Exploring out-of-focus camera calibration for improved UAV survey accuracy

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ABSTRACT

Calibrating large-range vision systems like UAV cameras is a complex task that often involves costly setups and the potential for errors due to inaccuracies in target fabrication. Traditional UAV surveying software typically estimates camera parameters alongside ground control points, but this method may lack optimal accuracy. Our study explores an alternative: using out-of-focus camera calibration to improve the reliability and accuracy of drone cameras for surveying. In our approach, the UAV camera is positioned several meters away from a low-cost target to ensure focus. We then calibrate the intrinsic camera parameters using an out-of-focus small calibration target, fixing these parameters before flight. For evaluation, we compare this method against the standard approach of estimating UAV camera parameters with survey imagery. Preliminary results suggest that this out-of-focus method offers a reliable and accurate solution for UAV surveying applications.

Keywords: Large-range vision system, UAV surveying, out-of-focus camera calibration, UAV camera calibration

1. INTRODUCTION

In the rapidly evolving field of aerial surveying, the calibration of large-range vision systems, such as those used in Unmanned Aerial Vehicles (UAVs), presents a significant challenge.[1] Traditional calibration methods arises not only from the intricate nature of the task but also from the substantial costs associated with setup and the potential for errors stemming from inaccuracies in target fabrication, such as these targets, typically created with aerosol and paint on surfaces within the study area, large ArUco or QR code prints, or even LED marker designs.[2–6] Moreover, UAV surveying software commonly estimates camera parameters in conjunction with ground control points, a process that may not always yield optimal accuracy and time-consuming process,[7] highlighting a pressing need for innovative calibration methods that can enhance the precision of drone cameras in surveying tasks.

Within this broader context, our research focuses on a promising yet underexplored area: the application of out-of-focus camera calibration techniques to improve UAV survey accuracy. By moving towards out-of-focus calibration, our study addresses a critical gap in current UAV surveying practices, proposing a method that could substantially mitigate the errors associated with target fabrication inaccuracies and other common pitfalls.[8,9] The method involves positioning the UAV camera several meters away from a low-cost target, with the internal settings of the drone adjusted to set the focal length to infinity. This setup ensures that the camera focuses on objects at long distances. Then by using an out-of-focus accurate small calibration target, such as a lab-generated circle pattern, positioned close enough to the drone camera to cover the whole field of view and, despite being blurred, the intrinsic camera parameters can be accurately calibrated. This defocused state of the camera allows capturing all necessary images to carry out conventional camera calibration method, using the OpenCV camera calibration algorithm to detect feature points on the calibration pattern.[10,11] This approach was validated in a large-scale structured light calibration method proposed by Marrugo et al.[12]

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In this paper, we adress all the process for calibrating a DJI Phantom 3 drone using an out-of-focus small circle calibration pattern printed on a flat surface as a glass and also shown on a digital screen. For evaluation, we compare this method against the standard procedure of estimating UAV camera parameters with survey imagery and analyzing the distances between different ground control points (GCPs) or targets in a field test both with and without calibration. Preliminary findings indicate that the out-of-focus calibration method offers a promising solution, providing a reliable and accurate means of improving UAV survey accuracy. This discovery not only addresses a crucial need within the field of dimensional optical metrology and inspection but also paves the way for future advancements in UAV survey applications.

2. METHOD

2.1 Pinhole camera model

In this article, the system model will initially be considered as a pinhole camera model, which describes the projection of a point from three-dimensional space onto two-dimensional space (the image plane of the camera), without considering any type of lens distortion. This means that each projection ray from points in the scene passes without any distortion to the image plane. Thus, the equation that describes a 3D coordinate point projected onto the image plane follows the following projection equation

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \mathbf{M} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}, \tag{1}$$

where the vector $[u, v, w]$ represents the 2D coordinate point in the image, M is the projection matrix, and $[X, Y, Z, 1]$ is the vector of 3D coordinates of the point in the scene, both vectors are represented in homogeneous coordinates. The projection matrix M is composed of an intrinsic matrix K associated with the internal parameters of the camera $f1, f2, cx, cy$, and an extrinsic matrix Mext that represents the pose of the world coordinate system M with respect to the camera coordinate system C. The image of Fig. 1 represents the pinhole camera model, in which it can be established that the distance between the optical center of the camera and the image plane is known as the focal length f, and the coordinate (x, y) in the image based on triangle similarity would be given by $x = f * (X/Z)$ and $y = f * (Y/Z)$.

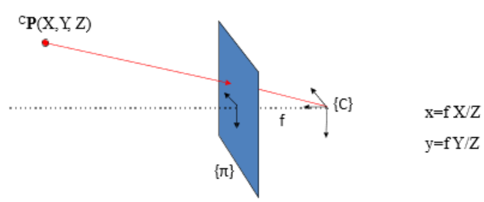

Figure 1. Pinhole Camera Model.

2.2 Distortion model

Lens distortion is a phenomenon that affects the projection of points in an image and deviates from the ideal pinhole camera model. The most common types of lens distortion are barrel distortion and pincushion distortion. In barrel distortion, the points in the image are displaced radially inward from their correct positions, creating a bulging effect towards the center as it is shown on Fig. 2 that comes from a DJI Phantom 3 drone used in this research.

In addition to radial distortions, tangential distortions can also occur. Tangential distortions manifest as a shift in the position of points along the tangential directions, causing image deformations.The following equations represent the model for radial and tangential lens distortion, using distortion coefficients that allow for the correction of image distortion in the camera. These coefficients capture imperfections in the physical construction

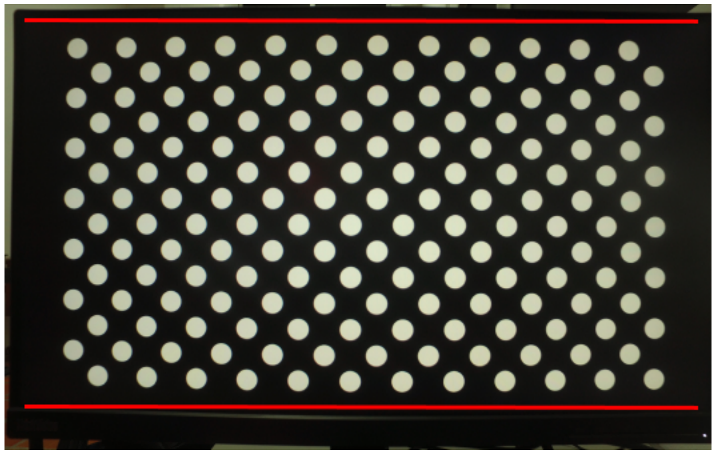

Figure 2. Barrel lens distortion of a DJI Phantom 3 drone camera. Red lines on the images give a perspective of how the points in the image are displaced radially inward from their correct positions.

of the lens, such as inclinations and deviations from the image plane, which result in curvature and other artifacts in the image.

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} (1 + k_1 r^2 + k_2 r^4 + k_5 r^6) \tag{2}$$

$$dx = \begin{bmatrix} 2k_3xy + k_4(r^2 + 2x^2) \\ k_3(r^2 + 2y^2) + 2k_4xy \end{bmatrix} \tag{3}$$

2.3 Traditional UAV Camera Calibration

In the domain of UAV camera calibration, two predominant methods have been extensively utilized: pre-calibration and self-calibration. The process of pre-calibration typically involves the construction of Ground Control Points (GCPs), targets, or markers characterized by specific patterns or features that facilitate easy detection. These are often large in size and placed across a vast area with controlled distances between them. The methodology requires capturing images of these markers and then estimating the camera's internal parameters. For pre-calibration, it is crucial that UAV cameras are adjusted for long distances, and short exposure times are mandated to minimize blurring effects. However, due to the shallow depth of field resultant from these settings, utilizing the same settings for varying flight heights becomes impractical. This calibration process demands a considerable expanse for testing, ensuring that calibration marks are in focus, thus escalating the requirement for substantial space and augmenting the workload due to the preparation of adequate testing infrastructure.[13,14]

Conversely, self-calibration refers to the method of computing the camera's internal and external orientation parameters solely based on image point correspondences. This technique can be executed with or without spatial object space constraints, typically in the form of known control points. However, the accuracy of self-calibration cannot match that of pre-calibration due to the necessity of estimating a larger array of parameters, thus presenting a more complex mathematical challenge.[15,16] In our research, we are particularly focusing on the pre-calibration process but using a target-based calibration method, which is the most common calibration strategy where a calibration pattern is used. This decision is underpinned by studies revealing that pre-calibration markedly improves accuracies on UAV-based survey data.

2.4 Exploring out-of-focus camera calibration for UAV

Camera calibration is a vital process for many machine vision and photogrammetry tasks, including drone-based imaging systems for terrain mapping and urban planning. It involves estimating the intrinsic and extrinsic parameters of a camera. The intrinsic parameters are related to the internal characteristics of the camera, such as focal length and lens distortion, while the extrinsic parameters refer to the orientation and position of the camera in space. The calibration process typically involves the use of a calibration pattern or set of markers, which provide a known reference point for the calculations, as it is shown in Fig. 3. Initially, calibration assumes that there is no lens distortion and solves for all other parameters. Once these are established, a final nonlinear optimization is performed, which includes solving for lens distortion. This two-step process allows for a more accurate calibration, ultimately enhancing the precision of the imaging system.

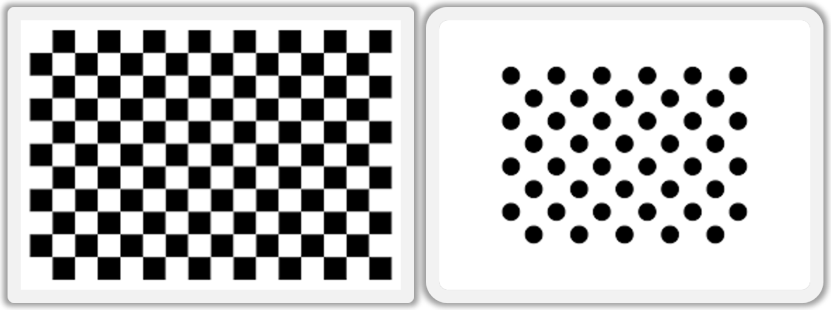

Figure 3. Calibration pattern or target. In this study, it was used a circular pattern to perform the calibration.

Bell T. demonstrated in their research that calibrating cameras in an out-of-focus state is nearly as accurate as calibrating them in focus. They provide a methodology for performing out-of-focus camera calibration using structured light phase shifting. This research is significant because it facilitates the calibration of long-range cameras such as drone cameras, where the focal length needs to remain at infinity to capture distant objects with optimal focus.

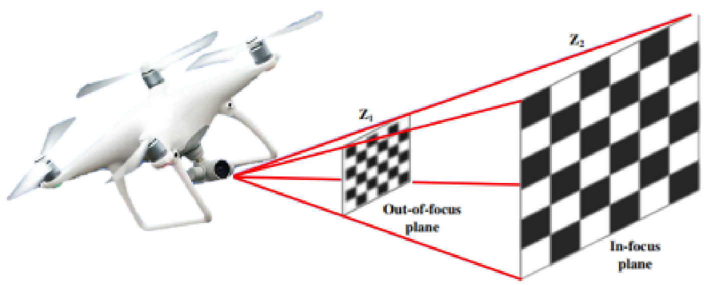

Figure 4. Calibration target in focus plane Z_2 and calibration target in out-of-focus plane Z_1.

For the calibration, we keep the concept of out-of-focus by incorporating a drone camera and project a calibration pattern onto an LCD screen or prinitng on a physical flat surface but, using the traditional target-based calibration method with a small circular calibration target for this study. Once these points are obtained, the intrinsic parameters and lens distortion of the drone camera can be estimated using the camera calibration toolbox in MATLAB or OpenCV, which are widely used by the research community. Fig. 4 is a representation of the idea of out-of-focus calibration can be observed. In this case, considering that drone cameras have an infinite focal length (several meters away), the out-of-focus plane involves keeping the camera fixed and bringing the LCD screen associated with the calibration target closer, in a controlled or proportional manner to the size of the monitor or screen being used.

3. EXPERIMENTS AND RESULTS

To evaluate the efficacy of our proposed calibration technique, we constructed a calibration system incorporating an LCD monitor (model: Lenovo ThinkVision t24m-20 24-inch IPS, WLED Backlight) and a camera from a DJI Phantom 3 Professional. The selected LCD monitor features a resolution of 1920 × 1080 and is designed with WLED backlighting technology, ensuring optimal visibility and color accuracy for the calibration process. The camera, equipped with a 1/2.3-inch CMOS sensor, boasts an image resolution of 4000 × 3000. It is fitted with a 20 mm lens (35 mm format equivalent) that offers an adjustable aperture range from F/2.8 to F/11. The focus range of the camera extends from approximately 300 mm to infinity, allowing for flexible calibration setups. Fig. 5 shows the Camera Calibartion Setup.

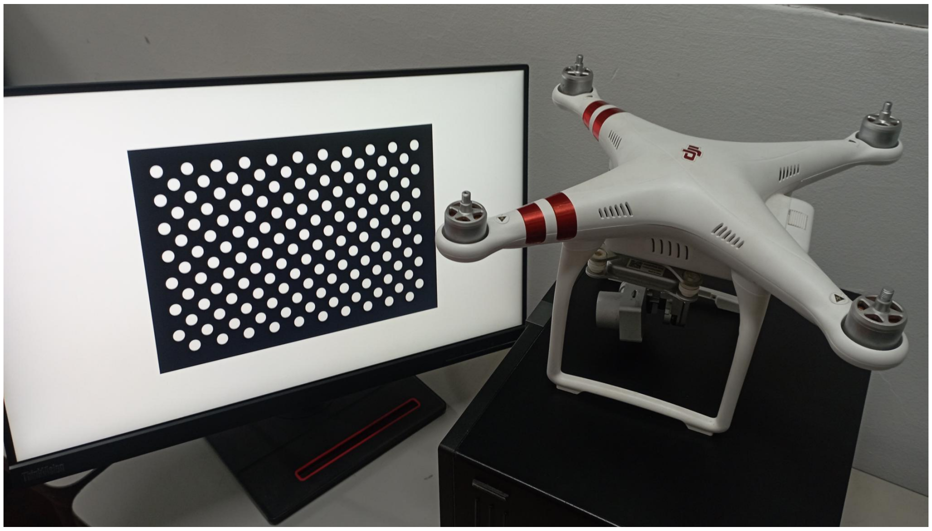

Figure 5. Camera Calibration setup using a 7x21 white circle asymmetric pattern and DJI Phantom 3 Professional drone.

Many professional drones have the feature of being able to configure the internal parameters of the camera. In the case of the DJI Phantom drone, the focal length is set to infinity by default and cannot be changed or modified. Therefore, it is necessary to ensure staying sufficiently close to the drone to maintain the range of planes out of focus. Fig. 6 shows an example of a blurry image (one of the captured pose used for calibration) when the calibration target is placed away from its camera focal plane (substantially defocused).

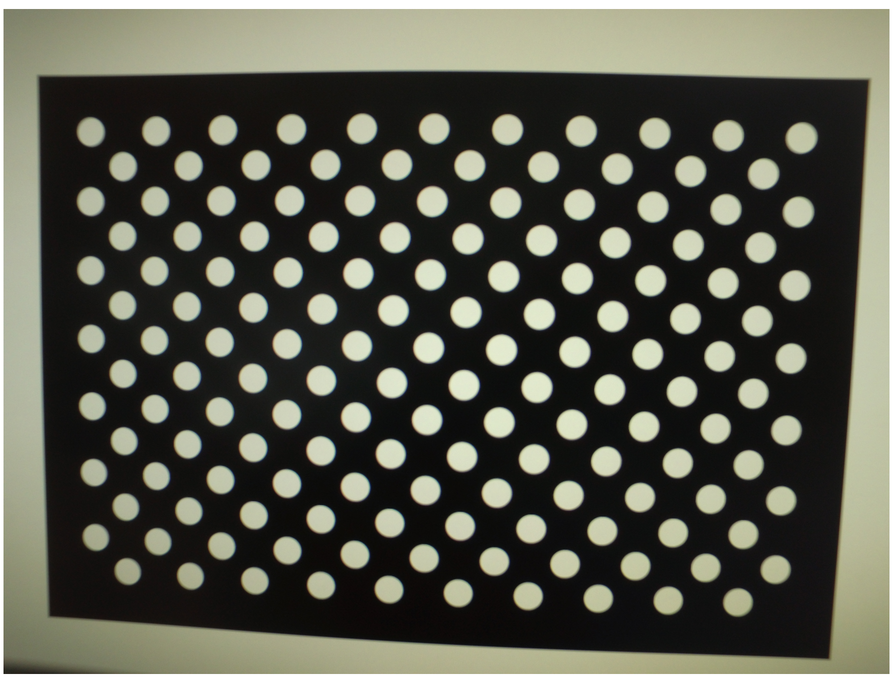

Figure 6. Blurry image from a pose of White circle asymmetric pattern of 7x21 captured from drone camera in a out-of-focus plane.

In that sense, following the steps mentioned in section 2.4 a camera calibration was performed implementing the OpenCV library, using 38 captured poses with an assymetric circular pattern. The reprojection errors in pixels of each pose are shown in Fig. 7. The maximum reprojection error registered was for pose 28 with an error of 0.034, and the overall mean error was of 0.0197 pixels. The camera intrinsic parameters obtained from calibration are shown in table 1, and their distortion parameters are shown in the table 2, where the high distortion present in the camera lens is evident.

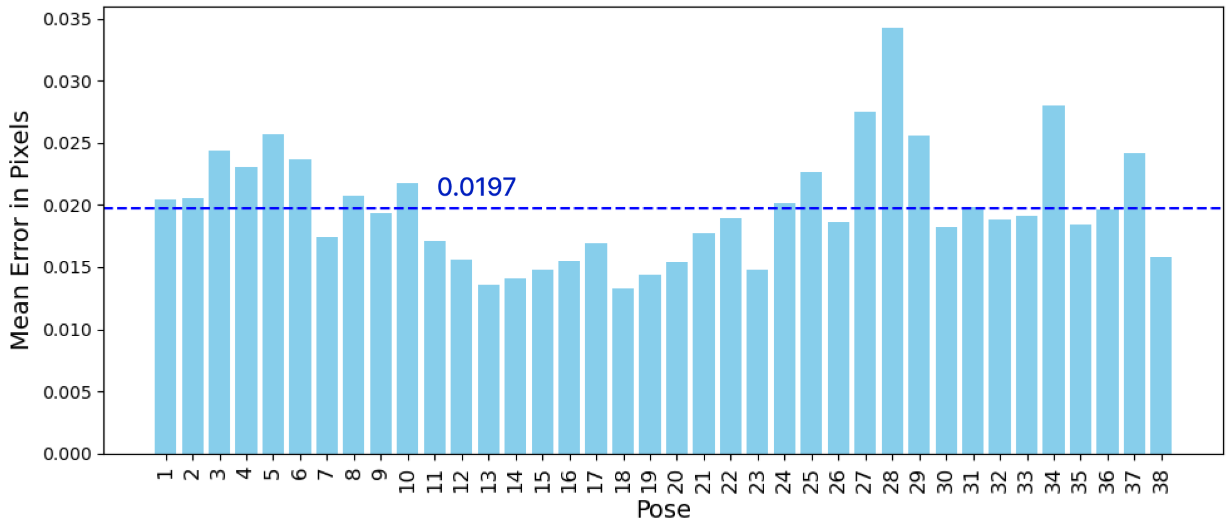

Figure 7. Mean reprojection error per captured image (pose).

Table 1. Intrinsic Parameters.

Parameter	$f_x(px)$	$f_y(px)$	$u_0(px)$	$v_0(px)$
Value	2692.97	2692.81	2023.65	1581.12

Table 2. Distortion Parameters.

Parameter	k1	k2	p1	p2	k3
Value	-0.134867	0.113938	0.000067	-0.000287	-0.025949

4. CONCLUSION

In this work, a suitable calibration procedure for a drone camera with defocus was implemented as an alternative to conventional methods. The results of the performance assessment showed a good estimation of the intrinsic parameters, with reprojection errors below 0.035 pixels. Compared to the literature, this is considered to be just as accurate and robust as the errors that can be obtained through calibration on the focused plane. This methodology also implies a reduction in the costs of manufacturing targets and extensive implementation times, as it can be executed in a laboratory. In this research, an LCD screen was used to display a calibration target from which correspondences of features of an asymmetric circular pattern could be obtained. As future work, considering implementing the proposed methodology with a stripe pattern to calibrate via phase shifting could further reduce calibration errors. Similarly, calibrating using a target that is large enough on a focused plane would allow for a point of comparison with the proposed method.

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