Accuracy assessment of real-time kinematics (RTK) measurements on unmanned aerial vehicles (UAV) for direct geo-referencing

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ABSTRACT
Geospatial information acquired with Unmanned Aerial Vehicles (UAV) provides valuable decision-making support in many different domains, and technological advances coincide with a demand for ever more sophisticated data products. One consequence is a research and development focus on more accurately referenced images and derivatives, which has long been a weakness especially of low to medium cost UAV systems equipped with relatively inexpensive inertial measurement unit (IMU) and Global Navigation Satellite System (GNSS) receivers. This research evaluates the positional accuracy of the real-time kinematics (RTK) GNSS on the DJI Matrice 600 Pro, one of the first available and widely used UAVs with potentially surveying-grade performance. Although a very high positional accuracy of the drone itself of 2 to 3 cm is claimed by DJI, the actual accuracy of the drone RTK for positioning the images and for using it for mapping purposes without additional ground control is not known. To begin with, the actual GNSS RTK position of reference center (the physical point on the antenna) on the drone is not indicated, and uncertainty regarding this also exists among the professional user community. In this study the reference center was determined through a set of experiments using the dual frequency static Leica GNSS with RTK capability. The RTK positioning data from the drone were then used for direct georeferencing, and its results were evaluated. Test flights were carried out over a 70 x 70 m area with an altitude of 40 m above the ground, with a ground sampling distance of 1.3 cm. Evaluated against ground control points, the planimetric accuracy of direct georeferencing for the photogrammetric product ranged between 30 and 60 cm. Analysis of direct georeferencing results showed a time delay of up to 0.28 seconds between the drone GNSS RTK and camera image acquisition affecting direct georeferencing results.

1. Introduction
Rapid and accurate direct georeferencing has been gaining importance in many domains where unmanned aerial vehicles (UAV, also referred to as drones) are seen as useful, such as in infrastructure monitoring and disaster response. Traditionally, UAV imagery or video streams were either broadly referenced through visual analysis within a given local context, or processed further through indirect georeferencing (Gabrilj et al. 2016; Jozkow and Toth 2014), via Ground Control Points (GCP) acquired by geodetic differential Global Navigation Satellite System (GNSS) receivers. Where GCP acquisition is impeded by site access difficulties or hazardous circumstances, but also to increase the surveying efficiency, direct georeferencing can be used. UAV images are located in an Earth-fixed coordinate system by accurately measuring the position and orientation of the sensors without GCP (Mostafa and Hutton 2001). This can be achieved through high quality GNSS and IMU measurements on the UAV itself (Chiang, Tsai, and Chu 2012; Cramer et al., 2000; Mian et al. 2015) to determine both the absolute positioning and the camera orientation. Given the very high cost of such sensors, a more economical solution is the use of Real-Time Kinematic (RTK) positioning, whereby the accuracy of the on-board GNSS receiver is improved via a correction signal sent by a fixed base station. Such RTK systems in theory allow the absolute position of the UAV to be determined to a few cm. The performance of GNSS can also be improved by regional Satellite-based Augmentation Systems (SBAS). The accuracy and reliability of the GNSS signal is improved using SBAS information about the accuracy, integrity, continuity and availability of the GNSS signals. However, the accuracy of direct georeferencing results depends on additional parameters that are untouched by the actual GNSS RTK performance, such as the quality of the IMU data and their processing, the adoption of motorized gimbals moving during the flights, the camera, the actual image acquisition in terms of image sharpness and overlap, and the photogrammetric processing, typically through Structure-from-Motion (SfM) (Sherwood et al. 2018; Torres-Martinez et al. 2015; Wang, Rottensteiner,
and Heipke 2019). A critical additional point is that the actual absolute position of the projection center is needed, not of the UAV frame itself. For large commercial multicopter UAV that carry the camera on an external gimbal the positional uncertainty can be very high, making it difficult to use for rapid mapping. Further, a synchronization error resulting from a time delay between camera exposure and GNSS receiver time stamp is a known error source affecting the accuracy of the georeferencing. According to Rehak and Skaloud (2017) for the carrier phase noise of around 2 cm, the time synchronization should be performed better than 1 ms for ground velocities of 10–30 m/s. The offset between the GNSS unit and camera projection center in the drone set up (i.e. the level arm offset) also affects the direct georeferencing result. This offset, or spatial displacement, between the sensors can be determined by applying a three-dimensional transformation of the interior and exterior orientation parameters (Skaloud, Cramer, and Schwarz 1996). The use of a motorized gimbal then leads to changes in the position of the lever arm during the flight, resulting in an additional source of uncertainty in the geolocalization of the acquired images.

In this study we investigate the effect of the above errors on the RTK onboard the DJI Matrice 600 Pro, and their consequences on the direct georeferencing performance. DJI has become the largest maker of commercial UAV, and the RTK function is becoming a common feature in professional versions of popular models, such as in the late 2018 release of the Phantom 4 RTK. Some of these error effects have been studied by other researchers (Cramer et al., 2000; Gerke and Przybilla 2016; Ip 2005; Jacobsen 2002; Mian et al. 2015; Padró et al. 2019; Peppa et al. 2019; Turner, Lucieer, and Wallace 2014) with studies based on light weight multirotor and fixed-wing UAVs. However, the Matrice 600 Pro (including the earlier versions of DJI S900 and S1000+) has a different sensor set up in terms of their placement on the platform, and the lever arm, miss-alignment and time delay are also different.

The accuracy of the measurements generated using D-RTK (DJI real-time kinematics mobile GNSS station) on the DJI Matrice 600 Pro is evaluated to understand the uncertainty range, with errors measured using the RMSE between the estimated and measured positions (Gómez-Candón, De Castro, and López-Granados 2014; Liba and Berg-Jürgens 2015; Ruzgjienë et al. 2015). In this study the assessment of the camera position estimated through photogrammetric bundle block adjustment (BBA) using Pix4D software and the camera position measured directly from the D-RTK unit onboard the aircraft is done. The focus of this study is, therefore, to examine whether the Matrice 600 Pro with D-RTK capability can be a solution for rapid mapping applications, and to determine if the theoretical 2 cm to 3 cm RTK accuracy (claimed by the manufacturer) can be achieved without additional GCP. In other words, to verify how far we are from achieving this value. This paper, however, does not consider the uncertainties arising from initial measurement errors or operator errors when computing the lever arm offset (i.e. considering perfect measurement), which can also affect the final result. Although the developed procedure was conceived to geolocalize any kind of image (i.e. nadir or oblique), only nadir images were used (given by the GNSS-RTK), fixing the initial gimbal position during the tests and reading the angle compensations directly from the log file delivered by the drone.

## 2. The UAV system

The capability of a UAV and the quality of its sensors and other system components affect the quality of the final mapping product. The sensors onboard our tested UAV are the GNSS receiver, IMU, and a Canon EOS 600D (for camera properties see Table 1). The GNSS receiver has two components: the redundant three antennas for position measurements, and two antennas for differential measurements (GNSS RTK), to ensure a real-time correction through the data link system (Datalink Pro) to facilitate communication with the base station. The D-RTK unit is placed on top of the aircraft above the upper plate, to ensure high accuracy positioning of the system. It includes two GNSS units of equal antenna height, a master antenna (ANT 1), and the slave unit (ANT 2). ANT 1 is mainly used for positioning, while ANT 2 provides the heading reference. The air system is connected to the base station through a Datalink Pro installed both on the air system and the ground system of the D-RTK unit. The antenna unit of the ground system is connected to the D-RTK unit through the antenna cable, and the D-RTK device

| Model          | Sensor (width x height) (mm) | Resolution (pixel) | Shutter speed (sec) | Principal point (x and y, respectively) (mm) | Focal length (mm) |
|----------------|-------------------------------|--------------------|--------------------|----------------------------------------------|------------------|
| Canon EOS 600D | 22.3 x 14.9 mm                | 18 megapixels      | 1/400 sec          | 11.49 and 7.66                               | 20               |

### Table 2. Flight parameters set for the test flight.

| Flight parameters | Values     |
|-------------------|------------|
| Forward overlap   | 78%        |
| Side overlap      | 78%        |
| Ground sampling distance (GSD) | 1.33 cm/pixel |
| Flight height     | 40 m      |
| Aircraft speed    | 4 m/s     |
| Camera exposure interval | 1 sec      |
is again connected through an 8-pin cable to the Datalink Pro on top of it, which in turn communicates with the air end.

One of the gimbal solutions for the Matrice 600 Pro is the Ronin-MX, designed to hold the camera and stabilize its movement as the aircraft moves during flight (Figure 5). The Ronin-MX contains a separate IMU to monitor its movement. It is attached to the main UAV body through the vibration absorber of the aircraft beneath the lower plate, to help decrease the effect of vibration on the imaging sensor. The Ronin-MX has a controlled angle accuracy of 0.02°. The angular measurements of the gimbal are stored with high frequency and can be therefore synchronized with the GNSS. A customized GNSS/camera synchronization module (Figure 2) developed by a company called DRONExpert (www.dronexpert.nl) was used as camera triggering module to synchronize the recorded GNSS RTK position information with the image from the camera. The module starts to trigger and record a GNSS RTK position after reaching an activation height that can be set as needed.

3. Methodology

A set of experiments was conducted to locate the RTK reference center, and is described here together with 3D transformations techniques for the lever-arm estimation. Subsequently the assessment method for the direct georeferencing results is discussed.

3.1. Position location of the GNSS RTK reference center on the drone

The GNSS reading from the D-RTK unit (Figure 1) is used to determine the precise location of the drone when performing the aerial survey. However, locating the drone itself is not enough, since the actual RTK GNSS reference location and the relative position between GNSS and camera projection center are still unknown. Two experiments were repeated separately in two different locations by using a geodetic GNSS RTK placed on a tripod (Figure 3). The barycenter position of the drone was determined beforehand. Then the tripod with the geodetic GNSS was placed on the nadir of the barycenter to determine its position: the tripod lens assures a high precision in this process. For the first location (Location 1) the D-RTK reading of the UAV recorded was compared with the geodetic GNSS RTK, and its deviation from the geodetic GNSS yields the location of the actual UAV RTK reference center. The base station was located 15 m from the UAV location. The geodetic GNSS RTK was also used for absolute positioning of the base station,
because the base station of the D-RTK system by default records the relative location. A total of 20 measurements was taken by the geodetic GNSS RTK receiver and the D-RTK unit on the UAV. The measurements were acquired at regular intervals (the whole procedure took two hours) and then averaged, and the results were obtained by subtracting the measurement from the geodetic GNSS RTK and from the D-RTK unit of the UAV. In order to verify the achieved results, the experiment was repeated in a nearby location, Location 2 (with a different base station and UAV location), using the same approach.

As the exact position of the GNSS is completely unknown, the eccentricities (i.e. the GNSS position is not in correspondence of the barycenter) were considered by placing the body of the drone with the two axes parallel to the North and East axes: the longitudinal axis of the UAV was aligned with the North axis. This process was done by tracing some reference points with the GNSS in the test area.

3.2. Lever arm correction

The quality of the final product depends on the accuracy of the positioning of the projection center with respect to the GNSS reference point. In the case of the Matrice 600, with an overall system height of approximately 80 cm, this gap is large, and a proper transformation of the GNSS readings to the projection center is required. Two transformation parts are needed, focusing on the main body of the aircraft (absolute transformation), and the transformation around the gimbal system (relative transformation with respect the main body part) (Figure 4). The rotation angles of the first part of the aircraft are measured by the IMU units placed on top of the aircraft.

The second part assumes the transformation of a point from the GNSS reading center (determined using experimental studies, see Section 3.1) to the top part of the gimbal point, k (Figure 4), and finally to the projection center, point p. The orientation of the gimbal (second part) is represented by three angles, the yaw (κ), pitch (ψ) and roll (ϕ) values, also called Euler angles, from the gimbal IMU. The general equation for rotation of a homogeneous coordinate for 3D vectors can be obtained using a 4 × 4 transformation matrix:

$$
\begin{bmatrix}
 x_k \\
 y_k \\
 z_k \\
 1
\end{bmatrix} =
\begin{bmatrix}
 r_{11} & r_{12} & r_{13} & t_x \\
 r_{21} & r_{22} & r_{23} & t_y \\
 r_{31} & r_{32} & r_{33} & t_z \\
 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
 X \\
 Y \\
 Z \\
 1
\end{bmatrix}
$$

For the sake of convenience, we begin with the second part (Figure 5). Assuming there is no rotation in the main body of the drone, the upper part (Figure 4, part A), we can estimate the positional value of the projection center at the point p, starting at the top part of the gimbal, point k. In other words, the main body has zero effect on the motion of the gimbal. The rotational procedure followed here is the ZYX; first around the z-axis, then the y-axis and finally around the x-axis, and the rotation follows a counterclockwise direction.

Rotation around the z-axis (Rκ) is defined using the yaw angle (κ)
Rotation around the $y$-axis ($R_\psi$) is defined using the pitch angle ($\psi$)

$$
R_\psi = \begin{bmatrix}
\cos \psi & 0 & \sin \psi \\
0 & 1 & 0 \\
-\sin \psi & 0 & \cos \psi
\end{bmatrix}
$$

Rotation around the $x$-axis ($R_\omega$) is defined using the roll angle ($\omega$)

$$
R_\omega = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \omega & -\sin \omega \\
0 & \sin \omega & \cos \omega
\end{bmatrix}
$$

The complete roto-translation at the top of the gimbal at point $k$ ($R_{t_k}$) from the GNSS reading center is the result of a transformation around the $x$, $y$, and $z$-axes, using the rotation angles from the main IMU unit. Vectors $T_k$, $T_l$, $T_m$, $T_n$, $T_o$, $T_p$ are notations used to represent the 3D translation vectors for points $k$, $l$, $m$, $n$, $o$, and $p$, respectively, in Figure 5 and in the procedure below.

$$
\begin{bmatrix}
X_k \\
Y_k \\
Z_k
\end{bmatrix} = R_{t_k} = [R_\kappa] \times [R_\psi] \times [R_\omega] \times [T] + \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
$$

Where $X$, $Y$, $Z$ are the original GNSS measurements, $X_k$, $Y_k$, $Z_k$ represent the new points for location $k$, and $T$ is the 3D translation vector. Therefore, to compute
this location (point \(k\)), the transformation is done one by one per rotation axis.

Transformation around the \(x\)-axis (\(R_{t_x}\)):
\[
R_{t_x} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega & -\sin \omega \\ 0 & \sin \omega & \cos \omega \end{bmatrix} \begin{bmatrix} T_{kx} \\ T_{ky} \\ -T_{kz} \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}
\]
(6)

Transformation around the \(y\)-axis (\(R_{t_y}\)):
\[
R_{t_y} = \begin{bmatrix} \cos \psi & 0 & \sin \psi \\ 0 & 1 & 0 \\ -\sin \psi & 0 & \cos \psi \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix}
\]
(7)

Transformation around the \(z\)-axis (\(R_{t_z}\)):
\[
R_{t_z} = \begin{bmatrix} \cos \kappa & -\sin \kappa & 0 \\ \sin \kappa & \cos \kappa & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = \begin{bmatrix} x''' \\ y''' \\ z''' \end{bmatrix}
\]
(8)

Finally, the transformation at point \(k\) is equal to:
\[
R_{t_k} = R_{t_x} \cdot R_{t_y} \cdot R_{t_z} = \begin{bmatrix} x''' \\ y''' \\ z''' \end{bmatrix} + \begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix}
\]
(9)

Consequently, the transformation at point, \(l\) (\(R_{t_l}\)):
\[
R_{t_l} = \begin{bmatrix} \cos \kappa & -\sin \kappa & 0 \\ \sin \kappa & \cos \kappa & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} T_{lx} \\ T_{ly} \\ T_{lz} \end{bmatrix} + \begin{bmatrix} X_l \\ Y_l \\ Z_l \end{bmatrix}
\]
(10)

Rigid body translation is applied at point \(m\) (\(R_{t_m}\)), since there is no rotation component between points \(l\) and \(m\):
\[
R_{t_m} = \begin{bmatrix} X_l \\ Y_l \\ Z_l \end{bmatrix} + \begin{bmatrix} T_{mx} \\ T_{my} \\ T_{mz} \end{bmatrix} = \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix}
\]
(11)

Transformation at point, \(n\) (\(R_{t_n}\)):
\[
R_{t_n} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega & -\sin \omega \\ 0 & \sin \omega & \cos \omega \end{bmatrix} \begin{bmatrix} T_{nx} \\ T_{ny} \\ T_{nz} \end{bmatrix} + \begin{bmatrix} X_n \\ Y_n \\ Z_n \end{bmatrix}
\]
(12)

Rigid body translation at point, \(o\) (\(R_{t,o}\)). Again, there is no rotation component between points \(n\) and \(o\):
\[
R_{t_o} = \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} + \begin{bmatrix} T_{ox} \\ T_{oy} \\ T_{oz} \end{bmatrix} = \begin{bmatrix} X_n \\ Y_n \\ Z_n \end{bmatrix}
\]
(13)

And finally, transformation at point, \(p\) (\(R_{t,p}\)) (\(p\) is the projection center):
\[
R_{t_p} = \begin{bmatrix} \cos \psi & 0 & \sin \psi \\ 0 & 1 & 0 \\ -\sin \psi & 0 & \cos \psi \end{bmatrix} \begin{bmatrix} T_{px} \\ T_{py} \\ T_{pz} \end{bmatrix} + \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} = \begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix}
\]
(14)

The lever arm vector (\(L_0\)) is then the difference between the GNSS reading from the GNSS center,
\[
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}
\]
and the transformed vector of the camera location,
\[
\begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix}:
\]
\[
L_0 = \begin{bmatrix} X - X_p \\ Y - Y_p \\ Z - Z_p \end{bmatrix}
\]
(15)

However, in reality, the main body of the aircraft (the first part) is in constant motion when flying, and it cannot be zero for the whole duration of the survey. The angles of this part of the aircraft are measured by the redundant main IMU units as mentioned above. The rotation angles \(\lambda\), \(\phi\) and \(\theta\) obtained from the main IMU unit define the movement of the aircraft. The combination of the three rotation angles results in the orthogonal transformation matrix and transform a coordinate system measured by the main IMU unit to the mapping frame (Cartesian coordinate system), and are written as:
\[
R_{t_0}^m = R_{t_1} \ast R_{t_2} \ast R_{t_3}
\]
(16)

\[
R_{t_0}^m = \begin{bmatrix} \cos \lambda & -\sin \lambda & 0 \\ \sin \lambda & \cos \lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \phi & 0 & \sin \phi \\ 0 & 1 & 0 \\ -\sin \phi & 0 & \cos \phi \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix}
\]
(17)

The lever arm (\(L\)) in the mapping frame is then determined by applying the transformation matrix on the lever arm vector (\(L_0\)) of the gimbal.
\[
L = R_{t_0}^m \ast L_0
\]
(19)
The lever arm vector varies during the flight with changing angles of the gimbal as well as the main body, and their values can be estimated from the Euler angles recorded by the gimbal IMU unit and the aircraft IMU units using Equation (20).

Based on these equations, a MATLAB procedure was developed to calculate the different lever arm vectors as per the given yaw, pitch and roll angles from both IMU units. These values are used to adjust the original GNSS measurements and locate the camera projection center used.

### 3.3. Implementation of lever arm offset on direct georeferencing

The GNSS RTK/camera offset was computed for every image and angle change because of the continuous change in the orientation of the aircraft and its gimbal system during the flight. The total offset in the x, y, and z-direction was determined based on the roll, pitch and yaw angles of both main IMU (aircraft IMU) and the gimbal IMU. The orientation of the aircraft angle was measured in quaternion, and it was converted to Euler angles. The resulting camera position (point, \( p \) in Figure 5) and the lever arm offset were determined following the procedure stated in section 3.2, accommodating the six degrees of freedom in the translation (x, y, z) and rotation (roll, pitch, yaw) directions. GNSS RTK position values of the aircraft were given in degrees (WGS 84 Latitude and Longitude) in the flight log, and were converted to meters in WGS 84 UTM using a MATLAB code developed by Palacios (2006) and then the offset estimation was made in meters.

### 3.4. Assessment of direct georeferencing

After the calibration for GNSS RTK/camera offset, the results of direct georeferencing were evaluated. Two types of evaluation methods were used: the first technique was to compare the camera position obtained from direct georeferencing with the camera position indirectly determined from aerial triangulation. Aerial triangulation was performed with eight evenly distributed Ground Control Points (GCP) and check points (CP) in the study area. The final results of the bundle adjusted camera position were then compared with the direct georeferencing results. The second technique was to run the bundle adjustment of the block without GCP, using only GNSS RTK direct georeferenced camera position, and to evaluate its accuracy with check points distributed in the study area.

### 3.5. Data acquisition for the test flight

Test flights were carried out in Bentelo in the western part of Enschede, The Netherlands (Figure 6). GCP were collected for the aerial triangulation and for assessing the spatial accuracy of direct georeferencing. Eight GCP collected using a static Leica GNSS RTK were used in total for image processing. Three test flights were conducted in a 70 × 70 m area. The flying height was set at 40 m above the ground for all three flight experiments. The images were recorded on a SD card, and the UAV flight log was obtained from the custom-made synchronization module developed by DRONEExpert. Flight parameters of the test flight are shown in Table 2.

### 4. Result and discussion

The final results obtained using the proposed methods are presented in this section. The results of the experimental studies to determine the GNSS reference center on the drone, as well as the GNSS RTK antenna offset and its correction, are explained in this chapter. These are followed by a discussion of the accuracy assessment for direct georeferencing based on the indirect georeferencing approach and the collected control points.

#### 4.1. GNSS RTK reference center on the drone

The horizontal and vertical measurements by the UAV and the geodetic GNSS were compared to determine the actual reference location of the D-RTK integrated in the drone. A total of 20 continuous measurements were obtained from the geodetic GNSS in two nearby locations (Location 1 and 2), together with 20 corresponding measurements by the drone. The measurements by the geodetic GNSS had...
a 3D error (standard deviation) of approximately 0.7 cm in all measurements. Table 3 shows the results of the measurements obtained.

In general, the experiment conducted indicated that the horizontal component of the x- and y-axes reading from the GNSS RTK reading of the drone refers to the point in the middle of the two RTK antenna, as the difference was quite close to the central point of the drone. The results of the height component showed a height difference of 0.287 cm for the first location, and 1.92 cm for the second location (Table 3 and Figure 7). This small discrepancy between the measures confirms that the ground point (ground surface) was considered the point of reference for the RTK measurement of the drone. In other words, the reference point was 63.5 cm below the RTK antenna height of the drone. Considering the used camera, the measured height of the camera was 14 cm above the ground when placed in nadir view, and the height to the top of the gimbal (point k in Figure 8) was 33.5 cm (see also Table 4) above the ground. It must be noticed that the eccentricity was always recorded below 1 cm and was neglected in the following tests considering this variability due to the noisy measurements.

Figure 6. Flight trajectory and distribution of GCP for the three flights. Red dotted lines for the first flight, blue dotted irregular lines for second flight, and solid yellow lines for the third flight.

Figure 7. Illustration of GNSS RTK reference center for the tests showing the difference between the geodetic GNSS (center) and the GNSS RTK from the drone.

Note: h is the height from the ground to the measured point. H is the height from the ground to the RTK antenna of the drone. x and y are the distance from the origin (center). (Modified after DJI user manual Matrice 600 Pro, 2016b).
4.2. Lever arm correction

The estimation of the lever arm offset between the GNSS reference location and the projection center commenced with an initial measurement of the physical distance between the two points (see Figures 5 and 8). This helped to determine the translation factors needed to complete the overall transformation process. A measuring tape was used for rough estimation of distance measurements between the points. The measures were repeated to prevent gross errors due to human mistakes. The distance for point $k$ (i.e. 33.5 cm) is the distance from the ground to the top of the gimbal in Figure 8.

Computation of the GNSS RTK/camera offset was done based on the initial measurements as an input value. Using the developed methodology and procedure described in section 3.2 the estimation of the offset was done, and the result showed a variation of the lever arm with varying gimbal angles. This was confirmed during the flights, when the gimbal compensated the movement of the drone (Figures 10–12), generating changes in the level arm values (Figure 9). The images were taken in nadir view, and the pitch angle was initially set at ~90°, while the roll and yaw angle show high variations, especially in the first flight because of the angle compensation made by the Ronin-MX during sudden changes in the flight direction. As can be seen from the numbers labeled (the time the image was taken and its position and attitude data were recorded) in Figure 9, the changes and the peak of the lever arm in the graph corresponds to the flight trajectory where changes in heading direction occur. In those cases the gimbal movements were usually late and inadequate to follow the sudden changes in direction. The highest lever arm offset computed for the first flight was 40 cm, and the lowest offset computed was 17.6 cm. The lever arm in the second flight in Figure 9(b) was relatively constant compared to the other flights, because unlike in the other experiments it does not have sharp changes in heading directions, reducing the need to move the gimbal. In other areas where there were no attitude changes, the lever arm was relatively constant in all of the three flights. The highest and lowest lever arm offset for the second flight was 22 and 15 cm, respectively, while the third flight has the highest offset of 29 cm and the lowest offset of 14.4 cm.

A late response of the gimbal system or delay between the attitude of the aircraft and the attitude of the Ronin gimbal was noticed from these results, especially in the yaw angle of the gimbal for all of the three flights (Figures 10–12). The gimbal system tends to stabilize the movement of the drone, as is shown in these graphs. However, the gimbal response to the change in attitude of the aircraft was often late or had

| Location 1 | Easting (cm) | Northing (cm) | Height (cm) |
|------------|--------------|---------------|-------------|
| Geodetic   | 35,551,436.14 | 578,794,855.89 | 8091.73     |
| UAV        | 35,551,436.61 | 578,794,855.51 | 8091.44     |
| Difference (Geodetic and UAV) | −0.47 | 0.37 | 0.28 |
| STD        | 0.52 | 0.59 | 0.85 |

| Location 2 | Easting (cm) | Northing (cm) | Height (cm) |
|------------|--------------|---------------|-------------|
| Geodetic   | 35,551,664.97 | 578,795,024.3 | 8089.47     |
| UAV        | 35,551,665.85 | 578,795,024.25 | 8091.39    |
| Difference (Geodetic and UAV) | −0.87 | 0.04 | −1.92 |
| STD        | 0.53 | 0.39 | 1.79 |

### Table 3. Test results of the experiment from location 1 and location 2. Please note that in these experiments height coordinates refer to the ground, while planimetric coordinates refer to the barycenter of the drone.

### Table 4. Initially measured values for the offset estimation.

| Distance between points | Points | Distance (cm) |
|-------------------------|-------|---------------|
| Reference center (the ground) and point $k$ | Tk | 33.5 |
| Point $k$ and $l$ | $T_l$ | −11.5 |
| Point $l$ and $m$ | $T_m$ | −19.5 |
| Point $m$ and $n$ | $T_n$ | 9 |
| Point $n$ and $o$ | $T_o$ | 19 |
| Point $o$ and $p$ | $T_p$ | −12 |

**Figure 8.** Translation vectors in the gimbal (from the top of the gimbal; point $k$ to the camera projection center point $p$).
imprecise movements that prevented to completely balance the camera position and thus affected the image acquisition process. In particular, the yaw angle seems to moderate (second flight), sometimes to accentuate (third flight), the movements of the drone, making this error very difficult to predict or model.

### 4.3. Assessment of direct georeferencing

The camera position determined through photogrammetric Bundle Block Adjustment (BBA) was compared and used as a reference point for the camera position (camera projection centers) measurement derived from the GNSS RTK unit onboard the aircraft after compensating for the lever arm offset. The first flight was carried out using the automatic flight planning in Pix4D software. The time delay was introduced in the GNSS time so that it matches with the camera image capturing time. The triggering module to the GNSS was set to 0.110 seconds for the first flight. The measured RMSE was close to 1 m, with the horizontal direction having an error of 0.93 m and the height component having an RMSE of 1.5 m.

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**Figure 9.** Lever arm offset between the GNSS reference center and camera lens with changes in attitude per images during the mission for the three flights: the gimbal tries to compensate the movements of the drone. (a) the first flight, (b) the second flight, and (c) the third flight. The peaks in attitude changes are indicated by white circles in the image. The numbers associated with the white circles show the time (in seconds) of the flight at that point.
A manual flight was carried out in the second experiment, using only the flight controller. The time delay from the triggering module to the GNSS was set to 0.310 seconds in the second flight, in order to better match the GNSS triggering time and the image capturing time, as the higher displacement was observed during the first flight. From the total of 152 images, 85 images collected at the right flight height were selected.

Figure 10. Comparison of the aircraft and gimbal attitude for the first flight (a) Roll angle (b) Pitch angle (c) Yaw angle.

Figure 11. Comparison of the aircraft and gimbal attitude for the second flight (a) Roll angle (b) Pitch angle (c) Yaw angle.
for processing in the second flight. The results of the GNSS RTK reading from the aircraft were then compared with the bundle adjusted camera position. The recorded offset was lower at the end of the flight strips due to the decrease in velocity, as will be discussed later in section 4.4. The RMS error of the offsets measured against the computed BBA position showed errors of 0.36 m in the horizontal direction. The difference measured in the vertical component was 0.379 m.

The third flight was again carried out using the automatic flight planning Pix4D software. The time delay was set to 0.11 seconds, the same as for the first flight. From the third flight 70 images were selected for processing. The observed offset showed a very large value of up to 8 m for the initial part of the flight, that quickly fell back to the lower offset variation. The large offset in the initial period of the flight was due to the mismatch between the GNSS triggering interval and the camera exposure interval. The triggering module was not able to match the GNSS and the camera time in the first eleven seconds. The GNSS RTK recorded two values per second and skipped the next seconds, while the camera exposed continuously every second. The RMSE in the horizontal and the vertical direction was 2.17 m and 0.1 m, respectively. The offset decreased significantly to 0.69 m and 0.08 m, respectively, when the first 11 readings were removed (i.e. after debugging the bad images) from the 70 images (Figure 13). The time adjustment (time delay of 0.310 introduced) and the manual flight plan contributed to the lower displacements in the case of the second flight. The vertical displacement observed for the third flight was very small compared to its horizontal components, because the mismatch of the GNSS and the camera time mentioned above for the first 11 readings affected the horizontal component.

These results are comparable to results obtained by Gabril (2015) for RTK-based direct georeferencing from a multi rover UAV, where the RMSE in the horizontal and the vertical components was 40 cm and 236 cm, respectively. The higher error in the vertical component in this case was attributed to the incorrect camera parameters, specifically to the focal length.

### 4.4. Aircraft speed and offset relationship

The relation between the observed offset and speed of the aircraft is shown in Figures 14–16. The positive and negative signs in the graph indicate the change in direction of the flight. The magnitude of the error was highly related to the speed of the aircraft. The higher the velocity of the aircraft, the higher the offset or deviation from the assumed true values (BBA computed position in this case).

A significant time gap was noticed between the camera and the GNSS measurements, because of the imprecise synchronization between GNSS and cameras. In the middle part of the trajectory where the speed was highest at around 4 m/s measured around
a mission time between 15 and 24 seconds, the recorded offset was 1.12 m (0.28 second delay) for the first flight. This can also be seen in the second and third flights (see Figures 15 and 16). At the same aircraft speed of 4 m/s, the average offset observed for the second flight was reduced to 0.3 m, and a time gap of 0.075 second was estimated from the observed speed and offset. The changes in the vertical direction came from the slight changes or variation in height (less than 0.3 m) during the flight.

The large differences observed in the third flight for the first 11 readings is indicated in Figure 16 by the large offset differences. At the speed of 4 m/s in the horizontal direction, the measured offset of 0.7 m was observed and a time delay of 0.17 second estimated.

4.5. Geometric accuracy assessment based on control points

The accuracy of the UAV image block orientation for direct georeferencing and indirect georeferencing was assessed using the GCP and the CP evenly distributed in the study area for the flight experiments. The summary of the spatial error in the first flight for indirect georeferencing presented in Table 5 shows an RMSE of 2.5 cm in the planimetric and RMSE of 2.4 cm in the vertical direction. At the CP the obtained accuracy was 2.7 cm in the planimetric and 8.7 cm in the height component. The spatial error of the first flight obtained for the direct georeferencing from RTK reading measured at CP was 33.6 cm in the horizontal and 40.8 cm in the vertical direction (Table 6).

The second flight data set shows improved accuracy for both direct and indirect georeferencing results (Tables 7 and 8). The RMSE measured for the indirect approach at GCP was 0.6 cm and 3.9 cm for the planimetric and height components, respectively. The spatial RMSE at check points was 1.3 cm in the planimetric and 16 cm in the height component. The residual error registered at check points for direct georeferencing using the RTK solution was 31 cm in the planimetric and 27.2 cm for the height direction (Table 8).

The residual error measured at the GCP location for the third flight was 1 cm for the horizontal direction and 1.9 cm in the vertical direction for the indirect georeferencing (Table 9). At the check points the obtained accuracy was 1.6 cm for the planimetric measurement and 0.8 cm for the height component. The quality of direct georeferencing measured against
the check points show an RMSE of 58.2 cm in the planimetric and 56.3 cm in the height component (Table 10).

The comparison of the spatial errors for the three flights is shown in Figure 17 for the image block orientation from direct georeferencing. The horizontal and vertical components measured at the check points for the three flights showed that the second test flight carried out manually outperformed the first and the third flights because of the time delay adjustment made in the triggering module. This can also be seen from the aircraft speed and offset relationship discussed in section 4.4, where the observed time was lower in comparison to the other flights. The overall D-RTK supported bundle block adjustments shows that the block accuracy for direct georeferencing observed in these three flights had an average error range of 41 cm. Although it was possible to identify the influences of imperfect synchronization (see section 4.4), the effect of gimbal compensation and/or its late

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**Figure 15.** Positional error and velocity relation in the (a) North, (b) East, and (c) Vertical (down) directions for the second flight.

**Figure 16.** Positional error and velocity relation in the (a) North, (b) East, and (c) Vertical (down) directions for the third flight.
response to the attitude change of the aircraft is still difficult to interpret. A similar study conducted by Fazeli, Samadzadegan, and Dadrasjavan (2016) on a RTK-enabled multi rotor UAV showed a lower error range of 16.4 and 23.5 cm in the horizontal and vertical components, respectively.

5. Conclusion

The experiments carried out to determine the drone GNSS RTK reference center of the Matrice 600 Pro showed a point near the ground surface, 0.287 cm (Location 1) and 1.92 cm (Location 2), as a reference center. Therefore, given the measurement errors that might be introduced, both from the geodetic GNSS RTK and the D-RTK unit of the drone, the reference center could be considered in correspondence of the ground. In other words, the positional reading from the drone RTK is approximately 63.5 cm (the height of the RTK antenna from the ground) below the phase center of the RTK antenna on the drone. The projection center is located 14 cm above the ground (i.e. reference center) in the vertical direction when it is in the nadir view, though this will differ for other camera models.

Implementation of the direct georeferencing process required the correction factor for this drone GNSS RTK/camera offset, also referred to in this study as lever arm offset, in all three axes. The lever arm was computed based on the initial measurement made manually using a measuring tape, and it changed during the flight due to the movements of the gimbal to compensate the different attitude of the UAV in the air. The lever arm offset computed shows a strong relation with the rotation angles of the aircraft. The highest lever arm offset calculated for the first flight was 40 cm, and the lowest value was 17.6 cm. The second flight had the highest lever arm offset values (22 cm and 15 cm, respectively). The third flight had the highest lever arm offset value of 29 cm and the lowest lever arm offset value of 14.4 cm. The direct georeferenced results were obtained after removal of these offset values. In all three cases, the movement of the gimbal was only partially able to compensate for UAV attitude changes, often introducing an additional source of error.

The results of the direct georeferencing described in section 4.3, based on comparison between GCP assisted BBA position and direct georeferencing
assessed against check points described in section 4.5, showed that the geometric accuracy of the direct georeferencing increases when photogrammetric adjustment is used. From the three flights the direct georeferencing obtained in the second flight showed a relatively higher accuracy for both direct comparisons with BBA position and image block orientation accuracy in the horizontal component. The average error margin obtained for the three flights was 41 cm for geometric accuracy of the direct georeferencing. Although this error is higher compared to the RMS error obtained by Fazeli, Samadzadegan, and Dadrasjavan (2016), it shows that a near decimeter level accuracy is still achievable for mapping purposes. The observed relationship between the speed of the aircraft and the recorded offset revealed that the time delay between the drone GNSS and the camera was the reason for the higher errors observed in direct georeferencing, and can be partially explained with the lack of an accurate synchronization of camera and GNSS. A residual time delay of 0.28 seconds estimated at a speed of 4 m/s resulted in an offset value of 1.12 m in the first flight. Subsequently, at the same speed of 4 m/s, a time delay of 0.075 and 0.17 seconds was estimated for the second and the third flights, respectively. The recorded offset for these delays was 0.3 m and 0.7 m for the second and third flight, respectively. The lowest time delay and offset value was recorded on the second flight and this was due to the initial time delay adjustment. From this it can be concluded that the synchronization error played a significant role in the recorded low accuracy of the direct georeferencing result. From the three flights carried out using manual and automated flight planning, the manual flights performed better in terms of accuracy. On the other hand, the contribution of the gimbal movements during the flights is still uncertain and makes the determination of the gimbal position much more complicated. Although it should return a more stable acquisition, the impression is that it is often late and introduces imprecise attitude changes, adding another source of error. The total obtained accuracy was affected by the lever arm offset computed, since the estimation of the lever arm offset depends on the accuracy of the manual measurements made for the initial estimation. The final accuracy was also affected by the time synchronization. The synchronization module developed by DRONExpert required manual time delay adjustment. A series of flight experiment with a different time delay adjustment could provide a better result. In our case 0.31 sec delay provided a relatively better result. In general, it was concluded that the direct georeferenced results of the Matrice 600 Pro with an onboard GNSS RTK unit can generate a photogrammetric product with decimeter accuracy.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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