Elkhan Sabziev

Institute of Control Systems of ANAS, Baku, Azerbaijan

DETERMINING THE LOCATION OF AN UNMANNED AERIAL VEHICLE BASED ON VIDEO CAMERA IMAGES

Abstract. The paper deals with the problem of determining the location of an unmanned aerial vehicle from video and photo images taken by surveillance cameras. As the observation area is considered to be sufficiently limited, the area under consideration can be taken as part of a plane. The solution to the problem is based on the construction of a bijective mapping between the known geographic coordinates of three different objects recognized in the images and their coordinates relative to the monitor plane. To this end, the geographical coordinates of the objects (latitude and longitude) are first converted to the Mercator projection, and a bijective mapping is built between the coordinates of the objects calculated in the Mercator projection and the coordinates relative to the camera monitor plane. Then, based on the current orientation angles of the unmanned aerial vehicle, the coordinates of the projection of its position on the monitor plane are calculated, and the geographical coordinates are found by applying the inverse of the constructed bijective mapping.

Keywords: geographical coordinates; Mercator projection; unmanned aerial vehicle; bijective mapping; linear functional mapping; orientation angles; identification problem.

Introduction

As we know, the location of an unmanned aerial vehicle can be determined by processing data received from navigation devices (e.g. [1, 2]). However, due to the complex nature of the processing results, the accuracy of calculation of the aircraft's current location decreases due to measurement errors. It is considered advisable to regularly adjust the current coordinates of the aircraft, using alternative information sources in order to reduce errors accumulated during flight control.

At present, satellite-referenced aids are used at everyday level to obtain sufficiently accurate geographical coordinates of an object. However, due to irregular access to GPS data and its errors, the use of this information is unacceptable. In this regard, images made by video cameras installed on the aircraft can be an alternative source of information.

An aircraft can determine its location by image processing on the basis of different principles [3-5]. Different approaches are used depending on the nature of the problem being solved, the characteristics of the cameras taking pictures, as well as the number of pictures taken, the accuracy of object identification, and other criteria.

This paper considers the problem of calculating the location of an unmanned aerial vehicle based on video and photo images, taking the following principles as a basis for its solution:

• Since the areas shown in the images are quite small, they can be considered as part of a plane.

• It is possible to construct a bijective mapping of a regular nature between the coordinates calculated relative to the image for three real objects recognized in the images and their geographic coordinates.

• The constructed bijective mapping can be used to determine the position of the unmanned aerial vehicle relative to the observed objects in accordance with the orientation determined from navigation data.

Since the problem of identifying (recognizing) objects in video and photo images has been interpreted in various studies (e.g. [6, 7]), we will assume that the problem of identifying objects in video and photo images has been solved and their geographic coordinates are known.

In view of the above, this study considers the problem of calculating the geographic coordinates of the projection of an aircraft on the earth's surface, on the basis of three objects recognized in images taken by the unmanned aerial vehicle, using the known orientation data of its camera.

Identification problem statement

For clarity, assume that the images from the video camera of an unmanned aerial vehicle are displayed on a rectangular monitor of a known size. To determine the position of the objects observed in the images relative to the monitor, we introduce the following $O\xi\eta\zeta$ coordinate system, which coincides with the center of the central monitor, i.e. the point of intersection of the rectangle diagonals.

Suppose the $O\xi$ and $O\eta$ axes, which are perpendicular to each other, go through the center of the monitor and are parallel to both its sides, and the $O\zeta$ axis is perpendicular to the $O\xi\eta$ plane and directed so that the $O\xi\eta\zeta$ coordinate system is a right-handed coordinate system (Fig. 1).
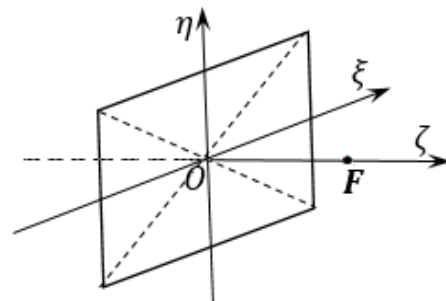

Fig. 1. $O\xi\eta\zeta$ local coordinate system relative to the monitor

In principle, the monitor can be positioned in space in such a way that the continuation of the straight lines connecting the monitor map of real points observed by the video camera intersect at the same point called the

point of view or observation. Let us denote the point of observation by F. It is clear from the design of the optical system of video cameras that point F will be located on the Oz axis.

In cartography, when transferring the earth's surface to 2D paper maps, the geographical coordinates of objects are reflected in a rectangular coordinate system called the Mercator projection [8, 9, 10]. Given the limited field of view of video cameras, the earth's surface in circles of medium length can be fairly accurately equated to the Mercator projection. This allows using the Mercator projection as an interval set and constructing a bijective mapping between the monitor coordinates of the objects and their geographic coordinates.

On the other hand, because of the fixed attachment of the video camera to the unmanned aerial vehicle, it is possible to determine the spatial position of the device relative to the earth, using the information from its navigation devices (gyroscopes). In other words, we can calculate how, relative to the earth, and, consequently, where the video camera aimed at the objects of observation is positioned.

The mathematical formalization of this approach is given in the following paragraphs.

Mathematical model of the identification problem

To this end, let us consider two tasks. The first task involves constructing a bijective mapping between the geographical coordinates of three points, which are recognized on the earth's surface and not located on a straight line, and the coordinates of the points reflected on the video camera monitor.

Suppose that an unmanned aerial vehicle through its video camera observes three points A_1, A_2, A_3 on the earth's surface, and the geographical coordinates (latitude and longitude) of these points are known. Denote the geographical coordinates of the points A_j by (v_j, u_j), respectively, (j = 1,2,3).

Suppose that the points A_1, A_2, A_3 are mapped onto some points B_1, B_2, B_3 on the video camera monitor. Let the coordinates of these points in the $O\xi\eta\zeta$ rectangular coordinate system introduced relative to the monitor be $(\xi_1, \eta_1, 0), (\xi_2, \eta_2, 0), (\xi_3, \eta_3, 0)$, respectively.

The bijective mapping $\Psi: (v, u) \to (\xi, \eta)$ can be constructed as follows.

Denote the coordinates of the object's Mercator projection by (x, y). According to [10, P.44], the transformation $\Psi_M: (v, u) \to (x, y)$ can be defined by formula (1).

$$\begin{cases} x = R \cdot v, \\ y = R \cdot \ln\left(tg\left(\frac{\pi}{4} + \frac{u}{2}\right)\left(\frac{1 - \varepsilon \cdot \sin u}{1 + \varepsilon \cdot \sin u}\right)^{\frac{\varepsilon}{2}} \right). \end{cases} \quad (1)$$

Here, $\varepsilon = \sqrt{1 - \frac{r}{R}}$, R and r are the equatorial and polar radii of the Earth, respectively.

Formulas (1) are given in analytical form, and using them, we can calculate the coordinates (x_j, y_j), $(j = 1,2,3)$ of the points A_j in the Mercator projection and thus consider them known.

Let us write the formulas for the connection between the coordinates of points in the Mercator projection and the known coordinates of their mapping on the monitor plane $O\xi\eta$. Essentially, these formulas can be written as an affine transformation $\Psi_A: (\xi, \eta) \to (x, y)$ in the following form:

$$\begin{cases} a_{11}\xi + a_{12}\eta + b_1 = x, \\ a_{21}\xi + a_{22}\eta + b_2 = y. \end{cases} \quad (2)$$

To calculate the coefficients of transformations (2), we need to solve the equations simultaneously $\Psi_A(\xi_j, \eta_j) = (x_j, y_j)$, $j = 1,2,3$. The unknowns in the first and second equations of system (2) are inherently independent of each other and can be calculated separately.

Consider the following system of equations for the unknowns a_{11}, a_{12}, b_1.

$$\begin{cases} a_{11}\xi_1 + a_{12}\eta_1 + b_1 = x_1, \\ a_{11}\xi_2 + a_{12}\eta_2 + b_1 = x_2, \\ a_{11}\xi_3 + a_{12}\eta_3 + b_1 = x_3. \end{cases} \quad (3)$$

Let us denote the main determinant of system of equations (3) by Δ, then from the explicit form of the main determinant

$$\Delta = \begin{vmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{vmatrix},$$

it is easy to see that if the points B_j are not located on a straight line, $\Delta \neq 0$ and the unknowns a_{11}, a_{12}, b_1 can be unambiguously calculated from system (3).

By writing a similar system of equations, we can also calculate the coefficients a_{21}, a_{22}, b_2. Thus, we have constructed the mapping Ψ_A. The mapping Ψ_A has the form of a linear functional dependence and it has the inverse Ψ_A^{-1}.

Consequently, the mapping Ψ is constructed as a superposition of the operators Ψ_M and Ψ_A^{-1}:

$$\Psi = \Psi_A^{-1} * \Psi_M.$$

Obviously, the inverse of the operator Ψ_M can be specified in iterative form, thus the bijective mapping Ψ is constructed.

Now let us proceed to the second task. It consists in calculating the coordinates of the point of the unmanned aerial vehicle's projection on the earth's surface, which will be observed on the video camera monitor, using the angles of the aircraft's spatial orientation.

As a rule, the field of view of the video camera is directed perpendicularly downward relative to the unmanned aerial vehicle that carries it. Therefore, based on the orientation angle of the vehicle, we can determine the direction of view of the video camera relative to the earth.

The orientation angles are yaw φ, pitch θ and roll γ angles, which determine the position of the unmanned aerial vehicle relative to the earth. Let us briefly explain the definition of these angles in accordance with [11]. To do this, we introduce the $O_g X_g Y_g Z_g$ earth-fixed coordinate system so that the $O_g X_g Y_g$ plane coincides with the Mercator projection, and the $O_g Z_g$ axis is directed perpendicularly upward relative to the $O_g X_g Y_g$ plane.

Let us define two specific directions related to unmanned aerial vehicles. In fixed-wing drones, we can distinguish a vector N directed along its longitudinal axis and a vector E perpendicular to the symmetry plane of the drone. In rotary-wing drones, vectors N and E are determined by selecting a direction defined as "forward-backward".

Yaw angle φ is the angle between the projection of the vector W on the $O_g X_g Y_g$ plane and the specific selected direction. As a rule, the north direction of the meridian is chosen as this direction.

Pitch angle θ is the angle between the vector W and the $O_g X_g Y_g$ plane.

Roll angle γ is the angle between the vector N and the OY_g axis of the $O_g X_g Y_g Z_g$ coordinate system, when the yaw angle is zero.

The coordinates of any vector fixed to an unmanned aerial vehicle during flight can be calculated by applying a vector transformation depending on the current orientation angles of the aerial vehicle as follows [11]. For the considered argument τ in formula (4), $\cos\tau$ and $\sin\tau$ are denoted by C_τ and S_τ, respectively, $\tau = \varphi, \theta, \gamma$.

$$\begin{pmatrix} x_0^r \\ y_0^r \\ z_0^r \end{pmatrix} = A \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix}, \qquad (4)$$

where $\begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix}$ is the coordinates of the vector under consideration relative to the earth, when $\varphi = \theta = \gamma = 0$, $\begin{pmatrix} x_0' \\ y_0' \\ z_0' \end{pmatrix}$ is the coordinates of that vector for the current $(\varphi, \theta, \gamma)$, calculated relative to the earth,

$$A = \begin{bmatrix} C_\theta C_\varphi & -C_\theta S_\varphi & -S_\theta \\ C_\gamma S_\varphi - S_\gamma S_\theta C_\varphi & C_\gamma C_\varphi + S_\gamma S_\theta S_\varphi & -S_\gamma C_\theta \\ S_\gamma S_\varphi + C_\gamma S_\theta C_\varphi & S_\gamma C_\varphi - C_\gamma S_\theta S_\varphi & +C_\gamma C_\theta \end{bmatrix}.$$

Take point $M(0,0,1)$ on the line of sight of the video camera. In principle, the location of the point M in space can be equated to the location of the aircraft. Let the point of projection of this point on the video camera monitor be $B_0(\xi_0, \eta_0, 0)$, and the point of projection on the earth's surface – $A_0(x_0, y_0)$. Then we can calculate the coordinates of the point B_0 by applying transformation (4):

$$\begin{cases} \xi_0 = -\sin\theta, \\ \eta_0 = -\sin\gamma\cos\theta. \end{cases}$$

Here we can calculate the geographic coordinates of the point A_0 corresponding to the point B_0 on the earth's surface by applying the inverse transformation $\Psi^{-1} = \Psi_M^{-1} * \Psi_A$ (Fig. 2).
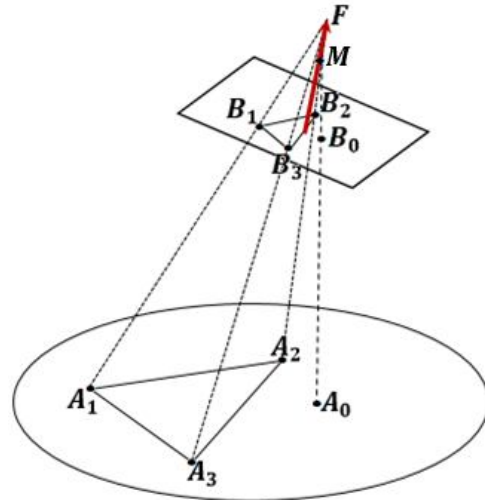

Fig. 2. Schematic representation of the points on the earth's surface mapped on the monitor plane

To this end, we first calculate the coordinates of the point A_0 in the Mercator projection, using the mapping Ψ_A, according to formulas (2):

$$\begin{cases} a_{11}\xi_0 + a_{12}\eta_0 + b_1 = x_0, \\ a_{21}\xi_0 + a_{22}\eta_0 + b_2 = y_0. \end{cases}$$

Now we can calculate the coordinates of the geographic latitude and longitude of the point A_0 by applying the inverse transformation Ψ_M^{-1}. As can be seen from (1), the geographic latitude of the point will be calculated using a simple formula:

$$v_0 = \frac{x_0}{R}.$$

Ψ_M is a nonlinear mapping, therefore, to construct its inverse, we need to apply an iterative calculation procedure.

For the value of geographical longitude, we construct successive approximations $u^{(k)}$ ($k = 0,1,2,...$) as follows. As the initial iteration $u^{(0)}$, we can take the geographic longitude of one of the base points or of the location of the unmanned aerial vehicle determined during the previous measurements. Then iterations (5) can be applied until the required accuracy is achieved [10, P.44]:

$$u_0^{(k+1)} = \frac{\pi}{2} -$$
$$-2\arctg\left(\left(\frac{1-\varepsilon\cdot\sin u_0^{(k)}}{1+\varepsilon\cdot\sin u_0^{(k)}}\right)^{\frac{\varepsilon}{2}} \exp\left(\frac{-y_0}{R}\right)\right), \qquad (5)$$
$$k = 0,1,2,....$$

Conclusions

Thus, in order to solve the problem of determining the location of an unmanned aerial vehicle from the video and photo images taken by it, we propose constructing a bijective mapping between the geographical coordinates and the images on the camera monitor. The construction of this mapping is based on the recognition of three different objects, which are shown in the images and whose geographic coordinates are known. To solve the problem, it is necessary that the recognized points should not be located on a straight line. The solution algorithm is simple and easily implementable by the processor of the unmanned aerial vehicle.

REFERENCES

1. Bukov, V.N., Bogdanov, V.D., Gladkov, B.M., Ivanov, D.G. & Serikov, N.N. (1995), *Automated processing of flight information*, VoyenIzdat, Moscow, 249 p.
2. Alyoshin, B.S., Afonin, A.A. & Veremeyenko, K.K. (2006), *Orientation and navigation of mobile objects: modern information technologies*, Fizmatlit, Moscow, 424 p.
3. Bezmenov, V.M. (2009), *Photogrammetry. Construction and adjustment of analytical phototriangulation*, KSU, Kazan, 86 p.
4. Krasnopevtsev, B.V. (2008), *Photogrammetry*, UPP "Reprografiya" MIIGAiK, Moscow, 160 p.
5. Martynova, L.A., Koryakin, A.V., Lantsov, K.V. & Lantsov, V.V. (2012), "Determination of coordinates and parameters of object movement based on image processing", *Kompyuternaya Optika*, Vol. 36, Issue 2, pp. 266-273.
6. Gostev, I.M. (2010), "Methods for identifying graphic objects based on geometric correlation", *Fizika Elementarnykh Chastits i Atomnogo Yadra*, Vol. 41, Issue 1, pp. 49-96.
7. Kazbekov, B.V. (2013), *Identification of mobile ground objects from an unmanned aerial vehicle*, Dissertation for a degree of Candidate of Technical Sciences, Moscow, 159 p.
8. Mozzherin, V.V. (2005), *Workshop on cartography. Mathematical basis of maps (teaching aid)*, KSU, Kazan, 99 p.
9. Levitskaya, T.I. (2017), *Basics of geodesy: a study guide*, Publishing House of the Ural University, Yekaterinburg, 88 p.
10. John J., Snyder (1987), *Map projections - A Working Manual United States Government Printing Office*, Washington, 383 p.
11. (1980), *Aircraft dynamics in the atmosphere. Terms, definitions and designations*, GOST 20058-80, Moscow, 52 p.

ВІДОМОСТІ ПРО АВТОРІВ/ ABOUT THE AUTHORS

Сабзієв Ельхан Наріман – кандидат фізико-математичних наук, старший науковий співробітник, провідний науковий співробітник Інституту систем управління Національної академії наук Азербайджану, Баку, Азербайджан;
Elkhan Sabziev – PhD in Physics and Mathematics, Senior scientific researcher, Leading scientific researcher at the Institute of Control Systems of the National Academy of Sciences of Azerbaijan, Baku, Azerbaijan;
e-mail: elkhan.sabziev@gmail.com; ORCID ID: http://orcid.org/0000-0001-8150-9439.

Визначення місця розташування безпілотного літального апарату на основі зображень відеокамер

Е. Н. Сабзієв

Анотація. У статті розглядається питання визначення місця розташування безпілотного літального апарату на основі фото, зроблених відеокамерами спостереження. Вважається, що зона спостереження досить обмежена і розглянуту територію можна сприймати як частину площини. Рішення проблеми засноване на побудові бієктивного відображення між відомими географічними координатами трьох різних об'єктів, розпізнаних на фотографіях, і їх координатами відносно площини монітора. Для цього спочатку переходимо від географічних координат об'єктів (широти і довготи) до координат в проекціях Меркатору і будуємо лінійно-функціональне відображення між координатами об'єктів, розрахованими в проекції Меркатору і координатами відносно площини монітора відеокамери. Потім, виходячи з поточних кутів орієнтації безпілотного літального апарату, обчислюються координати проекції його розташування на площині монітора і знаходяться географічні координати із застосуванням зворотного побудованого бієктивного відображення.

Ключові слова: географічні координати; проекція Меркатору; безпілотний літальний апарат; бієктивне відображення; лінійно-функціональне відображення; кути орієнтації; задача ідентифікації.

Определение места расположения беспилотного летательного аппарата на основе изображений видеокамер

Э. Н. Сабзиев

Аннотация. В статье рассматривается вопрос определения местоположения беспилотного летательного аппарата на основе фото, сделанных видеокамерами наблюдения. Считается, что зона наблюдения достаточно ограничена и рассматриваемую территорию можно принимать как часть плоскости. Решение проблемы основано на построении биективного отображения между известными географическими координатами трех различных объектов, распознанных на фотографиях и их координатами относительно плоскости монитора. Для этого сначала переходится от географических координат объектов (широты и долготы) к координатам в проекциях Меркатора и строится линейно-функциональное отображение между координатами объектов, рассчитанными в проекции Меркатора и координатами относительно плоскости монитора видеокамеры. Затем, исходя из текущих углов ориентации беспилотного летательного аппарата, вычисляются координаты проекции его расположение на плоскости монитора и находят географические координаты, применением обратного построенного биективного отражения.

Ключевые слова: географические координаты; проекция Меркатора; беспилотный летательный аппарат; биективное отображение; линейно-функциональное отражение; углы ориентации; задача идентификации.