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Photogrammetric Measurements in Oblique Aerial Images

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Summary: The characteristics of airborne oblique images are outlined and the determination of object dimensions like distances, areas, and heights as well as their spatial location in a reference system are explained. The unique methods of a commercial system called "Pictometry" are interpreted from its patent description. The system includes cameras, position and attitude sensors, and a software package. For the determination of dimensions and the spatial location of objects a Digital Terrain Model has to be available. Practical tests are carried out and the results are presented.

Zusammenfassung: *Photogrammetrische Messungen in Schräg-Luftbildern.* Die Eigenschaften von Schräg-Luftbildern werden skizziert und die Bestimmung von Dimensionen von Objekten, wie z. B. Entfernungen, Flächen und Höhen sowie ihre räumliche Lage in einem Bezugssystem erläutert. Die besonderen Methoden eines kommerziellen Systems, genannt Pictometry, werden auf Grundlage der Patentschrift interpretiert. Das System enthält Kameras, Lage- und Neigungssensoren und ein Software-Paket. Für die Bestimmung der Dimensionen und die räumliche Lage von Objekten muss ein Digitales Geländemodell zur Verfügung stehen. Praktische Tests werden ausgeführt und Ergebnisse präsentiert.

1 Introduction

Oblique images are well received by planners, real estate managers and the public because objects can easily be recognized. In order to measure distances, coordinates, elevations and areas or to project existing GIS data onto the oblique images a Digital Terrain Model (DTM) is necessary. Various tasks can be carried out shortly after image taking. Measurements and mapping can be done where it is needed, fieldwork can thus be avoided. One important application is in disaster management where the speed of compilation is an important factor.

The use of oblique aerial images for mapping and other measurements is already practised for many years. Knowledge about such mono plotting techniques can be found in textbooks of photogrammetry, for example in (MIKHAIL et al. 2001) or in (GRAHAM & KOH 2002).

New is the use of integrated systems which combine cameras of different viewing directions and sensors that enable the direct georeferencing of the imagery. Mapping and measurement of object dimensions can thus be carried out by means of single images and monocular measurement if a DTM is available. The availability of detailed and accurate DTM is nowadays very common. Furthermore, the processing and storage of large amount of image and DTM data is not a problem any longer. Commercial companies have developed such multi-camera integrated digital acquisition systems. The system of Pictometry Inc. will be described in detail and first experiences of practical tests will be presented.

Pictometry Inc. has produced a system for image taking **and** for the processing of the acquired data. It is based on the combined use of a DTM as well as oblique and vertical images, which are geo-referenced by means

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of GPS / IMU (Global Positioning System/ Inertial Measurement Unit) sensors. Surveying and mapping with single images becomes popular because everyone can do it and imagery of the Pictometry system will be available for many cities in Europe and elsewhere (SIMMONS & KARBO 2007). However, the measured distances, planimetric coordinates, elevations, heights, and areas depend on the calibration of the camera system, the accuracy of the outer orientation of the images and on the quality of the DTM. The use of oblique images has some special characteristics, which should be dealt with in order to understand the procedures and the results of the forthcoming investigations.

2 Characteristics of Oblique Images

The tilt of oblique images is bigger than 5 gon and may reach 55 gon. Oblique images have therefore a varying scale. The area, which the image pixels cover on the ground, is of different size and form. The image scale is variable even in flat terrain and the sides of the image are of different length. The scale number of a target point can be determined by formula (1):

$$m_T = \frac{h \cdot \cos(\beta - t)}{c \cdot \cos\beta}, \quad (1)$$

where m_T is the scale number of a target point (T), h the flying height above ground, c the camera constant, β the angle between a direct line from the lens to the target and the vertical, and t the tilt of the camera axis. These parameters are depicted in Fig. 1. The scale number at the front and the back of the oblique image can approximately be determined using

$\beta_{back} = t - \alpha$ (back) and $\beta_{front} = t + \alpha$ (front),

where α is the half of field of view. The scale number at the principal point of the image (PP') can be determined by formula (2):

$$m_{PP} = \frac{h}{c \cdot \cos t}. \quad (2)$$

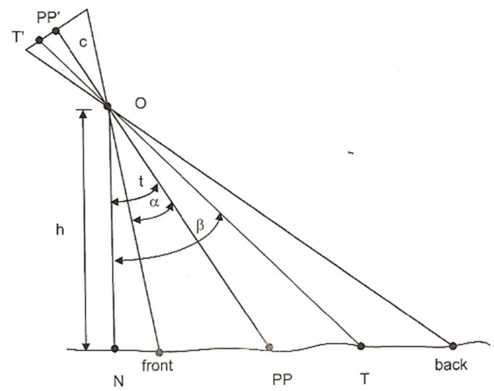

Fig. 1: Parameters of oblique images with T the target point, N the nadir point, PP the intersection of the camera axis with the terrain, PP' the principal point of the image, t the tilt of the camera axis, β the angle between a direct line from the lens to the target and the vertical direction, and α the half field of view.

Highly oblique images contain the horizon. The nadir point is then often outside of the image. Oblique images give a good view on facades of houses and into the backyards. Objects like lamp posts, telegraph poles, etc. can easily be recognized. Invisible areas ('dead zones') exist behind buildings and other elevated objects. In some parts of the image, the quality may be poor due to sun reflection (hot spot) and due to atmospheric effects (absorption and diffusion). In the neighbourhood of the horizon, overexposure can usually not be avoided.

3 Measurements in Oblique Images

The measurement of objects based on oblique images requires an accurate interior orientation of the camera. Even small errors in the location of the principal point will have great influence on the results. In addition, the exterior orientation of the image has to be known accurately.

The third prerequisite for accurate measurements with single images is the DTM. The measurements have to take into account that the measurements of coordinates, areas, etc. are correct on the ground (bare earth) only.

The pointing to objects with a cursor will be of different quality depending on the varying resolution and pixel form. Measurements are supplemented with annotations such as symbols, lines and texts. Symbols are plotted in a perspective view. Circles, for example, become ellipses.

The determination of heights of elevated objects can be carried out by measuring radial displacements. The heights may be determined approximately by formula (3):

$$dh \approx dr' \cdot m_T \cdot \frac{1}{\cos t \cdot \tan\beta}, \tag{3}$$

where dh is the height of elevated object, dr' the radial displacement of an elevated object, and m_T the scale number at the bottom of the elevated object. The scale number (m_T) is calculated by formula (1). The angle β is derived by

$$\beta = t + \tau,$$

with

$$\tau = \arctan\frac{r'}{c}.$$

The parameters of formula (3) are shown in Fig. 2.

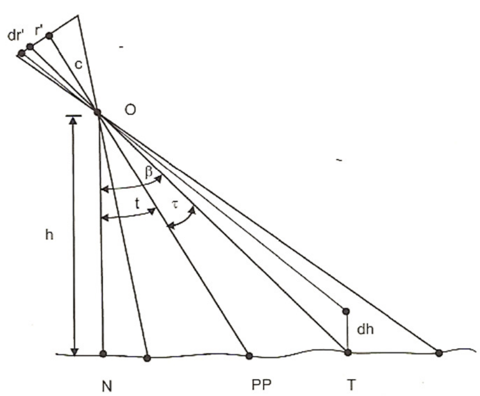

Fig. 2: Determination of heights of elevated objects.

4 The Methods Applied by Pictometry

Pictometry is a digital mapping system of Pictometry International Corporation, Rochester, N.Y., USA. It comprises

- camera and positional system which acquires geo-referenced imagery,
- data base which stores the acquired images,
- software package to process the acquired imagery,

The **camera system** consists of five cameras, of which four take oblique images (forward, backwards, left and right) and one takes vertical images. Geo-referencing of the images is achieved by acquiring data of a differential GPS (DGPS) and an IMU of Applanix. The camera system is calibrated so that the interior and relative orientation between the five cameras is known to the manufacturer. The user (licence buyer), however, has only knowledge of approximate values. The camera axis of the oblique images is about 50 degrees inclined. The focal length is about 85 mm and the format is 24 mm × 36 mm or 2672 pixels × 4008 pixels. The geometric resolution (pixel size) of the CCD is about 9 μm. The radiometric resolution of the colour images is 12 bit (or 4096 intensity values) per channel. The camera with the vertical axis has a focal length of about 65 mm; the same CCD sensor is used.

The **data base** of the imagery is organized in sectors and blocks containing 5 by 5 sectors. Each image is stored in a file. The file name indicates the location (sector name), type of the image (oblique or ortho), the direction of shooting (North, South, East, and West) and the date of photography. A service provider has rectified the vertical images into ortho images. The image database is part of a library, which also contains maps, DTM and GIS data.

The **software package**, called "Electronic Field Study" (EFS), allows to view and measure in images. The EFS user interface displays thumbnail images of all oblique images, ortho images and raster maps that are available in the current workspace. After clicking at one of the thumbnails, the selected image is displayed in a window. The measurement functions are activated from a toolbar. Furthermore, annotations can be added to the image and map data (shape files) can be superimposed onto the images.

The applied methods how to obtain coordinates, distances, elevations, heights, and areas from oblique images are presented in the following. The methods are part of Pictometry's patent, which is described in (EP 1 696 204 A2, 2006).

In the first step, ground coordinates of the image centre are derived by intersecting the camera axis with a horizontal line representing an average height (elevation) of the imaged area (cf. Fig. 3).

The distance between the vertical line through the perspective centre and the image centre projected on the ground can be calculated by means of formula (4):

$$r = h \cdot \tan(100^{gon} - \phi)\,. \qquad (4)$$

With the knowledge of the planimetric coordinates of the nadir point, the average height

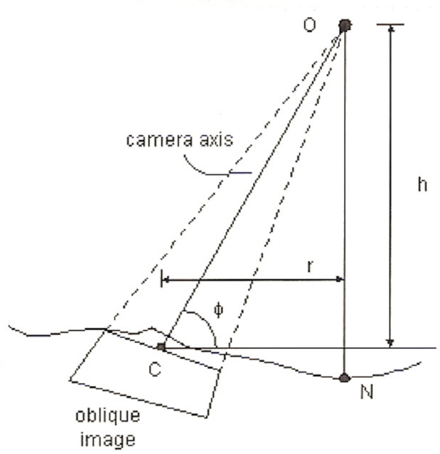

Fig. 3: Derivation of ground coordinates for oblique images with C the image centre projected on the (average) ground, N the nadir point, O the perspective centre, r the distance between the vertical line through the perspective centre and the image centre (C) projected on the ground, h the flying height above average ground, and ϕ the angle of the camera axis – the horizontal line represents the average elevation of the ground (EP 1 696 204 A2 2006).

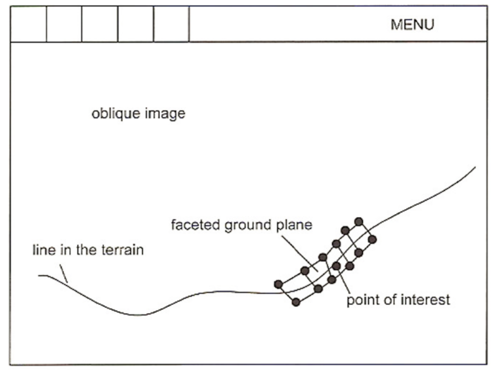

Fig. 4: Schematic sketch of a window with an oblique aerial image and superimposed DTM facets (EP 1 696 204 A2, 2006).

(elevation) of the area and the azimuth of the camera axis, coordinates of the image centre can be determined.

In the second step, coordinates for a 'point of interest' are calculated. The measured position in the oblique image, the interior orientation of the camera, and the facets of the DTM (cf. Fig. 4) are required in this calculation.

The measured image coordinates of a point will identify a facet. Its elevation and tilt are used to find the elevations of the four terrain points within a table. The imaging ray starting from the measured pixel intersects the identified DTM facet (cf. Fig. 5) and the plane coordinates of the intersection point can be determined. The elevation of the intersected point can be calculated by a

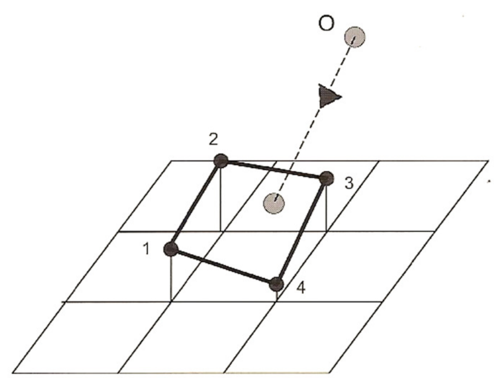

Fig. 5: Intersecting the imaging ray with a DTM facet with O the perspective centre, 1, 2, 3, and 4 the DTM points.

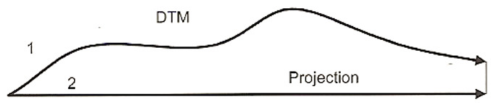

Fig. 6: Distance tool of the "EFS" software – Option 1: "Walk the earth distance", option 2: "Flat distance" (PICTOMETRY INTERNATIONAL CORP. 2002).

bilinear interpolation. In the third step, pixel coordinates are determined by projecting the derived spatial coordinates back to the image. The obtained values are compared with the measured values. If the differences are larger than a selected threshold, the last two steps have to be repeated.

Other points are determined in the same way. The distance between points can be calculated from the derived coordinates. A path can be continuously traced with intermediate points generated by the system. The distance between points can be calculated along the terrain itself (function "Walk the earth distance") or it can be reduced to the map projection ("Flat distance"), cf. Fig. 6.

The software package "EFS" is used for the following practical tests.

5 Practical Tests

Data, which have been used in the test, include oblique images, a DTM, vector and raster maps as well as orthoimages derived by means of the vertical images and the DTM. The results of the measurements of distances and coordinates by means of the "EFS" software package of Pictometry, have been checked by field measurements (using GPS / RTK – Real Time Kinematic) and stereo measurements (OVERBYE 2007). The author has carried out additional checks using stereo photogrammetry and tacheometer measurements. In the following, the used data are first described, and the obtained results are then summarized.

5.1 *Description of area and data*

Test area

The area used in the test is the city of Aalborg, Denmark. Differences in elevations are less than 50 metres and the houses are about 15 metres high.

Digital Terrain Model

The used DTM has been derived by laser scanning (using a LITEMAPPER 5600 of Riegl), georeferencing (using AERO Control of IGI mbH) and thinning of the dense point cloud. The spacing of the DTM posts is 10 m and the accuracy of the single posts is about $\sigma = 0.07$ m.

Imagery

The imagery was taken by Simmons Aerofilms Ltd., England, by means of the Pictometry Penta camera system from about 910 m above ground. The scale of the oblique images varies from 1 : 13 400 (front) to 1 : 22 400 (back) and the pixel size between 0.12 m (front) and 0.20 m (back). In the principal point of the image (PP') the scale is 1 : 16 700 and the pixel size is 0.15 m.

Map and field data

As map data the Danish topographic map 1 : 25 000 (in raster form) and the technical map, which is produced by stereo photogrammetry from image scales 1 : 5000, were used. The latter is a map in vector form and contains small objects like drain gratings, manhole covers, etc. Its specified accuracy is $\sigma_x = \sigma_y = 0.07$ m and $\sigma_z = 0.15$ m. This map has been used as reference data. Other reference data were measured in the field by means of GPS/RTK or by an electronic tacheometer (Leica TC1105).

5.2 *Results of measurement tasks*

In comparisons with reference data the following accuracy measures were derived: Root Mean Square Error (RMSE), average error, standard deviation and maximum error.

Measurement of distances

Tab. 1 shows the results of the comparison between measured distances in the EFS software package with the reference data. The mean distance is added in order to relate the accuracies.

Tab. 1: Accuracy measures for measured distances ("Flat distances").

number of checks	47	
mean distance	353 m	100 %
RMSE	1.5 m	0.42 %
average error	− 0.9 m	0.25 %
standard deviation	1.3 m	0.37 %
Δmax	3.9 m	1.10 %

Measurement of planimetric coordinates in oblique images

Tab. 2 shows the results of the comparison between measured coordinates in the EFS software package with the reference data. The root mean square errors are below the specification of the producer of the system. Systematic shifts of $\mu_x = 0.4\,m$ and $\mu_y = -0.8\,m$ occurred.

Tab. 2: Accuracy measures for measured planimetric coordinates.

Coordinate	X	Y
number of checks	40	40
RMSE	1.5 m	1.9 m
average error	0.4 m	− 0.8 m
standard deviation	1.4 m	1.8 m
Δmax	2.6 m	− 3.5 m

Measurement of heights

Heights of elevated objects (facades of houses, towers, etc.) were measured in different images and the average value is used in the comparison with the 'true' heights derived by field measurements or stereo measurements. The derived errors in Tab. 3 are therefore absolute errors.

Tab. 3: Height errors.

number of checks	6
RMSE	0.6 m
average error	− 0.2 m
standard deviation	0.6 m
Δmax	1.0 m

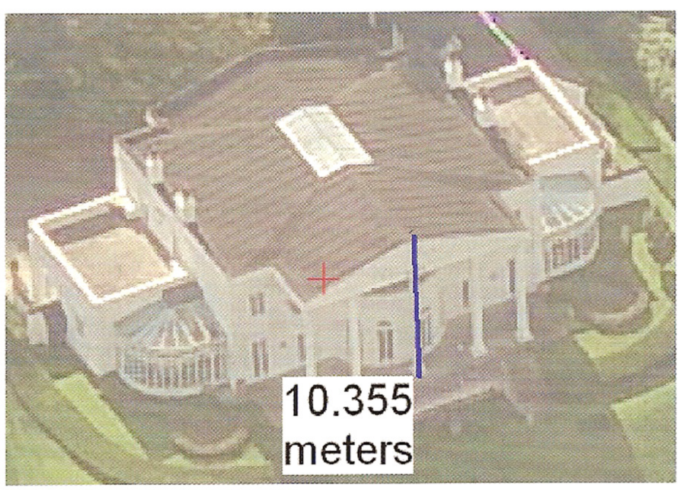

Fig. 7: Height measurement of a house.

The accuracy is worse when the bottom and the top of the object are not well defined in the images. Furthermore, the measured object height is supposed to correspond to the vertical direction. Fig. 7 shows an example of such a height measurement using the EFS package.

6 Other Applications

6.1 *Measurement of areas in facades*

The determination of rectangular areas of facades has to be carried out by measuring the width at the bottom of the house and the height from ground to top. The 'area tool' of Pictometry's EFS software package is not applicable for this task. It can only be used for areas on the terrain.

6.2 *Combination of ortho images and oblique images*

Ortho images have squared pixels and a unique scale. Measurements are very accurate. They can, therefore, advantageously be combined with oblique images. This is the idea behind the Pictometry system, where each object point is imaged from different directions. Up to 18 images can display the same area if parallel flight paths are flown. In this way cities and landscapes can quickly be displayed and easily interpreted and measured by non-photogrammetrists. For each pixel an elevation is given. Investigations in (Overbye 2007) with ortho images and the 10m-DTM showed that 44 determined elevations had a $RMSE_z$ of only 0.3 m. Elevations of terrain points can be determined by pointing to positions in the oblique images.

7 Discussion of the Results

The results obtained with oblique images and a 10m-DTM for planimetric coordinates had a $RMSE_{X,Y}$ of 1.7 m. Measured distances had a $RMSE_D$ of 1.5 m and heights of buildings could be determined with a $RMSE_{dh}$ of 0.6 m. The results showed systematic errors of $\mu_D = 0.9$ m, $\mu_{X,Y} = 0.9$ m, and $\mu_{dh} = 0.2$ m, respectively. An improved calibration of the system may reduce the systematic errors and better results would then be obtained. Elevations were determined with a $RMSE_z$ of only 0.3 m. The results for elevations are better than for the planimetric coordinates. This is due to the high accuracy of the DTM (which is derived by laser scanning) and the flatness of the test area. Improvements of the results are also possible with a denser DTM.

8 Conclusions

Oblique images show elevated objects like houses, masts, etc. very clearly and measurements of distances, coordinates, terrain elevations and heights can easily be carried out. The obtained results with oblique images and a 10m-DTM for planimetric coordinates are usable in many applications. The ability to view objects from different directions improves the readability of geographic information for non-photogrammetrists. Information systems with oblique images and DTM are an inexpensive alternative to photorealistic 3D models.

Acknowledgements

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