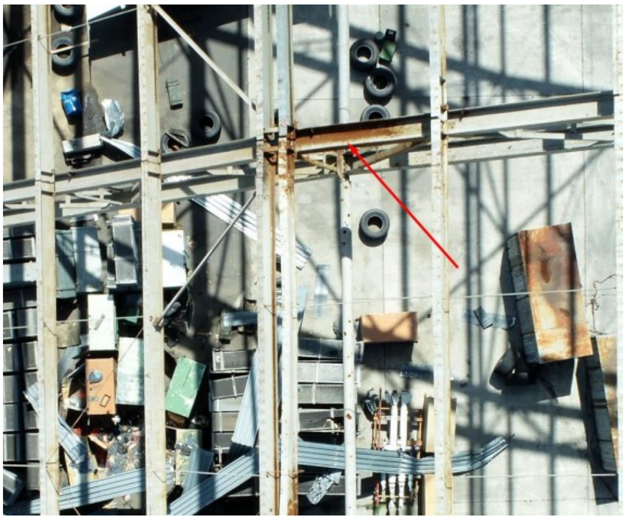


Figure 14. Truss damage.

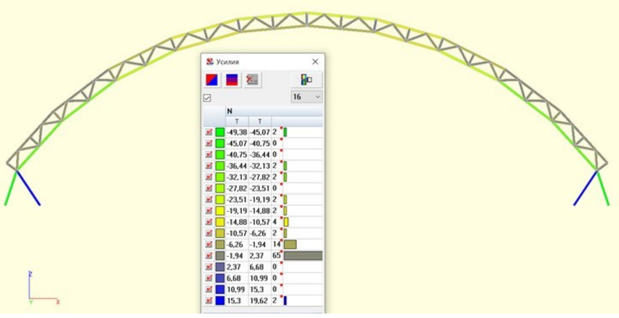
Figure 15. Coverage bar failure.

Figure 16. Bar buckling failure.

All of these documented failures were fused in BIM for in-depth structural analysis.

5.2 Structural analysis

The structural analysis is the final step that allows determining the further exploitation potential of construction to withstand the various external loads. Surveying results help correctly estimate the structural analysis results. Structural engineer uses the BIM model and surveying results to assign the correct loads and the places of their exert. The structural analysis was accomplished for the simplest case of dead load. The simulation was carried out using the finite element method. The ongoing failures were accounted for in the simulation. The simulation for the broken truss in the arch (Figure 5) is presented in Figure 17.



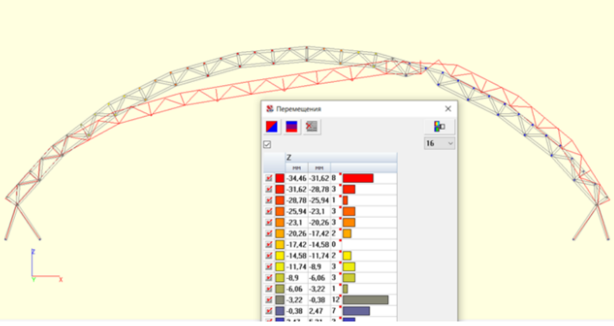
Усилия

16

N		
т	т	
-49,38	-45,07	2
-45,07	-40,75	0
-40,75	-36,44	0
-36,44	-32,13	2
-32,13	-27,82	2
-27,82	-23,51	0
-23,51	-19,19	2
-19,19	-14,88	2
-14,88	-10,57	4
-10,57	-6,26	2
-6,26	-1,94	14
-1,94	2,37	65
2,37	6,68	0
6,68	10,99	0
10,99	15,3	0
15,3	19,62	2

Figure 17. Loads along the coverage bars.

In Figure 17, as a case study, the loads along the coverage bars are portrayed. The loads allow calculating stresses along elements and transform them into displacements. For the same arch, the displacements are given in Figure 18 and scaled for better visual presentation.



Перемещения

16

Z		
мм	мм	
-34,46	-31,62	8
-31,62	-28,78	3
-28,78	-25,94	1
-25,94	-23,1	3
-23,1	-20,26	3
-20,26	-17,42	2
-17,42	-14,58	0
-14,58	-11,74	2
-11,74	-8,9	3
-8,9	-6,06	3
-6,06	-3,22	1
-3,22	-0,38	12
-0,38	2,47	7

Figure 18. Vertical displacements.

The simulation proved the further deformation of the structure only under the dead weight. The displacements are not critical. However, the displacements are continuous and develop over time. Thus, if the truss is not repaired, it will collapse in the near future. This inference is valid for the hangar in total, insofar as much damage was detected, and the simulation confirmed the impossibility of the future structure use before the complex revamp. Based on the simulation results, the structural engineer developed the appropriate measure for the reconstruction and urgent actions to protect the hangar from collapse.

CONCLUSIONS

The paper presents the high efficiency of the UAV data in complex studies for the integration with BIM. The results yielded preliminary evidence that UAV surveying from low heights can provide detailed data with the necessary accuracy for inventory and monitoring tasks. The general picture emerging from the study analysis is that UAV usage significantly facilitated the process of structure inventory. In this particular case, UAV data ensured the direct workflow of the inventory process. The whole study has been accomplished in line with standard BIM schemes, from data collection to redesign actions. The data are easily integrated into accepted BIM formats; therefore, the interaction level between surveying and civil engineers becomes more flexible and convenient. Future research will have to address the opportunities of UAVs for different building life-cycle studies as a core element of data collection for BIM operation.

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