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Nadir & Oblique Aerial Imagery – new possibilities in 3D mapping

Abstract: The new generation of aerial photogrammetric cameras brings camera constructions with several fields of view, instead of a traditional vertical one, which, in addition to vertical images, also enable oblique images. Although this imaging method allows higher quality when making a 3D model of the imaged area, it is still not used in Croatia. This paper describes the technology of aerial photogrammetric cameras with multiple fields of view and the advantages of using nadir & oblique aerial imagery, especially in photogrammetric algorithms that allow automated orientation and measurement of images. The tests were performed on nadir and oblique images taken by Vexcel Osprey nadir & oblique camera. Finally, the result obtained only with vertical images was compared with the result with oblique images when making a 3D model of the urban area. Special attention to the quality of modeling of buildings and urban vegetation is drawn and discussed.

Keywords: Photogrammetry, 3D city model, Nadir & oblique imaging, Multiple view camera

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Introduction

There is a high demand for current photogrammetric airborne and high-resolution satellite data due to the widespread use of standard vertical images as a topographic background in GISs today. Most of the National Mapping Agencies (NMAs) still rely on the traditional workflow based on vertical photography but changes are slowly taking place also at production level. The available orthophoto Internet services, for instance in Google Earth and other similar services, are primarily used for orientation and visual inspection of chosen features by planners, administrative users, and the general public. However, not everyone will be able to understand orthophotos. Oblique photography's undeniable benefits include the ability to show building facades and footprints. As a result, the data is easier for non-expert users to understand because it more closely resembles what is observed on the ground. (Fig. 1)

Fig. 1. View of the urban part in the central part of the vertical aerial photograph (left) and on the oblique photograph (right)
Source: Bakici et al., 2017

That is why in the past, oblique images have been used more for visualization and interpretation than for metric applications. The military and archaeology are applications, where oblique images have long been the norm for reconnaissance purposes (Welzer, 1985). But up until recently, photogrammetrists rarely paid attention to oblique images. They can therefore be considered to be a new source of data for photogrammetry and GIS. Oblique photogrammetry is a technique for creating 3D city models using texture information obtained from oblique images. It combines traditional nadir images with oblique images acquired at high angles (Petrie, 2008). This method can be applied to single or multiple camera systems mounted on an unmanned aerial vehicle, helicopter, or aircraft. It also uses the integration of GPS and IMU, just like traditional aerial photogrammetry. Oblique photogrammetry has the following advantages, which can be categorized as follows (Karbø & Schroth, 2009):

- Imaging of the entire structure and precise measurements on all sides;

- Measurement of distance, elevation, and slope in the terrain;
- Detection of blind spots;
- Identification of hard-to-see objects in orthophotos, e.g., lampposts, telephone poles, etc.;
- Use of a GIS database integration and 3D visualization of GIS data.

Numerous camera systems are used in oblique photogrammetry. Approaches vary depending on whether a system uses a single camera or multiple. The system where vertical and oblique cameras work together is considered the most popular and effective. Examples include Vexcel UltraCam Osprey, Pictometry's PENTA DigiCam, Hexagon Geosystems' Leica RCD30 (Fig. 2.), and Track'Air Aerial Survey Systems' MIDAS (Petrie, 2008). In such a system, oblique cameras are mounted at an angle of approximately 40°-45° looking forward/backward and left/right, comparing to nadir camera, which is placed in the center. The resolution is about 15 cm for nadir images and 12-18 cm for oblique images, when an average flight altitude is of 1000 m. (Nelson, 2013).

Fig. 2. Leica RCD30 Oblique Penta footprint with RCD30 cameras
Source: Pepe & Prezioso, 2016

A point can typically be represented by 12 to 24 images in this configuration. This allows for the creation of image libraries by compiling images that meet the required quality standards once the photogrammetric processes are complete. These image libraries can then be used for a variety of purposes, including mapping, land use change tracking, and disaster management. Unmanned aerial vehicles (UAVs) are also becoming increasingly popular as a means of aerial photography, as they can capture high-quality images for less money than traditional manned aircraft. In this article, the Vexcel Ultracam Osprey images and products are analised, that's why the imaging geometry of this camera is discussed.

Geometry of oblique images

The efficiency of an oblique camera system is built on the camera geometry. To design a highly effective camera system, key parameters including pixel size, length-to-width ratio of the imagery, focal length of the nadir and oblique cones, installation angle of the oblique cones, frame rate, flight speeds, and motion compensation must all be optimized against one another. To guarantee a similar ground sampling distance (GSD) in both nadir and oblique imagery, the focal length ratio between the nadir and oblique cones must be clearly defined. Unlike vertical aerial images, oblique aerial images have some properties that need to be taken into account when considering the mapping geometry. The imaging scale is not nearly constant across the entire recording format. Therefore, the size of the pixel imaged on the ground (Ground Sampling Distance – GSD) changes significantly along the image. And that, in the foreground of the image, the image scale is larger and the GSD is smaller, while in the background of the image, the image scale is smaller and the GSD is also larger (formula no. 2). When planning to take oblique images, you should take into account not only the field of view of the individual camera βy, but also the flight height hg and the deflection angle of the shooting axis αy (Fig. 3).

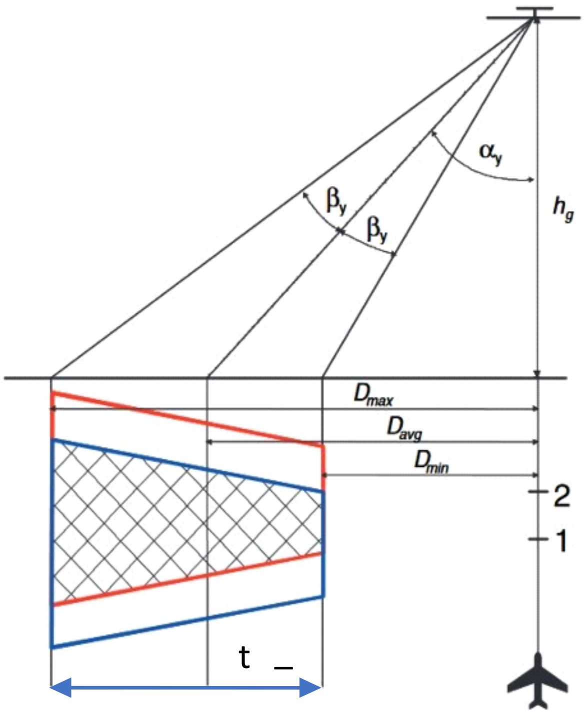

Fig. 3.Oblique imaging geometry
Source: Grenzdörffer et al., 2008

Acording figure 3 following relations can be derived (Grenzdörffe et al., 2008):

$$D_{min} = h_g \tan\left(\alpha_y - \beta_y\right),\; D_{max} = h_g \tan\left(\alpha_y + \beta_y\right),\; W = D_{max} - D_{min} \qquad (1)$$

Where are:
D_{min} – distance to image foreground, measured from projected trajectory of flight
D_{max} – distance to image backgroud, measured from projected trajectory of flight
D_{avg} – distance from the centre of image to the projected trajectory of flight
W – image width, that corespond to strip width in photogrammetric flight

And the denominator of imaging scale is calculated as follows:

$$m_{min} = \frac{h_g \cos(\beta_y)}{f cos(\alpha_y - \beta_y)}, \quad m_{max} = \frac{h_g \cos(\beta_y)}{f cos(\alpha_y + \beta_y)}, \quad m_{avg} = \frac{h_g}{f cos(\alpha_y)} \tag{2}$$

Where are:
m_{min} – image scale denominator in the image foreground
m_{max} – image scale denominator in the image background
m_{avg} – average image scale denominator

In conclusion, having a very large nadir footprint does not increase the effectiveness of an oblique camera system. With a 60 percent side overlap configuration, the UltraCam Osprey 4.1 creates a 25 percent forward and backward oblique footprint overlap, as marked with blue rectangles on figure 4. The flightlines must be extended for the left and right, as well as the forward and backward, oblique cones in order to ensure complete coverage of the area of interest. Extending the flightlines will not only ensure that the entire area is covered, but it will also enable the capture of more accurate and detailed imagery.

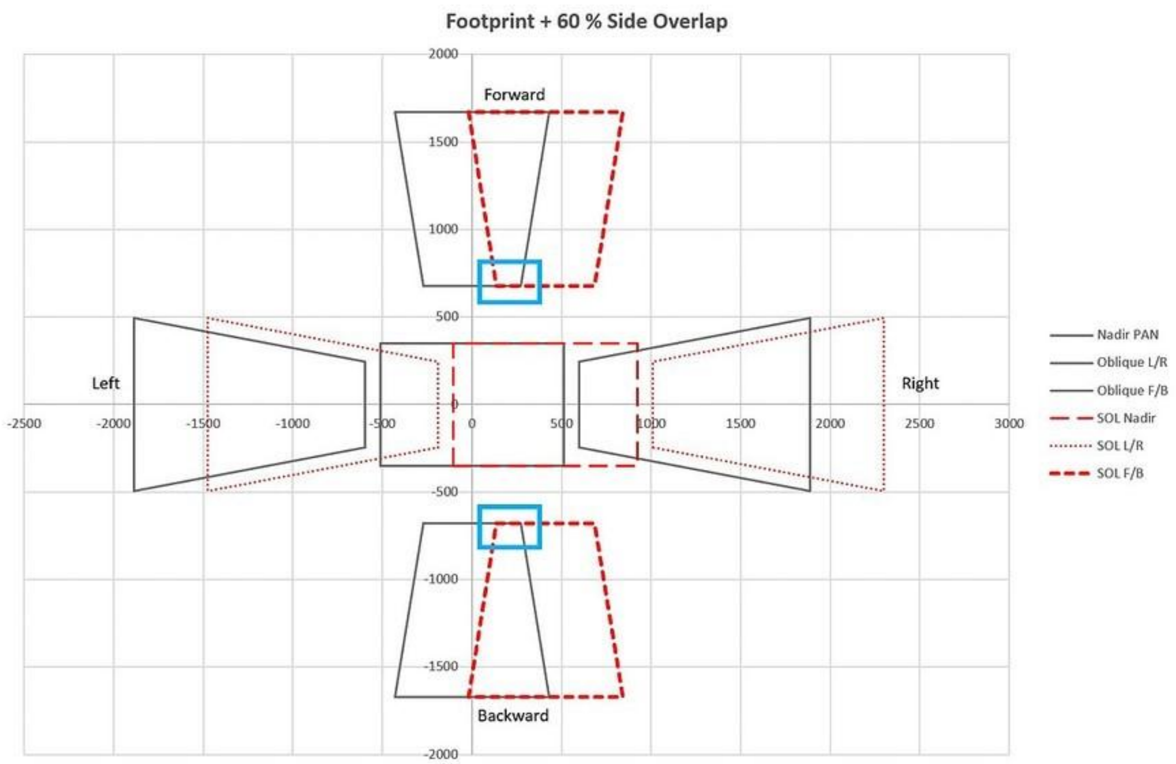

Fig. 4. Overlap geometry of Vexcel Ultracam Osprey camera with 5cm GSD and 60% side overlap
Source: Reinisch, 2022

Additionally, extending the flightlines enhances triangulation and the final product's overall quality. Therefore, to maximize the effectiveness and efficiency of the oblique camera system, careful planning and consideration must be made when deciding the length and placement of flightlines. The local topography and terrain should be taken into account when extending flightlines. In order to ensure the best image capture, the flight path may need to be adjusted for steep slopes or uneven terrain. To further ensure a smooth and thorough data collection process, coordination with other aerial survey operations in the area is essential to prevent any potential conflicts or overlaps.

Point matching

To get the dense point cloud from imagery, which is the base for 3D modeling of the earth's surface and objects on it, the matching algorithm is used. It heavily relies on the Structure from Motion (SfM) algorithm and Multiview Stereo (MVS) algorithm. Both of them help to reconstruct the 3D structure of a scene from a sequence of 2D images, as is shown on figure 5.

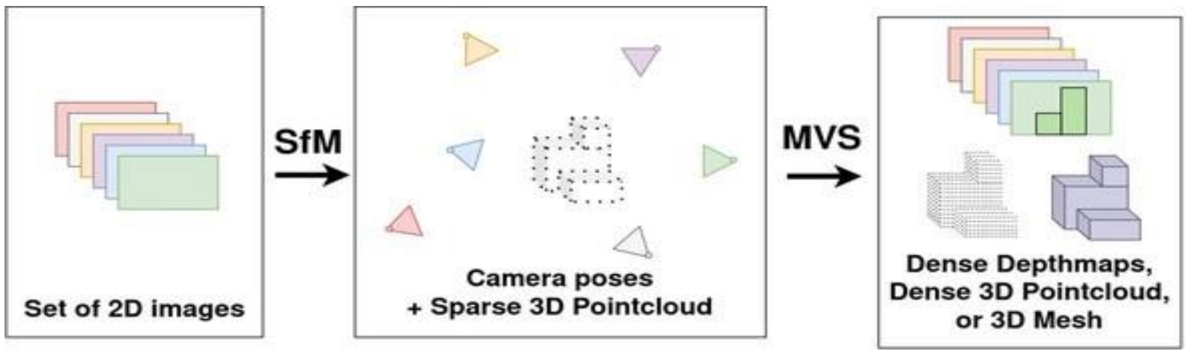

Fig. 5. SfM and MVS principles
Source: Reinisch, 2022

The key steps of the SfM followed by MVS algorithm are (Metashape Professional, 2023):

- Feature Extraction: The first step is to extract distinctive features from the input images. These features can be corners, edges, or other distinctive points that can be easily detected in multiple images.
- Feature Matching: The extracted features are then matched across different images to establish correspondence between the feature points. The matching process involves searching for similar feature descriptors or using geometric constraints to determine the correct matches.
- Camera Pose Estimation: Based on the matched feature points, the camera poses for each image are estimated. This involves determining the position and orientation of each camera relative to a common coordinate system.
- Triangulation and bundle adjustment: Once the camera poses are estimated, the 3D positions of the matched feature points are reconstructed through triangulation. This process involves intersecting the rays from multiple camera viewpoints to find the 3D coordinates of the corresponding points. Bundle adjustment is performed to refine the estimated camera poses and 3D point positions.

- Depth or disparity Estimation: Each pixel in the images is assigned a depth value or disparity map. This can be achieved by triangulating the matched features and estimating the depth based on parallax or using techniques like block matching.
- Depth refinement: The initial depth estimates are refined using optimization techniques. This could involve minimizing energy functions that enforce smoothness, consistency, or uniqueness of the depth map.
- Surface reconstruction: Finally, a 3D point cloud is generated by projecting the refined depth maps back into 3D space. This point cloud can be further processed to create a more detailed surface mesh representation of the object or scene.

In the last decade, matching algorithms have been improved and several of them even newly developed (Haala & Rothermel, 2012). These algorithms make it possible to create point clouds with 100 points/m2 from images with a GSD of 10 cm. However, these point clouds are usually noisier than those recorded by LIDAR. To achieve better results in point cloud reconstruction, increasing the number of overlapping images and better filtering are essential (Rupnik et al., 2014). Thus, there is a possibility of using oblique images, in order to achieve better reconstruction results and more extracted points compared to using only nadir images.

Study area

The part of Graz chosen for this study is highly urbanized and has a variety of topographic features, including wide and narrow streets, buildings, squares (Südtiroler Platz), modern buildings (Graz Museum of Contemporary Art), vegetation (Castle Hill), and water (river Mur). Graz is located in southeast Austria on both sides of the Mur River (Figure 6 A). The study area (Figure 6C) is about 15 hectares in size and is located primarily in the I. district, in the city center (Figure 6 B).

Fig. 6. Location of the study area (C) on Austria map (A) and on the map of Graz (B)
Source: Austria Base Map, 2023

Data source

This study made use of images captured by the photogrammetric Vexcel Ultracam Osprey M3p camera made by Vexcel Inc. and made accessible for research on the following URL: ftp.vexcel-imaging.com. A whole set has 60 pictures from 12 different places. Three parallel strips, each with 4 imaging locations, were used to image the entire study area. There were 5 images captured simultaneously at each imaging point. According to Figure 4, the central (nadir) image is captured using a vertical optical axis, and four oblique images were captured using an oblique optical axis in the four cardinal directions of the flight line (ahead, backward, left, and right).

Results and discussion

In this study, we analyze two datasets that were both created using photogrammetric data from an aerial camera, the Vexcel Ultracam Osprey M3p. To create the 3D model for the first dataset, we simply used the nadir photos. For the same purpose in the second, we combined nadir and oblique photos. Basic mesh statistics already reveal significant differences between these 3D models in terms of the total number of points and faces gathered across the same area (Table 1).

Table 1. Mesh statistics of 3D models

	3D model from nadir images	3D model from nadir & oblique images
Total faces	305102	2890461
Total vertices	280692	1450082
Similar vertices	3557	0
Open edges	251030	8501

Source: own elaboration

Similar vertices are vertices in the mesh model that are spatially close to each other, potentially indicating redundant or overlapping geometric information. Open edges refers to edges in the generated mesh model that do not form a complete loop or are not connected to other edges. These open edges can indicate potential issues in the mesh, such as missing or incomplete geometry, and may affect the overall quality and integrity of the model. When a mesh has open edges, it means that some parts of it are not properly connected or closed, resulting in gaps or holes in the geometry. These gaps can lead to inaccuracies in the reconstructed surface or affect the visual appearance of the final 3D model. Visually comparing the two models in an orthogonal projection from the top reveals that, even in that projection, the nadir & oblique images based photogrammetric reconstruction (Figure 8) has a substantially higher quality than the model that relies only on nadir photos (Figure 7).

Fig. 7. 3D model from nadir images in orthogonal projection
Source: own elaboration

Fig. 8. 3D model from nadir&oblique images in orthogonal projection
Source: own elaboration

As compared to reconstruction using only nadir images (Fig. 10), the quality of photogrammetric reconstruction using nadir and oblique images is significantly better due to better spatial resection of photogrammetric rays and the use of more images to measure individual points in the 3D model (Fig. 9).

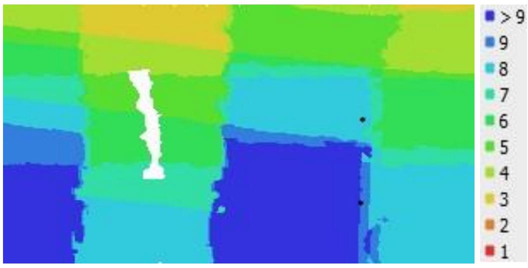

Fig. 9. Number of images in overlap nadir & oblique images
Source: own elaboration

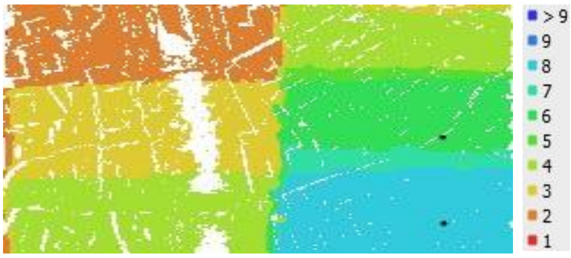

Fig. 10. Number of images in overlap by by nadir images
Source: own elaboration

The difference between reconstruction by nadir & oblique photos in comparison to results of reconstruction by nadir images is much more significant when looking at the quality of reconstruction of vertical sides of buildings (walls) and the vertical structure of greenery (particularly trees). In locations where the entire wall is photographed on numerous nadir photos (such as city squares, Figure 11A), nadir images may be sufficient for reconstructing details on vertical walls. The comprehensive reconstruction of vertical walls and urban vegetation using only nadir photos, however, is almost hardly practicable (particularly in narrow streets) (Figure 11B and 11C).

Fig. 11. Izometric view of 3D model from nadir images, (A – whole area, B – detail of building area, C – detail of urban vegatation)
Source: own elaboration

The reconstruction by nadir and oblique images is much more detailed and makes possible proper 3D modelling of urban areas with all objects within it (Figure 12A). Buildings are almost completely modeled correctly and detailed textures are projected onto the model with no visible deformations (Figure 12B). The trees are correctly modeled and photo-textured not only from above but also from the vertical sides (Figure 12C).

Fig. 12. Izometric view of 3D model from nadir & oblique images, (A – whole area, B – detail of building area, C – detail of urban vegatation)
Source: own elaboration

Conclusion

Although cameras with multiple fields of view and oblique images are not yet recognized as suitable imagery for photogrammetric survey in Croatia, this research shows that this method of recording with nadir and oblique images provides much more detailed and reliable photogrammetric measurement, especially in photogrammetric survey and the creation of complete 3D models of urban areas. The resistance to a wider application of the combination of nadir and oblique imagery is certainly due to the fact that the mapping geometry is much more complex in the case of nadir and oblique imagery compared to pure nadir imagery. Therefore, it is necessary to apply a more complex mathematical model of mapping and to use software and methods that make this possible. Today's modern photogrammetric technologies, based on fully automated photogrammetric measurement techniques and computers with processing power that allows large amounts of data to be processed in a timely manner, achieve better results in spatial reconstruction and the creation of 3D models when they have a larger number of images taken from different shooting positions and from different viewing angles. This means that cameras with multiple fields of view and the images obtained from them are becoming increasingly important.

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