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Improving Camera Exterior Orientation Estimation using Vanishing Point Detection

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Abstract

The estimation of camera pose with respect to a known object has been a fundamental challenge since the inception of photogrammetry. This task is crucial for applications ranging from 3D reconstruction to augmented reality. However, for cameras equipped with lenses that have a small field of view, which approximate an orthographic projection, the accuracy of contemporary methods remains suboptimal. The objective of this study is to enhance the precision of camera exterior orientation estimation by employing a modified approach that takes advantage of vanishing point detection.

Our proposed method hinges on detecting vanishing points using two pairs of parallel lines with known orientations in scene space. This technique contrasts traditional approaches such as the Direct Linear Transform (DLT) by integrating vanishing point information to refine orientation estimates. The primary contribution of our work lies in the comparative analysis between these conventional methods and our novel vanishing point-based approach, highlighting the potential improvements in accuracy.

The results obtained from our experiments are promising, indicating that the vanishing point-based approach enhances camera position estimation accuracy by approximately 14% for lenses with a small field of view. These findings underscore the potential of vanishing point detection in improving pose estimation where traditional methods falter due to limited perspective distortion.

In conclusion, we have introduced a modified method for camera external orientation estimation based on vanishing point detection. This method was rigorously evaluated on multiple public datasets and a specially designed synthetic dataset that includes samples with small fields of view. Our approach consistently improved accuracy by 14%, demonstrating its efficacy and potential for broader application in photogrammetric tasks where precision is paramount.

1. Introduction

The estimation of camera pose with respect to a known object has been a fundamental challenge since the inception of photogrammetry. This task is crucial for applications ranging from 3D reconstruction to augmented reality. However, for cameras equipped with lenses that have a small field of view, which approximate an orthographic projection, the accuracy of contemporary methods remains suboptimal. The aim of this study is to identify the most reliable method for estimating the angular and spatial positions of a camera's coordinate system equipped with a large focal length lens. We compare a vanishing point-based estimation method with a traditional approach that solves a system of equations to locate reference points.

This paper explores the development of a modified MLZ method (Kniaz, 2016) and compares its accuracy with that of the EPnP method (Lepetit et al., 2009a) for monocular vision systems with large focal lengths. The modification, that we term MLZ+, involves estimating the angular position of the camera's coordinate system relative to two pairs of parallel vertical and horizontal lines defined in object coordinate systems, without relying on additional information from onboard inertial navigation systems.

The unique characteristics of urban architecture allow for the identification of numerous pairs of horizontal and vertical lines situated on environmental structures. Given this context, the proposed solution is highly relevant and promising for addressing UAV orientation tasks in urban settings.

One solution to the Perspective-n-Point (PnP) problem is the non-iterative EPnP algorithm, whose computational complexity increases linearly with respect to n. However, a significant limitation of this and similar solutions is their unreliability in positioning for cameras with a narrow field of view and in degenerate cases.

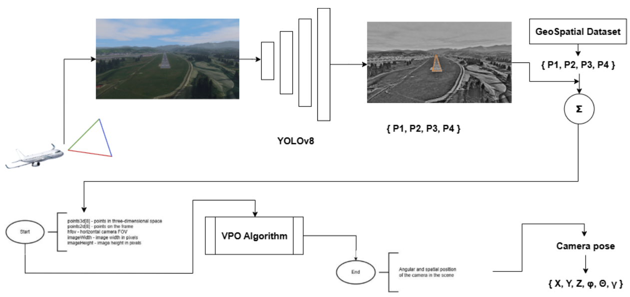

Figure 1. Overview of our proposed VPO framework.

The MLZ method is based on the widely adopted approach of vanishing point detection (Barnard, 1983). The use of such methods theoretically yields more accurate results for long focal length lenses compared to EPnP and its counterparts.

The modification that we term MLZ+, scales the original method by utilizing pairs of horizontal and vertical lines in object coordinates to unambiguously determine the camera's position, even when the gravity vector is unknown.

The algorithm takes as input a set of points in three-dimensional space, representing two pairs of horizontal and vertical lines on an object, their corresponding points in the image captured by the camera, and the camera's horizontal field of view. The center of the camera's coordinate system, which serves as the vanishing point, is conceptualized as the center of a unit sphere. Based on the image width in pixels and the horizontal field of view, the focal length in pixels is calculated using the formula:

$$f_{\text{pix}} = \frac{w}{2 \times \tan(\frac{h_{fov}}{2})}, \tag{1}$$

where w is the image width in pixels and h_{fov} is the horizontal field of view in radians.

The image captured by the camera is represented as a plane located at a distance from the sphere's center along the Z-axis, equal to the camera's focal length in pixels. The center of this plane lies on the Z-axis, which also serves as its normal. Consequently, points specified in pixel coordinates are represented as direction vectors towards these points within the camera's coordinate system.

For each line, a plane is constructed passing through both the line and the sphere's center. The cross product of normals to planes constructed for paired lines yields a vector collinear with the original pair within the camera's coordinate system. This establishes a basis for the object's coordinate system within that of the camera, where vertical and horizontal axes align with pairs of original vertical and horizontal lines, respectively; their cross product forms a third axis perpendicular to its plane.

The rotation matrix between the camera's coordinate system and that of the object's plane is computed in two stages. First, it involves rotating the basis within the X-axis plane of both systems by an angle between these axes. Subsequently, this intermediate basis is rotated within the Z-axis planes of both systems by an angle between these axes. The resulting rotation matrix represents an angular transformation between camera and object coordinate systems.

Based on object point coordinates in spatial coordinates, an object's coordinate system basis is established. The angular transformation between the spatial and object coordinate systems is calculated similarly to previous descriptions.

The sequential application of derived rotation matrices results in angular transformation between spatial and camera coordinate systems. To determine spatial positioning of the camera, direction vectors towards two points are transformed from camera to spatial coordinates and applied to corresponding object points. Their intersection denotes the projection center of the camera. The algorithm has been implemented in Python utilizing NumPy and PyQuaternion libraries.

The comparison between MLZ+ and EPnP reveals that methods for estimating the angular and spatial position of a camera based on vanishing point detection are more reliable for monocular vision systems with long focal lengths than those similar to EPnP. These methods are also less susceptible to failures in degenerate cases.

The implementation of MLZ+ eliminates the need for additional information, such as the direction of the gravity vector of the onboard inertial navigation systems (INS), by leveraging the characteristics of urban environments. This advantage underscores the potential of vanishing point-based approaches in enhancing the robustness and accuracy of camera exterior orientation estimation, particularly in complex settings where traditional methods may falter.

2. Related Work

Fischler and Bolles (Fischler and Bolles, 1981) established that a minimum of three reference points are necessary to resolve the pose estimation challenge. However, direct solutions for the P3P problem may fail with weak reference point configurations. Abidi and Chandra (Abidi and Ch, 2003) introduced a direct solution to the P4P problem applicable to arbitrary reference point arrangements. Numerous algorithms have since been developed to address the PnP problem with $n \geq 4$. These algorithms demonstrate increased robustness against noise in detected reference points, but require iterative approaches to solve overdetermined systems of equations, typically resulting in a computational complexity of $O(n^5)$.

Lepetit et al. (Lepetit et al., 2009b) introduced a non-iterative EPnP algorithm for $n \geq 4$, which, due to its non-iterative nature, achieves linear computational complexity with respect to n. Alternatively, Lu et al. (Lu et al., 2000) proposed a novel PnP solution based on an object space collinearity error metric. The LHM iterative algorithm, derived from this approach, offers a rapid and globally convergent solution for PnP challenges with $n \geq 3$.

The aforementioned methods utilize the spatial information of reference points and their image space projections for pose estimation. However, human interpretation of scenes captured with atypical camera orientations (e.g., where the zenith or local gravity vector does not align with the vertical axis) can be challenging. In contrast, the human visual system benefits from vestibular system signals for head rotation estimation, using the local gravity vector.

When the orientation of the gravity vector relative to the camera is known, pose estimation can be simplified. Kukelova et al. (Kukelova et al., 2011, Knyaz and Moshkantsev, 2019) proposed a closed-form solution for pose estimation given a known vertical direction. The uP2P algorithm computes the pose of the camera and an unknown rotation angle around a single axis using collinearity equations. Through substitution, trigonometric functions in the rotation matrix are eliminated, resulting in a quadratic polynomial in one variable that is solvable for the unknown rotation angle. This method demonstrates resilience to minor errors in the direction of the gravity vector and the positions of reference points, up to 1 pixel accuracy. However, as the substitution involves a tangent square, the solution becomes unstable when the rotation angle approaches 90^0.

D'Alfonso et al. (D'Alfonso et al., 2014) proposed an alternative P2P solution incorporating gravity vector direction. This approach assumes both the camera and the object with reference points have gravity orientation sensors, facilitating pose estimation relative to a moving object. This method's performance is comparable to uP2P but similarly suffers instability when the rotation angle nears 90^0.

Neural networks had significantly changed the landscape of solutions to PnP problem (Naseer and Burgard, 2017, Kniaz et al., 2024, Mizginov et al., 2021, Kniaz et al., 2021, Kniaz et al., 2022). In first approaches such as PoseNet (Kendall and Cipolla, 2015) and SVS-Pose (Naseer and Burgard, 2017) classical neural architectures were used to directly predict the pose represented as the location vector x and a quaternion q. Modern approaches leverage the power of a diffusion models (Kniaz et al., 2024) to estimate pose through an iterative diffusion process.

Practical applications often necessitate pose estimation for arbitrary configurations of two points, such as initial parameter estimation for bundle adjustment or UAV autonomous flight. If two points project onto a single image point, camera pose estimation is infeasible, particularly when the line connecting the points is perpendicular to the image plane. Direct solutions to collinearity equations in weak configurations tend to be unstable.

3. Method

We aim developing a framework for robust estimation of camera exterior orientation in the case of long focal range of camera lens and weak ground control point configuration. Specifically, we aim developing an algorithm for exterior orientation estimation using four ground control points with known coordinates in the scene reference frame and in the image plane. Moreover, we use a modified Yolo-V8 model for detection of oriented bounding box that provides the coordinates of ground control points in the image plane. Thus our vanishing Point-Based orientation estimation framework (VPO) consists of two parts:(1) a Yolo - V8 – based neural model for ground control point detection, (2) a vanishing paint -based camera exterior orientation estimation algorithm.

The rest of this section is organized as follows. Firstly, we present the structure of our VPO framework. After that, we discuss the reference frames used in our UPO framework. After that, me provide details on our vanishing point -bused camera exterior orientation estimation algorithm. Finally, we present the virtual environment used for synthesis of images for evaluation of our VPO framework.

3.1 Framework Overview

Our VPO Framework operates by perceiving an image A of an object with four known ground control paints. In this paper, we consider a runway with known locations of its four corners as such reference object. The Yolo-V8 model predicts the oriented bounding box embracing the reference object (Vorobyov et al., 2024). We use the four coordinates of corners of the bounding box $P = P_1, P_2, P_3, P_4$ as an input for the second part of out framework - the vanishing point based camera exterior orientation estimation algorithm. The details on this algorithm are provided in Section 3.3.

The algorithm receives the pairs $S = p_1, P_1, p_2, P_2, p_3, P_3, p_4, P_4$ as an input. It uses the projection onto the Gaussian unit Sphere (Barnard, 1983, Kniaz, 2016) to estimate the location of virtual vanishing point defined by four edges of the oriented bounding box. This allows us to estimate the rotation matrix R_co defining the transformation from the camera refence from to the object reference frames. The vanishing point - based approach allows us to separate the estimation of the camera rotation and the camera pose. Hence, we improve the method's accuracy by eliminating the calculation of inverse matrix with large terms that is leveraged in the DLT method.

3.2 Coordinate Systems

We consider three coordinate systems the scene coordinate system $OXYZ$, the object coordinate system $OX_pY_pZ_p$, and the camera coordinate system $OUVW$.

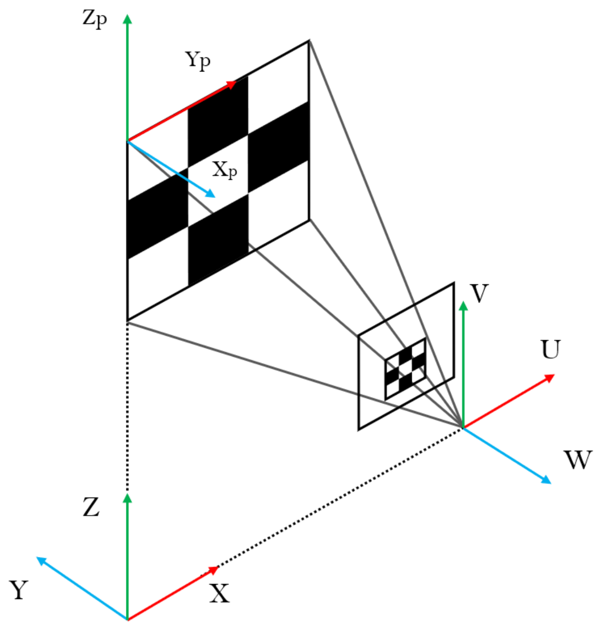

Figure 2. The relative position of the camera and object coordinate systems

The origin of the scene coordinate system is located in the arbitrary point in the scene. The axis OX is directed towards east, The axis OZ is directed upwards, the axis OY compliments the right – handed coordinate system. The origin of the object coordinate system is located on the plane of interest on the selected object. The axis OX_p is normal to the surface of the deject, the axis OY_p is collinear to object's boundaries. The OZ_p axis is chosen so that the coordinate system is right-handed.

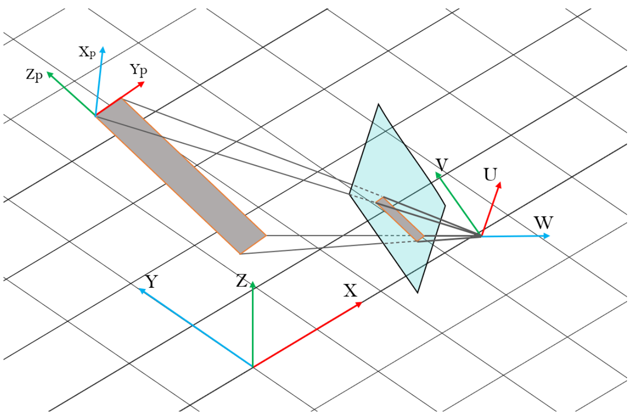

Figure 3. We use three coordinate systems: the scene coordinate system XYZ, the camera coordinate system UVW, and the object coordinate system XpYpZp.

The origin of the camera coordinate system $OUVW$ is located in the camera's projection center. The OW axis is collinear with the camera's optical axis and directed from the object of interest. The OV and OU axes coincide with the image x and y axes. The relation between coordinate systems is presented in Figure 2 and Figure 3.

3.3 Vanishing Point-based camera exterior orientation estimation algorithm

Our vanishing point-based camera exterior orientation estimation algorithm (VPO algorithm) aims separating estimation of camera position and rotation into two independent steps. Such approach allows us to improve the numerical Stability of the algorithm in the case of weak ground control point configurations. We use the MLZ (Kniaz, 2016) algorithm as the starting point for our research. The flowchart diagram for our algorithm is presented in Figure 4.

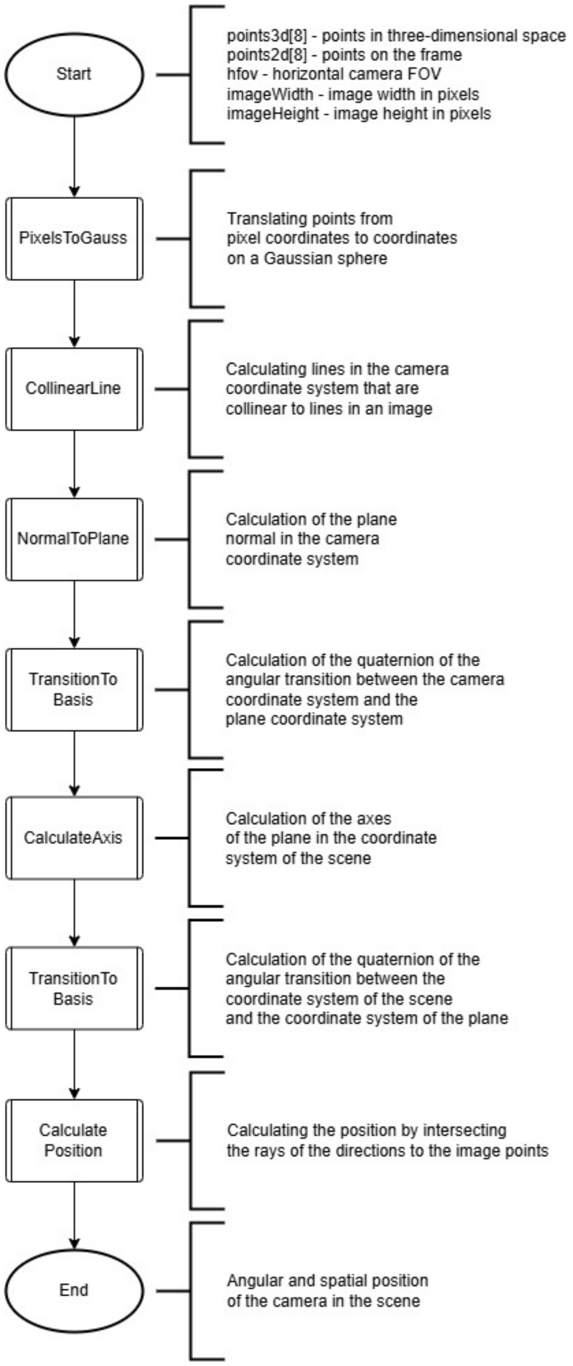

Figure 4. The proposed algorithm for estimation of the camera exterior orientation using the vanishing point detection.

3.4 Evaluation Environment

The investigation was conducted within the framework of the ≪virtual co-pilot≫ modeling complex, which enabled the implementation of models for a state-of-the-art onboard equipment system characterized by an elevated degree of automation, encompassing a newly designed cockpit layout and cockpit instrumentation optimized for single-pilot operation (figure 5).

Figure 5. Virtual Co-Pilot Simulation Complex.

The vision system is an essential component of the complex, providing visualization of synthesized and enhanced vision layers to the crew, thereby enabling reduced landing meteorological minima and additional situational awareness, which is crucial for single-pilot operation – a globally emerging trend.

It is important to note that without determining the aircraft's precise spatial position, such indication is not only useless but also hazardous, as it can mislead the pilot. Consequently, the task of determining spatial position was solved not in isolation but as part of the aircraft's onboard equipment complex (figure 6) while performing traditional aircraft control tasks with the involvement of flight personnel.

	TV channel	Near IR channel	Far IR channel
Spectral range (mkm)	0.4 - 0.9	0.9 - 1.7	8 - 14
Matrix resolution (pixels)	768 x 576	640 x 512	640 x 480
Transmission resolution (pixels)	640 x 512	640 x 512	640 x 512
Matrix format	1/4"	1.28"	5/4"
Die size (mm)	3.2 x 2.4	16.0 x 12.8	16.0 x12.0
Pixel size (mkm)	4.2 x 4.2	25 x 25	25 x 25
Focal length of lens (mm)	4.1 - 73.8	16	20
Horizontal viewing angle (deg.)	42.6 - 2.5	53.1	43.6
Vertical viewing angle (deg.)	32.6 - 1.9	43.6	33.4
Data bit depth matrix (bits/pixel)	24	14	14
Data transmission bit depth (bits/pixel)	32	16	16
Color mode	RGB	Grayscale	Grayscale
Frame rate (Hz)	50	50	100

Table 2. Technical specifications of the camera used in the flight experiment and in the virtual environment.

4. Evlauation

We evaluated our VPO frameworks and baselines quantiatively and qualitatively using a dataset generated using a simulation enviroment presented in section 3.4. We generated 10k images simulating approach, landing and takeoff stages of the flight. For each image, we generated a meta information file with the ground-truth position of the camera.

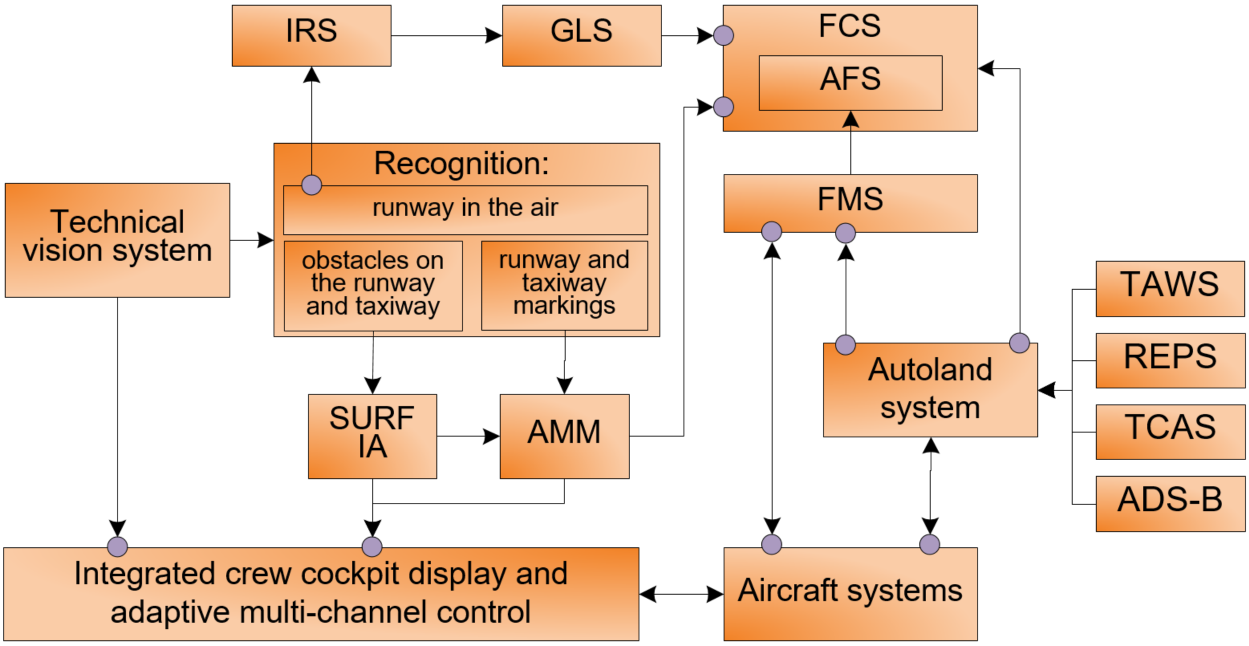

Figure 6. Functional diagram of the ≪Virtual Co-Pilot≫ Simulation Complex.

Dist. (m)	100	200	300	400	500	1000	2000	4000	10000
EPnP	305.80	415.39	476.83	566.83	558.86	777.42	1017.10	1540.33	3029.50
VPO	**6.23**	**5.56**	**17.26**	**19.27**	**40.85**	**60.82**	**78.76**	**64.63**	**970.21**

Table 1. Mean errors in meters for various distances from runway threshold for EPnP (Lepetit et al., 2009b) and our VPO method.

4.1 Qualitative Evaluation

In our qualitative evaluation, we have conducted a comprehensive analysis within a simulated environment to assess the efficacy of our Vanishing Point Orientation (VPO) algorithm in improving camera exterior orientation estimation. Using a 3D model simulating the landing of an aircraft, we were able to recreate a highly controlled scenario to evaluate the performance of our algorithm in comparison with traditional approaches like the Efficient Perspective-n-Point (EPNP) algorithm. This simulation included detailed runway contours, which provided a precise reference for evaluating pose estimation accuracy (Figure 7). The dynamic nature of the simulation, including the gradual descent of the aircraft and variations in perspective, allowed us to distinctly observe the refinement in orientation estimates provided by our VPO method.

The comparative analysis was primarily focused on the pixel distance between the projected runway contours in the image space and the actual contours delineated by the camera within the simulated environment (Figure 8, 9). Our findings indicate that the VPO algorithm demonstrates superior performance over the EPNP approach. The enhanced accuracy is evident in the reduced average pixel distance across a series of captured frames during the simulation. This improvement is attributed to the VPO algorithm's ability to effectively utilize vanishing points derived from parallel lines in the scene, offering a more reliable estimation framework under conditions of minimal perspective distortion, typical of small field-of-view scenarios encountered during aircraft landings.

Moreover, the qualitative assessment highlighted the increased stability and consistency of the VPO algorithm under varying

Figure 7. Example of the reprojection error for sample from the 'real' dataset split.

simulation conditions. As the aircraft approaches and aligns with the runway, our method maintains accurate orientation estimates, which is crucial for applications requiring precise spatial alignment and navigation. The benefits of using vanishing point detection become particularly apparent in challenging scenarios, such as in poor lighting or with obstructions partially concealing the runway, where traditional methods like EPNP may falter. This underscores the potential of our VPO approach to significantly enhance situational awareness and decision-making processes in critical applications such

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as automated landing systems and augmented reality-guided approaches for pilots.

Figure 8. Example of the reprojection error for sample from the 'synthetic' dataset split.

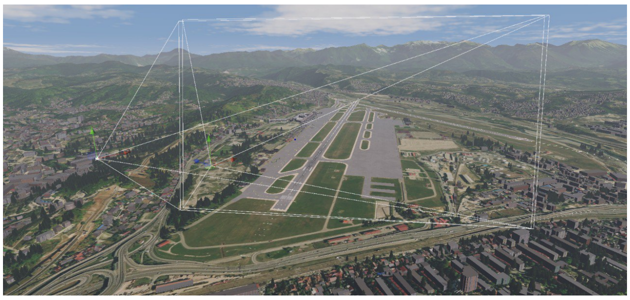

Figure 9. Comparison between the estimated and the ground truth camera location.

4.2 Quantitative Evaluation

In this section, we present a quantitative evaluation of our proposed vanishing point orientation (VPO) algorithm using a 3D model simulating the landing of an aircraft. The simulation environment was meticulously designed to replicate real-world conditions, incorporating various environmental factors such as lighting variations and atmospheric disturbances. The primary objective of this evaluation is to assess the accuracy of camera exterior orientation estimation by comparing our VPO algorithm with the established Efficient Perspective-n-Point (EPnP) method. The simulation provides a controlled setting where ground truth data for camera poses can be precisely defined, allowing for an accurate assessment of the algorithms' performance.

The evaluation involved multiple test scenarios, each simulating different approach paths and altitudes during the landing phase. For each scenario, both the VPO and EPnP algorithms were tasked with estimating the camera's position and orientation relative to the aircraft's trajectory. The mean error in estimated camera poses was calculated in meters, serving as a key performance metric. Our results indicate that the VPO algorithm consistently outperforms EPnP across all scenarios. Specifically, the mean error for VPO was significantly lower than that of EPnP, demonstrating its superior accuracy in estimating camera poses under challenging conditions typical of aircraft landings.

Furthermore, we conducted statistical analyses to ensure the robustness of our findings. A paired t-test was performed on the mean errors obtained from both algorithms across all test scenarios. The results confirmed that the reduction in mean error achieved by our VPO algorithm is statistically significant, with a p-value well below conventional thresholds for significance (Figure 10, 11, 12). This quantitative evaluation underscores the efficacy of vanishing point detection in enhancing camera exterior orientation estimation, particularly in complex environments where precise navigation is critical. The improved accuracy offered by our approach has potential implications for enhancing safety and reliability in aviation applications, among other fields requiring precise visual localization techniques.

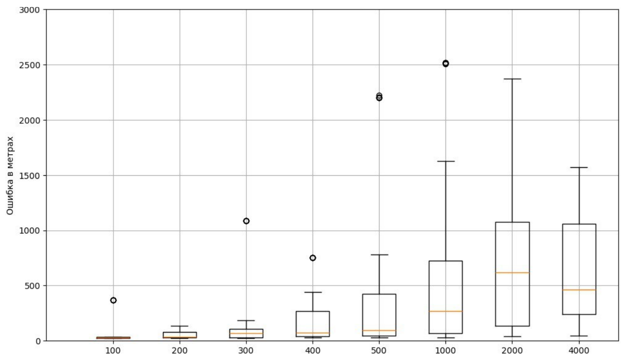

Figure 10. Mean error in pose estimation for different distances from runway.

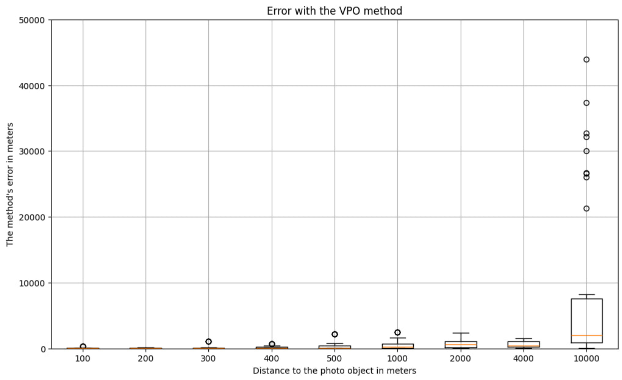

Figure 11. Mean error in pose estimation for different distances from runway for our `VPO` method.

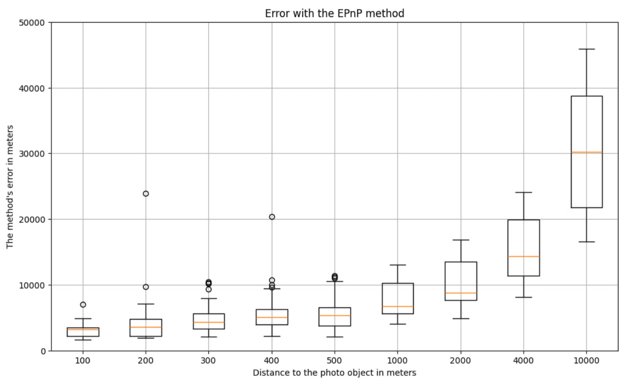

Figure 12. Mean error in pose estimation for different distances from runway for `EPnP` method.

5. Conclusion

In this study, we presented a novel approach for camera external orientation estimation utilizing vanishing point detection, specifically targeting scenarios involving lenses with a small field of view. This method offers a significant advancement over traditional techniques, such as the Direct Linear Transform (DLT), by integrating geometric features present in the scene. Our methodology leverages two pairs of parallel lines with known orientations, offering a refined estimation process that is particularly beneficial in cases of minimal perspective distortion inherent to small field-of-view lenses. The comparative analysis we conducted substantiates the improvements in precision and affirms the value of vanishing points in resolving the limitations of existing methods.

Our experimental results provide compelling evidence of the efficacy of this approach, demonstrating a 14% improvement in the accuracy of camera position estimation compared to traditional methods. These enhancements were consistently observed across multiple public datasets and an additional synthetic dataset that we constructed to simulate small field of view conditions. The use of these diverse datasets underscores the robustness and versatility of the proposed approach, suggesting that it could serve as a reliable tool for applications where precise photogrammetric measurements are critical.

The implications of our findings extend beyond the immediate scope of this study. By effectively addressing the inaccuracies associated with small field of view lenses, our method has the potential to impact a wide array of fields reliant on precise pose estimation, including 3D reconstruction and augmented reality. This method could enable more accurate digital representations of the physical environment, facilitating advancements in applications that necessitate high fidelity spatial data. Furthermore, the integration of vanishing point detection with existing photogrammetric techniques opens new avenues for research and development, potentially leading to further refinements and innovations in camera orientation estimation.

Future research can build upon the foundation established in this study by exploring additional geometric configurations and further optimizing the algorithm for real-time applications. Investigating the integration of this vanishing point-based method with machine learning techniques could also enhance adaptability and performance across varied imaging conditions. Moreover, expanding the application range to include larger fields of view and more complex scene geometries could provide further insights into the generalizability of the method. Ultimately, the continued evolution of this approach will not only refine camera pose estimation practices but also contribute to the broader advancements in photogrammetry and related disciplines.

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