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Ground Operational Picture Improvement Through Direct Georeferencing from an Unmanned Aerial System

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Abstract **- This paper presents an approach to improving the ground operational picture by applying direct georeferencing techniques from an unmanned aerial system (UAS). The study addresses the growing need for rapid and accurate target localization within time-critical operational environments, where minimizing latency and maximizing spatial accuracy are essential.**

The proposed methodology leverages onboard GNSS/INS data and calibrated imaging sensors to assist in determining the geospatial coordinates of observed objects without reliance on ground control points. A transformation model based on intrinsic and extrinsic camera parameters is implemented to ensure precise mapping between image space and object space.

The integration of direct georeferencing into the target management cycle significantly reduces processing time compared to conventional indirect methods. Experimental results indicate improved time performance and, consequently, enhanced operational efficiency, particularly in dynamic and data-intensive scenarios such as surveillance and reconnaissance missions.

The proposed approach supports near real-time performance and provides a scalable solution for advanced UAS-based targeting systems.

Keywords — Direct Georeferencing; GNSS/INS Integration; Real-Time Geospatial Processing, Unmanned Aerial Systems (UAS).

I. Introduction

In modern operational environments, particularly in military, security, and emergency response contexts, the ground operational picture (GOP) represents the real-time or near-real-time understanding of the situation on the ground. This includes the location, identification, and tracking of targets, assets, and threats [1]. Traditional methods for building and updating the GOP often rely on indirect georeferencing techniques that require extensive post-processing, ground control points (GCPs), or manual intervention. While these methods provide high accuracy, they are time-consuming and unsuitable for time-critical missions. In dynamic operational environments, the delay between data acquisition and actionable intelligence can significantly impact mission success. Conventional workflows involve multiple stages of data processing, including image triangulation and adjustment, which introduce latency.

The rapid development of Unmanned Aerial Systems (UAS) has significantly transformed modern surveillance, reconnaissance, and targeting operations. UAS, commonly known as drones, have emerged as powerful platforms for aerial reconnaissance and surveillance due to their flexibility, low operational cost, and ability to operate in contested or inaccessible areas [2], [3]. However, the full potential of UAS-derived imagery is realized only when the collected data can be accurately and rapidly georeferenced to real-world coordinates.

Direct georeferencing offers a compelling solution by determining the geospatial position and orientation of the imaging sensor directly from onboard navigation systems (GNSS/INS) without the need for GCPs or complex aerial triangulation. This approach minimizes latency, reduces dependency on ground infrastructure, and enables faster integration of imagery into command-and-control systems.

This paper explores the application of direct georeferencing from a UAS to enhance the GOP. We present a methodology that integrates calibrated camera parameters with high-precision onboard navigation data, implement a collinearity-based transformation model, and evaluate its performance in terms of accuracy and processing time. The results demonstrate significant

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improvements in operational efficiency for surveillance and reconnaissance missions.

II. Materials

The georeferencing procedure has been used extensively not only for updating but also creating digital GIS data. Specialized software products are known where a desirable effect is achieved with the intervention of a human operator and by following a certain sequence of actions. The necessity of instantly updatable digital geographic data demands greater automation of the georeferencing process.

One of the approaches for automated georeferencing is presented in the publication [4]. The authors Xiangyu Zhuo at all are proposing to apply Image Processing methods in the georeferencing of a photo image captured by an Unmanned Aerial Vehicle (UAV) onto previously georeferenced by various techniques single objects that are expected to be included in the field of view of the capturing camera. The authors have declared the achievement of sufficiently high accuracy. Thus, the proposed approach would have a more limited application when the image to be georeferenced is captured at an incorrect angle, and is inapplicable when some of the fixed objects with known coordinates are not in the frame.

A universal approach called "direct georeferencing" is represented in the publication [5]. The authors of the material Carlos A. M. Correia at all consider a mathematical computational approach where the input data from the UAV's on-board sensors, the Global Positioning System (GPS) receiver and the Inertial Measurement Unit (IMU) are implemented in a way that given pixels of the captured image can be correlated with real geographical coordinates of the captured terrain. Computation simulation results using the specialized software MATLAB, Unreal Engine 4 and AirSim are described. A practical experiment with the Robot Operating System shows the applicability of the direct georeferencing method. The optimal choice of the used mathematical technique and the estimation of the error resulting from the inherent uncertainties in the readings of the on-board sensors remain a matter of discussion.

Materials [6], [7] are focused on real-time monitoring of natural disasters, such as fire, volcano, flood, landslide, and coastal inundation, highly-accurate georeferenced remotely sensed imagery is needed. Georeferenced imagery can be fused with geographic spatial data sets to provide geographic coordinates and positing for regions of interest. In this paper authors proposes an on-board georeferencing method for remotely sensed imagery, which contains five modules: input data, coordinate transformation, bilinear interpolation, and output data. The experimental results demonstrate multiple benefits of the proposed method.

There is a well-known mode Real-Time Kinematic (RTK). This mode of automated image processing is designed for fast, near-real-time georeferencing with the highest possible accuracy. As a rule, a satellite navigation reference system is used, employing reference ground stations from the national network or proprietary, specialized GPS devices designed for this purpose. In addition to the geographic coordinates at the time of capture, the current spatial position data of the optical axis of the camera lens are also recorded. In commercially available RTK photo-video devices, the subsystem is independent of the rest of the onboard equipment and has its own precise GPS and IMU. Georeferencing data is recorded in the metadata section of the image file, typically using the Exchangeable Image File Format (EXIF) [6]. In the same EXIF format, characteristic parameters of the photo-electronic system, such as resolution, optical sensor dimensions, pixel size, focal length, field of view, and exposure time, are also recorded in the image metadata. The images prepared in this way are transmitted to the Ground Control Station (GCS) via a digital wireless data link, or downloaded to an electronic storage media after the aircraft lands.

As discussed in the materials previously cited, the direct georeferencing approach is appropriate when there is a need to rapidly acquire up-to-date georeferenced digital mapping information. In order to establish the usefulness of the practical application of such an approach in this paper, the authors propose mathematical apparatus, experimental environment and field-testing results of a practical use of the Automatic Direct Georeferencing approach.

III. Methods

A. Georeferencing a raster image

The raster image obtained by the drone camera is considered as a collection of its smallest constituent unit - pixels (picture elements) arranged in a matrix. The arrangement of the pixels in the matrix depends on their position (row and column) in the digital image. The amount of pixels determines the resolution of the image, expressed in number of pixels in width and height. Unlike mathematical coordinate systems, the origin of the coordinate system of the pixels in the image (0,0) is the upper left corner [8], [9].

Georeferencing a raster image superimposed on a map rendered as a vector graphic (vector map), we need to determine the correction coefficients. The purpose of the correction coefficients is to ensure that each pixel of the image corresponds as closely as possible to the actual ground coordinates of the vector map. The applicable system of correction coefficients depends on the chosen transformation model. Transformation models can be of several types which generally perform translation, rotation, scaling and shearing.

One basic and commonly used transformation model is the affine transformation, which has a mathematical representation as a first-order polynomial.

$$x_i = a_0 + a_1 X_i + a_2 Y_i \quad (1)$$

$$y_i = b_0 + b_1 X_i + b_2 Y_i \quad (2)$$

where:

P{X_i, Y_i} – coordinates (column, row) of pixels in the image matrix, starting from the upper left corner;

L{x_i, y_i} – coordinates (in metric coordinate system) of Ground Control Points in the terrestrial coordinate system that correspond to {x_i, y_i};

a_1 is pixel size in x-direction;

b_1 is rotation about y-axis;

a_2 is rotation about x-axis;

b_2 is pixel size in y-direction;

a_0 is x-coordinate of center of the upper left pixel;

b_0 is y- coordinate of center of the upper left pixel;

i = 0 … N-1, N ≥ 3 (the number of GCPs required is at least 3 when working with a first order polynomial).

When certain values of P{X_i, Y_i} and L{x_i, y_i} are known, the values of the coefficients a and b must be determined in order to perform the coordinate transformation.

Equations (1) and (2) could also be described mathematically in matrix form:

$$L_x = \text{Aa} \tag{3}$$

$$L_y = \text{Ab} \tag{4}$$

where for N=5:

$$\text{A} = \begin{pmatrix} 1 & X_0 & Y_0 \\ 1 & X_1 & Y_1 \\ 1 & X_2 & Y_2 \\ 1 & X_3 & Y_3 \\ 1 & X_4 & Y_4 \end{pmatrix} \tag{5}$$

$$a = (a_0 \quad a_1 \quad a_2)^\top \tag{6}$$

$$b = (b_0 \quad b_1 \quad b_2)^\top \tag{7}$$

$$L_x = (x_0 \quad x_1 \quad x_2 \quad x_3 \quad x_4)^\top \tag{8}$$

$$L_y = (y_0 \quad y_1 \quad y_2 \quad y_3 \quad y_4)^\top \tag{9}$$

Solving equations (3) and (4) for the unknown coefficients a and b takes the form:

$$a = (A^T A)^{-1} A^T L_x \tag{10}$$

$$b = (A^T A)^{-1} A^T L_y \tag{11}$$

The matrix equations (10) and (11) have a solution when the following condition is fulfilled:

$$(A^T A)^{-1}(A^T A) = (A^T A)(A^T A)^{-1} = I \tag{12}$$

where I denotes identity matrix.

B. Obtaining GCP coordinates

As it is illustrated in expressions (3...11), to determine the correction coefficients it is required to know the pixel coordinates of distinctive points P{X_i, Y_i} and their corresponding ground coordinates L{x_i, y_i}. In the direct georeferencing case for the P{X_i, Y_i}, can be selected the center of the image matrix and the four end corner points. The question here is how to determine the coordinates of the corresponding GCPs L{x_i, y_i} when the image is captured by an on-board camera of a UAV.

In order to do this, additional data from the drone's GPS and IMU is required - GPS coordinates and 3-axes inclination. These data are used to associate the P{X_i, Y_i} points of the captured image with the actual GPS coordinates of the terrain - Fig.1.

For the final association of the captured image with the real area, it is necessary to know the values of the geographical coordinates of the boundary positions {L_0, L_1, L_2, L_3, L_4}. To determine the coordinates of the boundary positions, also called control points, it is convenient to apply the methods presented in detail in the material [1].

The inertial coordinate system is denoted as Earth by x axe, North by y axe, and Up by z axe (ENU), it coincides with the reference system. The UAV is in a local coordinate system, named North by x axe, East by y axe and Down by z axe (NED) in the Fig. 1. The coordinates of the UAV concerning the ENU are named the point B (x, y, z). The spatial state of the UAV is set by the angles of the local relative to the inertial coordinate system and for this the yaw, ψ, pitch, θ, and roll, ϕ angles are denoted.

Assumptions: the video camera is fixed at the center of mass of the UAV, the optical axis of the video camera is directed in the positive z direction of the local coordinate system, and the distance D from the Earth's surface are determined with a UAVs flight height via onboard barometric sensor.

The mathematical task consists in determining coordinates L(x, y, z), with input data B(x, y, z), ψ, θ, ϕ, and D. This data is presented by the onboard IMU and GPS.

The mathematical expression, without taking into account the distortions caused by the camera's optical system, has the form:

$$L = R_z(\psi).R_y(\theta).R_x(\phi).N.T_B(x,y,z).T_D \tag{13}$$

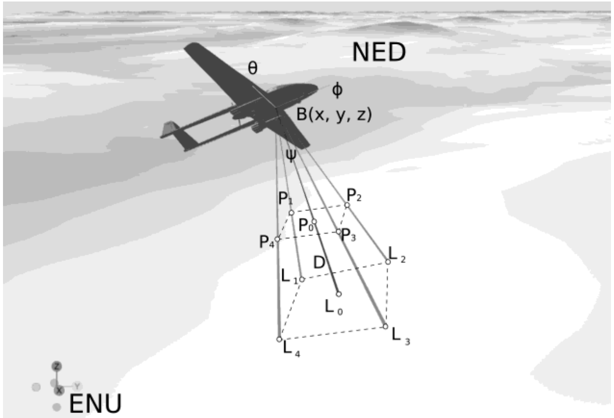

Fig. 1. Association of the captured image with real coordinates

where:
Rz, Ry, Rx – rotation matrices in NED;
N – transformation matrix NED to ENU;
T_B – matrix - UAV position in ENU;
T_D – matrix - distance to L.

For the central point L_0 the determination of the ground coordinates has the form:

$$L_{0,x} = -\big((D+z)\cos(\varphi)\sin(\theta) + x\sin(\theta)\sin(\varphi) + y\cos(\theta)\big)\cos(\psi) + (x\cos(\varphi) - (D+z)\sin(\varphi))\sin(\psi) \quad (14)$$

$$L_{0,y} = -(x\cos(\varphi) - (D+z)\sin(\varphi))\cos(\psi) - \big((D+z)\cos(\varphi)\sin(\theta) + x\sin(\theta)\sin(\varphi) + y\cos(\theta)\big)\sin(\psi) \quad (15)$$

$$L_{0,z} = -(D+z)\cos(\theta)\cos(\varphi) - x\cos(\theta)\sin(\varphi) + y\sin(\theta) \quad (16)$$

In the proposed mathematical apparatus, the expressions (14) and (15) determine the geographical coordinates of the central position, in Fig. 1 is shown as L_0. The geographical coordinates of the bounding positions $\{L_1, L_2, L_3, L_4\}$ can be determined by correcting the corresponding values of the angles ψ, θ and the distance D with the values of the horizontal HFoV and vertical VFoV viewing angle of the video camera used. Computational results are applicable when applied in the role of GCP from the earth's surface, which coincide with the limiting end pixels from the sensor matrix of the video camera used.

C. Experimental environment

A quadcopter-type drone was constructed for conducting field experiments. Widespread components were used, such as an F450 frame type, 2212 920KV BLDC motors, and a 4S battery configuration with a capacity of 3300mAh. The flight time is approximately 7 minutes. The main electronic components are a Pixhawk v. 2.4.8 Flight Controller (FC), an M10 GPS module with a QMC5883 electronic compass, a Raspberry Pi 4 Companion Computer (CC), and a video camera with an IMX219-77 optical sensor. The important data regarding the optical sensor for the experiment are: FoV 75^0; Focal length 2.9 mm; Sensor width 3.67 mm; Sensor Height 2.76 mm; Resolution: width 1920 pixels, height 1080 pixels.

The CC communicates with the FC via a UART port using the MAVLINK2 protocol and monitors the GPIO for a signal to trigger image capture. A software environment has been created with core components and a Python programming tool that includes the pymavlink and picamera2 modules, as well as the EXIFTool image metadata editing tool.

The test flight follows a programmed route with automatic image capture; the route was programmed using the QGroundControl software (Fig. 2). A single image is captured upon sending the MAV_CMD_DO_DIGICAM_CONTROL command via the MAVLINK2 protocol.

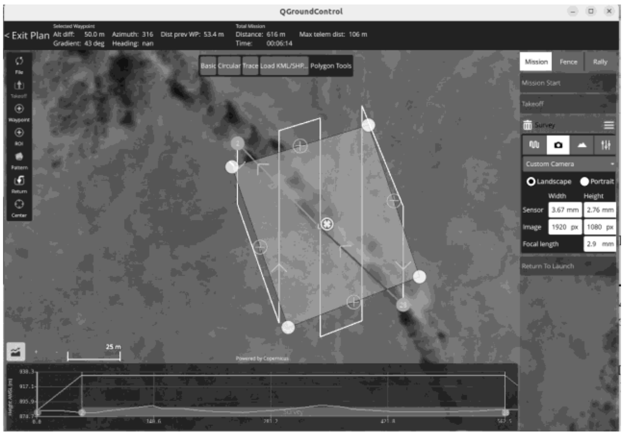

Fig. 2. Flight Plan for Automated Imaging

Upon receiving a capture signal, the CC receives the image in .jpeg format, adds EXIF data regarding the UAV's position and alttitude from the FC, and saves the image to the onboard SD card. After the UAV lands, the captured images are transferred to a personal computer (PC).

A software module has been developed to verify the intermediate results of the mathematical processing of the dependencies (10, 11, 14, 15) and to visualize the graphical output of the direct georeferencing of the image. The program code is written in Python 3 and uses the numpy software module. The software module has a simplified graphical interface and functions as a plugin for the specialized product Quantum GIS. As a result of the mathematical processing, a .wld file is automatically generated with the determined values of the coefficients a and b, which QuantumGIS uses to position the image within the screen area.

IV. RESULTS

Table 1 shows the numerical values of the input data used for the mathematical processing required for automated georeferencing. These values are extracted from the EXIF data of the image to be processed. The geographic coordinates from the GPS in the WGS 84 Coordinate

Reference System (CRS) are measured in decimal degrees. For the purposes of the mathematical processing, they have been converted to the CRS UTM zone 34N, where the measurement is in meters.

TABLE 1. INPUT DATA

	Longitude x		**Latitude y**		**Height**	
UAV coordinates B(x, y, z), D	***WGS 84***	23.405555^0	***WGS 84***	42.571909^0	*z*	***D***
	UTM 34N	4716082.54 m	***UTM 34N***	697433.49 m	897.97 m	50m
Inclination angles ψ (yaw), θ (pitch), ϕ(roll)	***ψ***		***θ***		***ϕ***	
	92.66^0		1.43^0		2.25^0	

The ground control points GCP {L0 ... L4} were located using equations (14) and (15). The coordinate values of these points, which serve as intermediate results in the calculations, are shown in Table 2.

If all the necessary data are available and the dependencies (10, 11) are applied, the desired values for the coefficients a and b are obtained. These values are shown in Table 3. The program-generated .wld file, whose contents are shown in Table 3, allows the automatically georeferenced image to be positioned on the QuantumGIS screen at its actual geographic location in the CRS UTM zone 34N.

To assess the accuracy of the direct georeferencing procedure, the processed image is overlaid as a raster layer on an existing vector map. A fragment of the vector map (part of the road network) obtained from the OpenStreetMap system is shown in Fig. 3. This section of the road network can also be seen in Fig. 2.

V. DISCUSSION

The results of the field experiments provide guidance for improving the tested procedure for direct georeferencing of UAS images. In some cases, a problem was identified with the content of the position and angular deviation data received in the CC from the FC, even though there was no indication of a failed connection between the data ports.

TABLE 2. PRELIMINARY RESULTS

	L_0	**L_1**	**L_2**	**L_3**	**L_4**
x	4716080.64	4716109.39	4716049.92	4716052.01	4716111.48
y	697432.16	697455.93	697453.21	697408.47	697411.18

TABLE 3. CALCULATED COEFFICIENTS

a_1	-0.0014141557408927606
b_1	-0.030975223754473605
a_2	-0.04142991173263196
b_2	0.0019320338591064577
a_0	697455.9229481166
b_0	4716109.384786936

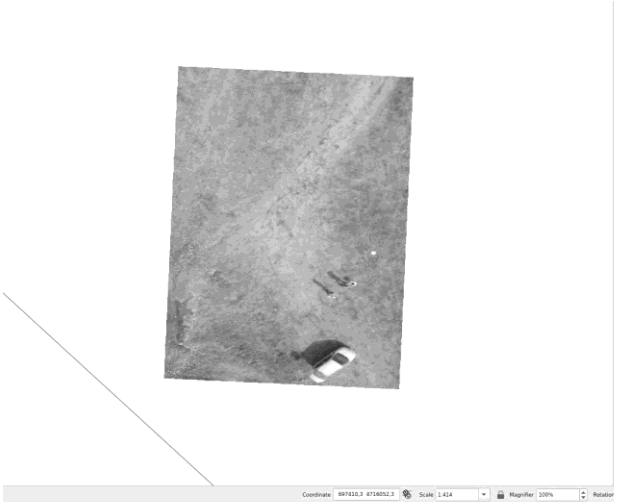

Fig. 3. Result of direct georeferencing

It is necessary for this communication channel to be automatically tested and for a way to be found to include it in the mandatory pre-flight check of the drone.

The goal of aerial photography is to capture images with the highest possible resolution. The maximum resolution of the IMX 219 camera used is 3280 x 2464 pixels. At this resolution, saving a single image to the onboard SD card takes about 5 seconds, which is not acceptable when executing the flight plan. Experiments were conducted with various software modules for controlling the video camera, libcamera and picamera2. We consider the use of picamera2 at a resolution of 1920x1080 pixels with a capture time of 1.5 s to be an acceptable temporary solution.

The Raspberry Pi 4 based CC unit runs on the multi-tasking Bullseye operating system. This could potentially cause a time desynchronization between the image and the data required for automatic georeferencing. Such desynchronization, in addition to the observed delay in capturing a single image, could completely compromise the procedure. It is necessary to explore other hardware solutions for the CC or switch to bare-metal programming on the Raspberry Pi.

Assessing errors in the direct georeferencing process is a crucial step in addressing specific operational and tactical tasks. It is necessary to conduct an in-depth study of the factors that can lead to inaccuracy. Such factors, in addition to the aforementioned possibility of desynchronization of the image, include insufficient precision of GPS coordinates and the determination of elevation using a barometric sensor. Another group of errors is expected to arise from the determination of the angular values used in formulas (14, 15). The impact of angular errors could be reduced by using the Extended Kalman Filter (EKF).

VI. Conclusion

This article discusses an approach to the direct georeferencing of aerial photographs, suitable for fully computer-based processing. The mathematical foundations of the georeferencing process are presented, as well as the relationships for determining control points on the Earth's surface. The proposed mathematical framework forms the basis of the program code developed by the authors.

Field experiments were conducted using a quadcopter drone specifically designed for this purpose. A full cycle of software processing was performed on the image data obtained during the experiments. This demonstrated the functionality of the mathematical framework and its readiness for practical application. Potential implementation issues were presented in a discussion format. Guidelines for improving the direct georeferencing procedure were considered.

The results achieved so far provide confidence to proceed with further research into the potential scientific applications of this topic. Research should continue in the following directions: adding a communication channel for real-time processing, testing higher-performance hardware, and transitioning to direct georeferencing of video streams. It is necessary to develop a methodology for determining the accuracy of the automated procedure. As a final result, the authors envision the creation of an original, proprietary hardware and software solution that would serve as a cost-effective replacement for existing commercial RTK systems and find application in military operations.

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