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DIRECT GEOREFERENCING USING UNMANNED AERIAL VEHICLES (UAVs)

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Abstract

Unmanned Aerial Vehicles (UAVs) have become an attractive data acquisition platform in photogrammetric applications. As we know, the fundamental photogrammetric and remote sensing problem is the determination with high accuracy of the attitude, the position and the intrinsic geometric characteristics of the sensor. At the beginning, the aerial photogrammetric systems had a fairly low accuracy position, but today's, the new aerial photogrammetric systems allow the real-time determination of all parameters of exterior orientation with a good enough accuracy. Because of this, the advantage is that we can achieve direct georeferencing without needing to determine the coordinates of ground's control points, before or after the photogrammetric flight. In this paper I present some practical results of so called direct georeferencing of digital images, using of direct measurements of the image's exterior orientation parameters by a GNSS/IMU system. This application is achieved by the aid of the collinearity concept, and just for a good accuracy estimation of the method, I have used few ground control points.

Key words: *Direct georeferencing, GNSS, IMU, Photogrammetry, UAV.*

INTRODUCTION

As the term implies, Direct Georeferencing is the direct measurement of exterior orientation parameters such as position (X; Y; Z coordinates) and attitude (roll; pitch; heading) in the real time when an aerial photograph is taken. That method can be used as an alternative or complement to Aerial Triangulation (AT). The parameters are obtained exactly at the time of photogrammetric flight, using data collected from Global Navigation Satellite Systems (GNSS) integrated with measurements from inertial sensors concerning Inertial Navigation System (INS) or Inertial Measurement Unit (IMU) that is directly attached to the mapping sensor, so that each pixel or range can be georeferenced to the Earth without the need for ground information collected on the field. Because of that, direct georeferencing method is essential for rapid mapping since it doesn't require the ground control points (GCP) which may require manual intervention.

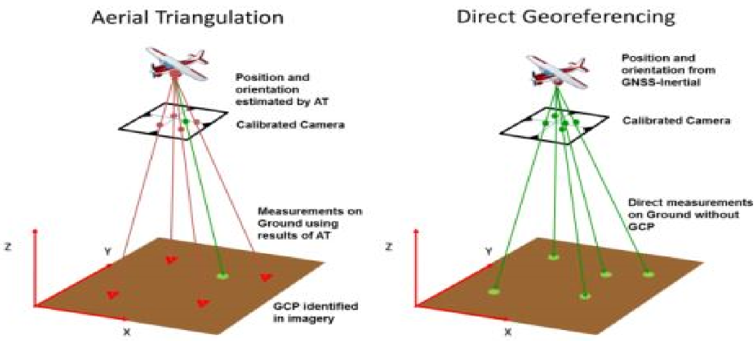
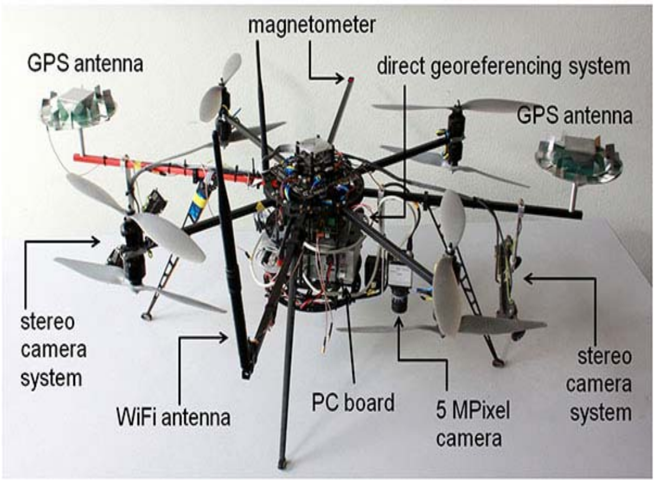


Figure 1: Direct Georeferencing Concept versus Aerial Triangulation

In this paper we present an application of direct georeferencing based on a system consisting of a GNSS, a IMU and a digital camera which allow us to know the exterior orientation parameters for aerial images. The method of direct geo-referencing allows us to transfer sensor or object data immediately into a local or global coordinate system (WGS'84) and makes their further processing possible.
It is very important to note that even if all these parameters are measured directly in real time, must be respected the fundamental photogrammetric conditions: collinearity, coplanarity and coangularity. (Popescu, 2016).

MATERIALS AND METHODS

The present paper uses the theoretical and practical experience of the authors in geomatics domain and it is practical applied using three aerial images and photogrammetric measurements, with a software program especially written for direct georeferencing based on a system consisting of a GNSS, a IMU and a digital camera which allow us to know the exterior orientation parameters for aerial images.



Unmanned Aerial Vehicle equipped for direct georeferencing

For our application of direct georeferencing we have used three digital images shown below in Figure 2.


Figure 2 . Digital images used for direct georeferencing

The mathematical model, which uses the collinearity equations, is a direct linear relationship between stereo-comparator coordinates and object coordinates (Abdel Aziz and Karara, 1971). This model is based on the two following collinearity equations (1):

$$
\begin{cases} x_c = -f \dfrac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)} \\ y_c = -f \dfrac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)} \end{cases} \quad (1)
$$

The relationship between the camera position (x_c,z_c) and the object (X,Y,Z) is determined by the seven parameters of the three-dimensional space, namely: the scale, three translation parameters and three rotation parameters. These relationships are expressed by collinearity equations (1) which express the basic condition in which an object point and its image lie on a straight line passing through the perspective centre.

Theoretically, a straight line has six degrees of freedom in the 3D Euclidean space: the coordinates of an arbitrary point lying on this line and the components of its orientation vector and in our application we have known all six parameters given by GNSS+IMU system (Popescu et al., 2015).

In our application, collinearity equations above use rotation matrix "R", whose elements r_{ij} ($i=1\ldots3, j=1\ldots3$) are given by (2):

$$
\begin{cases} r_{11} = \cos(\Phi)\cos(K) \\ r_{12} = -\cos(\Phi)\sin(K) \\ r_{13} = \sin(\Phi) \\ r_{21} = \cos(\Omega)\sin(K) + \sin(\Omega)\sin(\Phi)\cos(K) \\ r_{22} = \cos(\Omega)\cos(K) - \sin(\Omega)\sin(\Phi)\cos(K) \\ r_{23} = -\sin(\Omega)\cos(\Phi) \\ r_{31} = \sin(\Omega)\sin(K) - \cos(\Omega)\sin(\Phi)\sin(K) \\ r_{32} = \sin(\Omega)\cos(K) + \cos(\Omega)\sin(\Phi)\sin(K) \\ r_{33} = \cos(\Omega)\cos(\Phi) \end{cases} \quad (2)
$$

So, we shall have a different rotation matrix "R", calculated with relations (2) for every image, like in aplication below.

RESULTS AND DISCUSSIONS

Knowing the following initial data, measured for three photograms from a band (for example: 1235, 1236, 1237) as follows:

a) Exterior orientation parameters of the camera for the three photograms in band 12 (1235, 1236, 1237) obtained using GNSS and INS / IMU are shown in Table 1, with the remark that the rotation angles are measured by IMU / INS in sexagesimal degrees.

Table 1. Exterior orientation parameters of the camera for the three photograms 1235, 1236, 1237 in UTM coordinates and sexagesimal degrees

photogr.	Xo (m)	Yo (m)	Zo (m)	Ω (°)	Φ (°)	K (°)
1235	432588,642	4921230,837	1550,103	-0,041011144	-0,038839342	-1,59315834
1236	433038,785	4921222,373	1550,445	-0,061545766	-0,052895769	-0,77850741
1237	433502,122	4921218,087	1549,643	-0,027192757	-0,016737128	-0,469175836

Before direct georeferencing processing we converted the rotation angles from sexagesimal

:

Table 2. Exterior orientation parameters of the camera for the three photograms 1235, 1236, 1237 with rotation angles expressed in radians

photograms	Ω (rad)	Φ (rad)	K (rad)
1235	-0,000715779	-0,000677874	-0,027805859
1236	-0,001074176	-0,000923205	-0,013587518
1237	-0,000474603	-0,000292118	-0,008188663

b) Image-coordinates of 12 points of space-image on photos 1235, 1236, 1237, obtained with an accuracy of ± 2 μm (Table 3).

:

Table 3. Image-coordinates of points

Nr.Point	Image - Coordinates					
	x (μm)	y (μm)	x (μm)	y (μm)	x (μm)	y (μm)
	1235		1236		1237	
11235	4018,444	76714,556	-31650	76907,02		
11236	38459,984	81184,516	3126	80891,405	-33900	80872,983
11237			40204,5	80669,587	2970	80459,285
21235	804,745	-498,625	-35916	-276,666		
21236	39083,272	2429,228	2418	2111,635	-35244	2069,329
21237			38959,5	4043,924	1344	3809,619
31235						
31236	43669,591	-72924,091	5976	-73295,995	-32046	-73446,304
31237			37275	-74279,736	-708	-74604,043
8833	30606,224	24756,586	-5755,583	24556,447	-43321,536	24570,721
8834			27805,5	29804,717	-9674,662	29646,372
8878			16570,5	-82352,868	-21462,932	-82576,736

c) Ground coordinates (in UTM map projection system and the reference altimetric plane *0 Black Sea 1975*) for three checkpoints in space-object, obtained with the help of ROMPOS RTK GPS with an accuracy of ± 1 cm (Table 4).

Table 4. Ground control points measured in the field and used for accuracy estimation of the method

Nr.Point	Ground Control Points		
	X (m)	Y (m)	Z (m)
8833	432973,714	4921522,930	77,027
8834	433386,403	4921582,038	76,102
8878	433229,952	4920204,247	74,495

For processing of the three images through direct georeferencing method, first of all we calculated the three rotation matrices with relations (2) for every image:

- The rotation matrix for the perspective centre 1235 is:

$$\begin{bmatrix} 0{,}999613212 & 0{,}027802269 & -0{,}000677874 \\ -0{,}027801783 & 0{,}999612701 & 0{,}000715779 \\ 1{,}05385E\text{-}06 & -0{,}000696656 & 0{,}999999514 \end{bmatrix}$$

- The rotation matrix for the perspective centre 1236 is:

$$\begin{bmatrix} 0{,}999907265 & 0{,}013587094 & -0{,}000923205 \\ -0{,}0135861 & 0{,}999906123 & 0{,}001074176 \\ 2{,}05126E\text{-}06 & -0{,}001061533 & 0{,}999998997 \end{bmatrix}$$

- The rotation matrix for the perspective centre 1237 is:

$$\begin{bmatrix} 0{,}99996643 & 0{,}008188571 & -0{,}000292118 \\ -0{,}008188432 & 0{,}999966222 & 0{,}000474603 \\ 1{,}49429E\text{-}06 & -0{,}000472195 & 0{,}999999845 \end{bmatrix}$$

Then we use the collinearity equations condition (3) and use several notations (4) for their ease calculation, which can be done in Microsoft Excel:

$$X = (Z - Z_0)\frac{r_{11}(x_c - x_0) + r_{12}(y_c - y_0) + r_{13}(-f)}{r_{31}(x_c - x_0) + r_{32}(y_c - y_0) + r_{33}(-f)} + X_0$$
$$Y = (Z - Z_0)\frac{r_{21}(x_c - x_0) + r_{22}(y_c - y_0) + r_{23}(-f)}{r_{31}(x_c - x_0) + r_{32}(y_c - y_0) + r_{33}(-f)} + Y_0 \qquad (3)$$

$$A_1 = \frac{r_{11}(X_c - X_{o1}) + r_{12}(Y_c - Y_{o1}) + r_{13}(-f)}{r_{31}(X_c - X_{o1}) + r_{32}(Y_c - Y_{o1}) + r_{33}(-f)} \qquad \begin{cases} Xp = (Z_p - Z_{o1}) * A_1 + X_{o1} \\ Yp = (Z_p - Z_{o1}) * B_1 + Y_{o1} \end{cases}$$
$$A_2 = \frac{r_{11}(X_c - X_{o2}) + r_{12}(Y_c - Y_{o2}) + r_{13}(-f)}{r_{31}(X_c - X_{o2}) + r_{32}(Y_c - Y_{o2}) + r_{33}(-f)} \qquad \begin{cases} Xp = (Z_p - Z_{o2}) * A_2 + X_{o2} \\ Yp = (Z_p - Z_{o2}) * B_2 + Y_{o2} \end{cases} \qquad (4)$$
$$A_3 = \frac{r_{11}(X_c - X_{o3}) + r_{12}(Y_c - Y_{o3}) + r_{13}(-f)}{r_{31}(X_c - X_{o3}) + r_{32}(Y_c - Y_{o3}) + r_{33}(-f)} \qquad \begin{cases} Xp = (Z_p - Z_{o3}) * A_3 + X_{o3} \\ Yp = (Z_p - Z_{o3}) * B_3 + Y_{o3} \end{cases}$$

Where rij (i=1…3, j=1…3) are cosines directories of every photogram and (Xc,Yc) are the image-

coordinates of the point “p” on every photogram.
So, if we consider, for example, every stereo-couple 1235/1236, 1236/1237, 1235/1237, then ground-coordinate Z_p of the point “p” can be calculated and checked with relationships (5), as follows:

$$X_p = (Z_p - Z_{o1}) * A_1 + X_{o1} = (Z_p - Z_{o2}) * A_2 + X_{o2}$$

$$Z_p(A_1 - A_2) = Z_{o1}A_1 - Z_{o2}A_2 + X_{o2} - X_{o1} \implies Z_p = \frac{Z_{o1}A_1 - Z_{o2}A_2 + X_{o2} - X_{o1}}{A_1 - A_2} \qquad (5)$$

$$Z_p(A_2 - A_3) = Z_{o2}A_2 - Z_{o3}A_3 + X_{o3} - X_{o2} \implies Z_p = \frac{Z_{o2}A_2 - Z_{o3}A_3 + X_{o3} - X_{o2}}{A_2 - A_3}$$

In a similar way shall be determined values for notations B1, B2 and B3, and then is calculated the value of ground coordinate.“Yp” for points which appear on the three photograms, according to the relations (6):

For the photogram 1235: $Y_p = (Z_p - Z_{o1}) * B_1 + Y_{o1}$

For the photogram 1236: $Y_p = (Z_p - Z_{o2}) * B_2 + Y_{o2}$ (6)

For the photogram 1237: $Y_p = (Z_p - Z_{o3}) * B_3 + Y_{o3}$

The notations A1, B1, A2, B2, A3, B3, mentioned in relationships above, are calculated in Table 5.

Table 5. The notations A1, A2, A3, B1, B2, B3 (the position vectors) for 12 points of space-image on photograms 1235, 1236, 1237

the position's vertors						
Nr.Point	A1	A2	A3	B1	B2	B3
	1235	1236	1237	1235	1236	1237
11235	-0,051902523	0,253921846		-0,637110179	-0,642903738	
11236	-0,33970323	-0,036103985	0,276591686	-0,666335859	-0,672123422	-0,67554223
11237		-0,344818029	-0,030522018		-0,666083222	-0,669582263
21235	-0,007265989	0,298381211		0,00505584	-0,000686813	
21236	-0,326804312	-0,021310052	0,293254345	-0,010464936	-0,016247084	-0,019174004
21237		-0,326002356	-0,011751529		-0,028210168	-0,031178977
31235						
31236	-0,347702421	-0,04244716	0,271839251	0,618561024	0,612891448	0,610496031
31237		-0,303308816	0,010701665		0,624645519	0,622288422
8833	-0,261329472	0,044245544	0,358997056	-0,198389942	-0,204151142	-0,207210504
8834		-0,235927025	0,078295216		-0,244063092	-0,247201492
8878		-0,129768135	0,184254374		0,689663029	0,687349529

In Table 6 are presented the calculated values of ground coordinates of object-points.

Table 6.

Nr.Point	Ground Coordinates								
	Xp	Yp	Zp	Xp	Yp	Zp	Xp	Yp	Zp
	1235			1236			1237		
11235	432665,023	4922168,418	78,488	432665,023	4922168,699	78,488			
11236	433092,330	4922218,831	67,376	433092,330	4922219,178	67,376	433092,225	4922219,213	67,685
11237				433547,091	4922204,266	76,316	433547,091	4922204,601	76,316
21235	432599,341	4921223,393	77,685	432599,341	4921223,384	77,685			
21236	433070,193	4921246,257	76,591	433070,193	4921246,319	76,591	433070,167	4921246,330	76,671
21237				433519,439	4921263,966	76,056	433519,439	4921264,032	76,056
31235									
31236	433101,396	4920318,651	75,413	433101,396	4920318,338	75,413	433101,381	4920318,102	75,457
31237				433486,340	4920300,662	74,870	433486,340	4920300,353	74,870
8833	432973,594	4921523,075	77,053	432973,594	4921523,168	77,053	432973,540	4921523,181	77,258
8834				433386,719	4921582,306	75,692	433386,719	4921582,450	75,692
8878				433230,318	4920204,457	74,484	433230,318	4920204,137	74,484

For the accuracy estimation, it's recommended to do an average between the ground coordinates of photograms which was determined.

Nr.Point	Final Ground Coordinates			Accuracy estimation		
	Xp (m)	Yp (m)	Zp (m)	Δ X (m)	Δ Y (m)	Δ Z (m)
11235	432665,023	4922168,559	78,488			
11236	433092,295	4922219,074	67,479			
11237	433547,091	4922204,434	76,316			
21235	432599,341	4921223,389	77,685			
21236	433070,184	4921246,302	76,617			
21237	433519,439	4921263,999	76,056			
31235						
31236	433101,391	4920318,364	75,428			
31237	433486,340	4920300,507	74,870			
8833	432973,576	4921523,141	77,122	0,138	-0,211	-0,095
8834	433386,719	4921582,378	75,692	-0,316	-0,340	0,410
8878	433230,318	4920204,297	74,484	-0,366	-0,050	0,011

CONCLUSIONS

Direct georeferencing using UAVs has a lot of benefits compared to traditional aerial triangulation. This solution that has become a standard in wide area photogrammetric mapping is a GNSS-aided INS comprising an inertial measurement unit (IMU), a GNSS receiver, and a processing engine that implements a GNSS-aided INS solution both in real time and after mission via post-processing software with optimal smoothing running on a PC. So it makes possible getting a real-time aerial data acquisition system which is developed for the purpose of providing rapid and accurate geo-spatial information in the emergency situation such as disasters or accidents.

It also reduces the processing time required to create map products compared to traditional aerial triangulation techniques thereby increasing productivity.

A direct georeferencing method is also desired in order to reduce or eliminate field control expenses, such as making ground control points on a hard accessible area.

In conclusion, the emerging technology that appears to meet the challenging and sometimes conflicting requirements of direct georeferencing accuracy, size, weight, power consumption and cost is a new generation of GNSS-aided INS products using micro-electro-mechanical system accelerometers and gyros.

It is important to know that UAV photogrammetry is emerging as an alternative method of acquiring photogrammetry data to the traditional systems using full-size manned aircraft.

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