Research Article

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# Principles of self-calibration and visual effects for digital camera distortion

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**Abstract:** Producing accurate spatial data with stereo photogrammetric techniques is a challenging task, and the central projection of the space needs to be defined as closely as possible to its real form in each image taken for the relevant production. Interior camera parameters that define the exact imaging geometry of the camera and the exterior orientation parameters that locate and rotate the imaging directions in a coordinate system have to be known accurately for this correct definition. All distortions sourcing from lens and sensor planes and their recording geometry are significant as they are not suitable for detection with manual measurements. It is of vital importance to clearly understand the camera self-calibration concept with respect to the lens and the sensor plane geometry and include every possible distortion source as an unknown parameter in the calibration adjustments as they are all modellable systematic errors. In this study, possible distortion sources and self-calibration adjustments are explained in detail with a recently developed visualization software. The distortion sources investigated in the study are radial, tangential, differential scale, and axial skewing distortion. Thanks to the developed software, image center point, distorted grids, undistorted grids, and principal points were visualized. As a result, the most important element of obtaining accurate and precise photogrammetric productions is the correct definition of the central projection of the space for each image, and therefore, the study explains an accurate and robust procedure with the correct definition and use of correct camera internal parameters.

**Keywords:** camera calibration, sensor calibration, least-squares adjustment, lens distortion, sensor plane distortion

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## 1 Introduction

It has been the main study area of photogrammetry for years to define and calculate the camera internal parameters, which can truly represent every distortion that disrupts the image and eventually affects the spatial coordinate accuracies. Self-calibration approaches have been studied and used intensively in the photogrammetry community [1–4]. The Brown model has been widely recognized as a classic model in computer vision [5,6], with significant applications in various areas. In self-calibration, the zoom effects of the Brown model have been observed by several researchers [7–9].

In this study, bibliometric analyses were used for literature research [10,11]. With this analysis, the topics that researchers focus on can be examined with the help of relationship maps on a time scale, and application areas on similar topics can be followed [12]. In addition, popular scientists and countries that have done the most work on the relevant topics can be investigated [13]. The data source of bibliometric analyses is usually databases such as Scopus and Web of Science. Reliable information obtained from these sources directs literature research. In this study, VOSviewer software was used for bibliometric analysis [14]. The bibliometric analysis result obtained according to keyword matching of similar studies is given in Figure 1.

In Figure 1, studies in this research field were accessed by using the keywords "self-calibration" and "digital camera distortion." The Web of Science database was used as a data source in VOSviewer software since there are quality and reliable publications, and all indexed journals are included in the database. The main focuses and most researched topics in these studies are lens distortion, photogrammetry, radial distortion, bundle adjustment, autonomous aerial vehicles, digital image processing, and the use of parameters in recent studies. The region with the most research is China (47), followed by England (4), Germany (3), and Canada (3). China is the country where the most studies and research have been conducted among 25 countries. This is clearly due to the available facility for this country, and so there is a

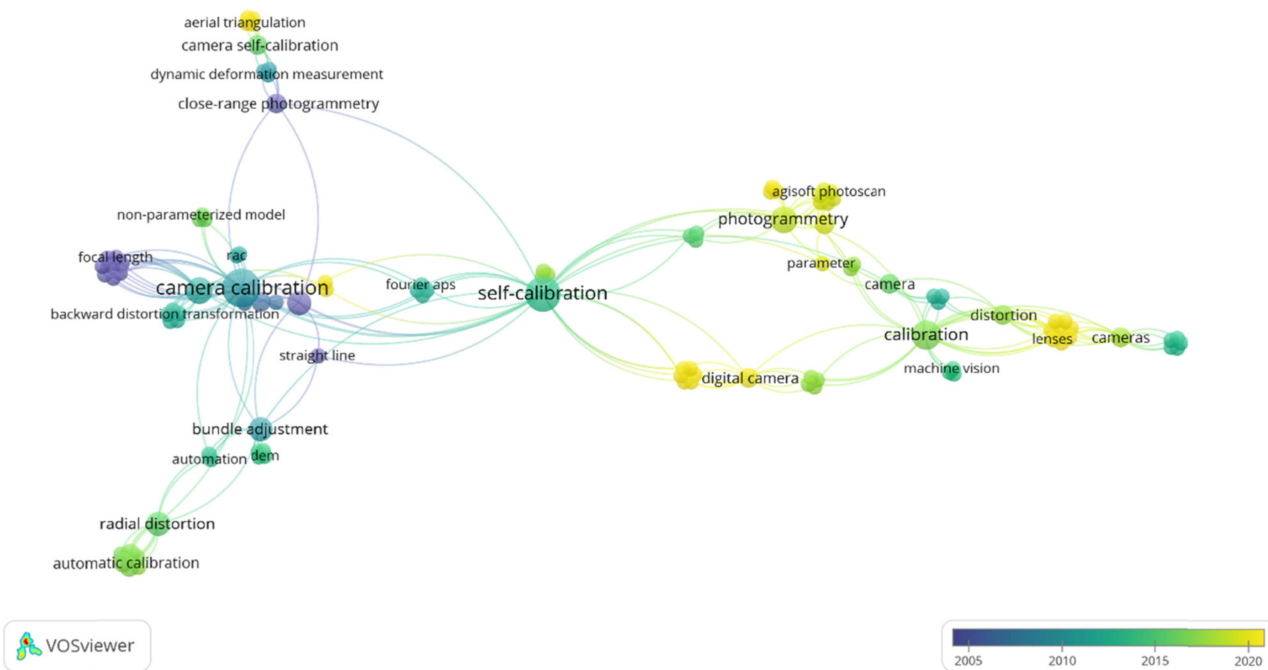


**Figure 1:** The most used keywords for the published research on the self-calibration and digital camera distortion.

need for an advanced understanding of this topic and the possibility for a wider array of investigations.

To produce accurate and precise spatial data with stereo photogrammetric techniques, the central projection of space has to be defined as correct as to its real form for every image taken for related production. For this correct definition, the interior camera parameters that define the exact imaging geometry of the camera and the exterior orientation parameters that locate and rotate the imaging directions in a coordinate system have to be known accurately. While the image coordinates serve as observations, the interior and the exterior orientation parameters as well as the spatial coordinates of the marker positions are parameters to be estimated [15,16]. Exterior orientation parameters can be obtained directly from a highly accurate inertial measurement unit (IMU) system or can be calculated by using ground control points (GCPs), which are clearly detectable in the images. The interior orientation parameters can only be calculated by camera self-calibration processes that consist of advanced adjustment techniques with highly accurate image coordinates and their object space coordinates taken from advanced and accurate calibration scenes. Algorithms commonly rely on either perspective or projective camera models, with the widely recognized self-calibrating bundle adjustment being the most favored approach [17–19].

Lens distortion generates a misalignment between the perspective center, the image point, and the object point [20]. For digital cameras, not only the lens distortions but also the distortions caused by sensor planes and their recording geometry are significant as they are not detectable with manual measurements. At that point, it is of vital importance to clearly understand the lens and the sensor plane geometry and also include every possible distortion source as an unknown parameter in the calibration adjustments for an exact definition and calculation. Although it is possible to find a variety of distortion models and calculation techniques in the literature based on the choice of focal length, there is a variety of misunderstandings about the concepts and fundamentals as well [21]. Pennington discussed tangential distortion and its impact on photogrammetric control extension [22]. Macdonald used the calibration technique of lens, camera, and photographic material combination for total camera calibration [23]. Merritt investigated several camera calibration techniques and noted that methods using protractor or star exposure were a strong preference [24]. Lewis commented on the radial distortion curve's nature and how its magnitude was a direct function of the camera's equivalent focal length [25]. Hothmer found differences in calibration results for the same type of camera. The study noted that this was due to production limitations, particularly regarding the refractive indices of glass lenses, which differ slightly from one production batch to the next [26]. Hallert investigated the least squares method applied to multi-camera calibration. In the study, resection was combined with camera calibration, and then tests were performed using both film and glass plates. Additionally, some statistical fit checks were performed for Hallert-generated radial distortion curves and other camera calibration components. The results indicate that there is a significant difference in the radial distortion curves found from the film and glass plates [27]. In the 1950s, research on the production and calibration of aerial cameras gained momentum, and the investigation of the properties of lens distortions was accelerated. However, the reports were confidential and did not become public until Brown published a series of important papers in the 1960s and 1970s [1,9,21]. Nowadays, with the advent of new technical advancements like unmanned aerial vehicles (UAVs) and autonomous software programs, smartphones, drone photogrammetric productions became incredibly useful and practical to use [28–32]. At first glance, it looks perfect that all products (orthomosaic, point cloud, digital surface model, digital terrain model, etc.) are done by the software within one block adjustments, including the camera self-calibration, but it becomes very challenging when it needs to go more steps beyond such as accurate stereo digitization with these images and calibration reports. It is also a typical error to interpret all calibration parameters as having the same meaning without considering their calibration and computation model. As all calibration reports declare their own model, concerning camera internal orientation parameters should be implemented in the same way of definition when defining a camera in a professional photogrammetry software to set the related calibration report to its exact meaning.

The purpose of this study is to identify the sources of distortions in digital images and to explain the concepts and foundations of computation theory. For this purpose, software has been developed to visualize camera distortions and determine distortion parameters. In addition, the study provides a framework for explaining the theory of self-calibration in digital cameras and reducing systematic errors in calibration adjustments.

## 2 Theoretical background and visualization software

In all kinds of photogrammetric productions, using a fixed focus (lens) camera is a necessity for accurate and precise results. The focus will be firmly upon “photogrammetric calibration” which implies the generation of camera interior orientation and lens distortion parameters that are scene-independent to the maximum extent possible, so that they will generally be applicable to the chosen camera settings [33]. Although recent software solutions tolerate this necessity by taking every single image separately as if they are taken by different cameras and calculating camera internal parameters for each, it goes wrong when it comes to making some stereo data collection with one camera definition. What changes significantly in a non-fixed focal length camera is mainly the changing projection geometry and the changing relation between the lens and sensor plane. In non-fixed focal length cameras, every time the focus or zoom changes, it affects the focal length, location of the principal point, and the lens distortions, especially the tangential (decentering) one.

Lens distortions can be calculated with one single image of a calibration scene only if the focal length is known or assumed beforehand [34]. There are several application examples produced in various programming languages, but the majority of them are built for basic lens distortions and the method of non-photogrammetric camera calibration [35]. For a professional photogrammetric camera calibration, all camera internal parameters, including focal length, principal point, and distortions, should be calculated with at least two different images of the same calibration scene [36]. It is a necessity in calibration adjustments to keep the focal distance to converge its accurate value while converging the other distortion parameters, unless false corrections will be distributed to unknowns in each iteration. In other terms, the adjustment can catch the same convergence while pushing the focal distance and distortion parameters to the wrong values. Even if some distortions are assumed that they have a very limited accuracy impact on final spatial coordinate accuracies, they should be defined as unknowns in calibration adjustments and have to be verified whether or not they have the presumed limited impact [37,38].

For a clear understanding of possible distortions on the images recorded by digital cameras, visualization software, as shown in Figure 2, was developed in Visual C# by the first author. With the help of developed software, it is possible to create a virtual camera with user-defined distortion parameters and visualize every distortion effect separately on the respective recorded image [37].

Figure 2 shows the interface of the developed software, distortion display formats, camera parameters, and legend information about the distortion images in the following sections.

## 3 Definitions of distortion sources and distortion components

Lens and camera manufacturing technologies are getting more precise day by day; however, they still include

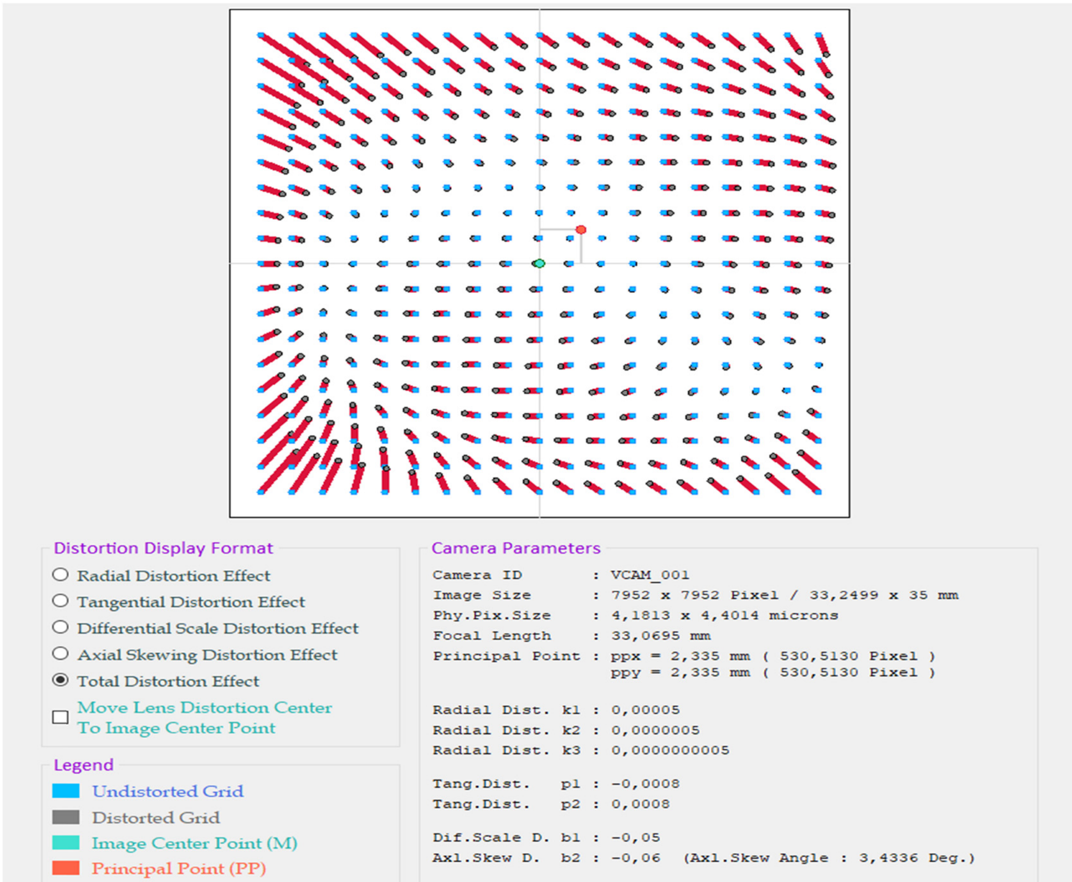


**Figure 2:** Visualization software for camera details and distortions.

distortions that might not be very crucial for other reasons but the photogrammetry [3,37]. In fact, even if they were produced with zero distortion, this should be proved again by camera self-calibration processes. Prior to the following subheadings, it is necessary to describe all the terms used in the equations. The descriptions of the terms and symbols shown in Table 1 are very important for a proper understanding of the professional photogrammetric camera self-calibration concept. To present every distortion effect in the following sections, virtually generated camera coefficients and parameters, including the principal point offset, are set to exaggerated values, as shown in Figure 2.

### 3.1 Principal point (lens distortion center)

Principal point substantially defines the offset between the lens and the sensor plane centers, and it is also the location of the lens distortion center in the image coordinate system according to the image center. For that reason, it should be modeled, defined, and optimized (calculated) together with the lens distortion parameters [37].

### 3.2 Radial distortion – sourcing from the lens glass

Radial lens distortion is the most common and the most affecting factor of the image coordinates [39,40]. In that case, the projection center in the lens collects the lights and sends them to the sensor plane with different angles. If the lights coming to the projection center are simply simulated as a cone, they form a wider or narrower cone after passing the projection center, and they are projected as bigger or smaller circles in the sensor plane than they should be. This circular contraction or expansion is seen on rectangular image planes as barrel or pincushion-shaped distortions. In this given case, barrel distortion caused by contraction can clearly be seen in Figure 3. For the definition of that distortion, it should be formulated with enough coefficients depending on the desired accuracy and precision level. For both $x$ and $y$ distorted image coordinates, equations (1) and (2) can be used for the correction of the radial lens distortion effects [16]

$$\delta x_1 = \tilde{x}(k_1 r^2 + k_2 r^4 + k_3 r^6 + \ldots), \qquad (1)$$

**Table 1:** Self-calibration components, terms, and descriptions

| Symbol | Description |
|---|---|
| $c$ | Focal distance between the projection center and the principal point |
| $x_0$, $y_0$ | Undistorted image coordinates of the principal point (as the lens distortion center) according to image center (*ppx* and *ppy*) |
| $x$, $y$ | Distorted image coordinates according to image center (raw image coordinates that are directly read from the image) |
| $\tilde{x}$, $\tilde{y}$ | Distorted image coordinates according to principal point $\tilde{x} = x - x_0$, $\tilde{y} = y - y_0$ |
| $r$ | Radial distance according to principal point (distortion center) $r = \sqrt{\tilde{x}^2 + \tilde{y}^2}$ |
| $\dot{x}$, $\dot{y}$ | Undistorted Image coordinates according to the image center |
| $\ddot{x}$, $\ddot{y}$ | Undistorted Image coordinates according to principal point |
| $k_1, k_2, k_3, \ldots k_n$ | Radial distortion coefficients |
| $p_1, p_1, \ldots p_n$ | Tangential (decentering) distortion coefficients |
| $b_1$ | Differential scaling parameter between horizontal and vertical pixel sizes |
| $b_2$ | Non-orthogonality (axial skew) parameter between $x$ and $y$ image coordinate axes |

$$\delta y_1 = \tilde{y}\,(k_1 r^2 + k_2 r^4 + k_3 r^6 + \ldots). \quad (2)$$

## 3.3 Tangential distortion – sourcing from the lens and the sensor plane installation

Tangential (decentering) distortion is the second affecting factor of the image coordinates. It is caused by the imperfect installation of the lens and the sensor plane, which are not parallel and centered. That is not a manufacturing defect or fault; it is the nature of every production and just needs to be identified and calculated. This imperfection is also the indirect cause of the principal point that does not fit on the image center. The parallelization problem of the sensor plane according to the lens plane causes tangential distortion, and the offset between each plane center defines the location of the principal point. For the definition of that distortion, it should be formulated with enough coefficients depending on the desired accuracy and precision level. For both $x$ and $y$ distorted image coordinates, equations (3) and (4) can be used for the correction of the tangential (decentering) distortion effects. In this given case, it can be clearly seen in Figure 4 that the upper left corner of the sensor plane is closer to the lens plane than the bottom right corner [16,37]

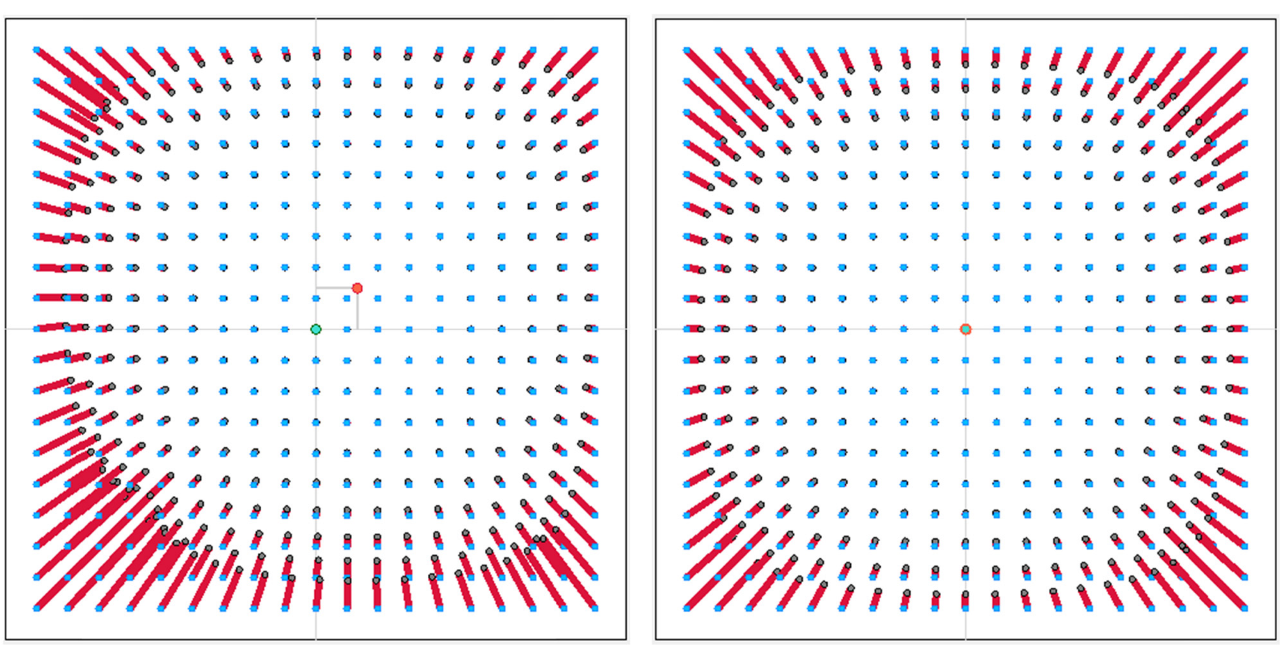

**Figure 3:** Radial distortion effects on the recorded image (lens distortion center is set to image center on the right).

$$\delta x_2 = (p_1(r^2 + 2\tilde{x}^2) + 2p_2\tilde{x}\tilde{y})(1 + p_3r^2 + p_4r^4 + \ldots), \quad (3)$$

$$\delta y_2 = (p_2(r^2 + 2\tilde{y}^2) + 2p_1\tilde{x}\tilde{y})(1 + p_3r^2 + p_4r^4 + \ldots). \quad (4)$$

## 3.4 Differential scaling and axial skewing distortions – sourcing from the sensor plane

For the proper definition of the central projection of space, it is of vital importance to know the physical (metric) dimensions and the geometry of the projected image accurately. For the analog cameras, projected photos were physically available and measurable. For digital cameras, their recorded images are assumed that they consist of square pixels in a perpendicular design, but in fact they are recorded (projected) by sensors (charge coupled device or complementary metal oxide semiconductor), which are systematically located on a sensor plane. Therefore, the relation between the location where the light hits the sensor plane and its recorded pixel coordinate should be analyzed and clarified. For that reason, the systematic recording (projection) geometry of that conversion and the physical pixel dimensions should be determined by some additional (in-plane correction) parameters [16,37,41]. These in-plane distortion parameters are the differential scaling parameters between horizontal and vertical pixel sizes ($b_1$) and non-orthogonality (axial skew) parameter between $x$ and $y$ image coordinate axes ($b_2$). As $b_1$ and $b_2$ parameters define the scaling and skewing between each other, they should be written only in one image coordinate equation. For $x$ and $y$ distorted image coordinates, equations (5) or (6) can be used for the corrections of differential scaling and axial skewing distortion effects (equation selection must be the same as used in the calibration adjustment model)

$$\delta x_3 = b_1x + b_2y \quad (5)$$

or

$$\delta y_3 = b_1y + b_2x. \quad (6)$$

For a clear understanding of differential scaling and non-orthogonality (axial skewing) parameters, as they are not related to the lens distortion center and their obvious origin is the sensor plane center (image center), the multipliers of $b_1$ and $b_2$ should be $x$ and $y$ distorted image coordinates instead of $\tilde{x}$ and $\tilde{y}$. However, modeling and using with $\tilde{x}$ and $\tilde{y}$ result the same.

For further advanced applications and productions, in case of notable distortions related to $b_1$ and $b_2$ parameters exist, they should be used with normal (5) or (6) correction equations. In case of only notable $b_1$ exist and lack of $b_1$ definition in any software, it can also be used by adjusting the corresponding pixel size in a related direction ($x$ or $y$) instead of using correction equations. In this given case, it can be clearly seen in the left image of Figure 5 that the pixel size along the $x$-axis is smaller than the size along the $y$-axis, so the points get an offset along both sides of the

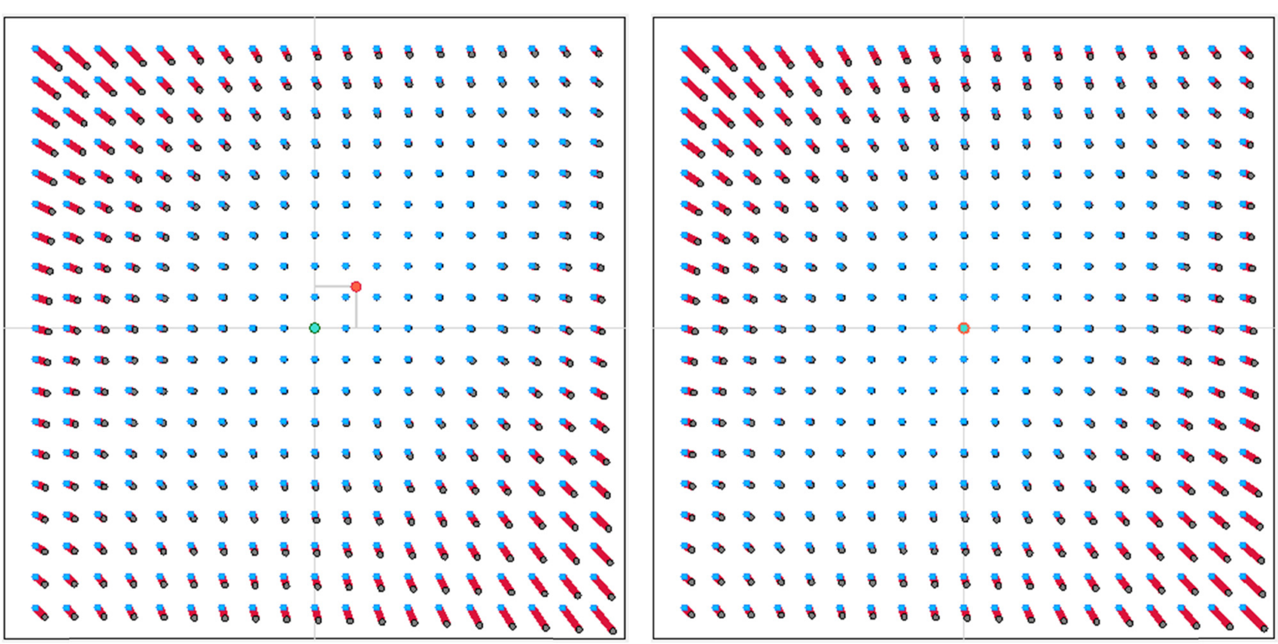

**Figure 4:** Tangential distortion effects on the recorded image (lens distortion center is set to image center on the right).

axis proportionally depending on their distances from the center point when they are recorded as an image. On the right image of Figure 5, it can also be seen that the recording sensors are not designed or located as perpendicular, and this situation leads the points to move different locations in the $x$-axis in a skewing manner depending on their $y$-coordinate distances from the center point when they are recorded as image.

### 3.5 Summary of distortion corrections

As all possible distortion sources and corrections are explained in previous sections for both $x$ and $y$ distorted image coordinates, equations (7)–(10) can be used for the correction of all defined distortion effects and calculation of undistorted image coordinates $\dot{x}$ and $\dot{y}$ according to the image center and $\ddot{x}$ and $\ddot{y}$ according to the principal point. In this given case, total (combined) distortion effects on the recorded image can be seen in Figure 6, which shows the differentiating distortion values on every side of the image. It should be pointed out that equations (7) and (8) should be used in undistorted image generation processes [37]. It should also be noted that the general perception about the distortions that they have greater values near edges cannot be thought of for every camera as this case demonstrates a particular one

$$\dot{x} = x + \delta x_1 + \delta x_2 + \delta x_3, \tag{7}$$

$$\dot{y} = y + \delta y_1 + \delta y_2, \tag{8}$$

$$\ddot{x} = \tilde{x} + \delta x_1 + \delta x_2 + \delta x_3, \tag{9}$$

$$\ddot{y} = \tilde{y} + \delta y_1 + \delta y_2. \tag{10}$$

## 4 Handling the camera self-calibration adjustments

Camera self-calibrations are performed on least-squares adjustments given characteristics in Table 2, which include all camera interior parameters given in Table 3 as unknowns ($u$) with enough observation measurements ($n$) of calibration scenes (markers) that consist of distorted image coordinates according to image center ($x$ and $y$) and their accurately known object space coordinates ($X, Y, Z$).

When it comes to demonstrating the central projection of space with 3D similarity transformation by equation (11), summarized collinearity equations (15) and (16) could be rewritten with the derived equations (12)–(14) for $\ddot{x}$ and $\ddot{y}$ undistorted image coordinates according to the principal point [37,42]. It should be noted that equations (15) and (16) include the exterior orientation unknowns for every image of the calibration scene [18,43]

$$\begin{bmatrix} x \\ y \\ -c \end{bmatrix} = m \begin{bmatrix} r_{11} & r_{21} & r_{31} \\ r_{12} & r_{22} & r_{32} \\ r_{13} & r_{23} & r_{33} \end{bmatrix} \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix}, \tag{11}$$

$$Z_x = r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0), \tag{12}$$

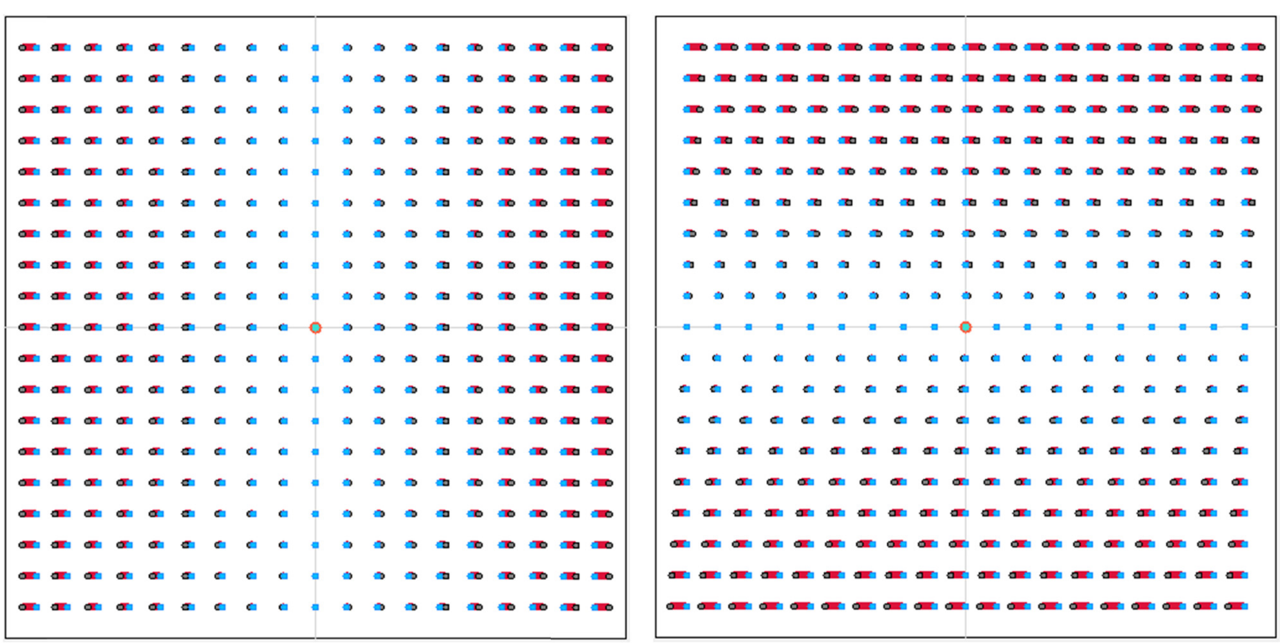

**Figure 5:** Differential scaling (left) and axial skewing (right) distortion effects on the recorded image.

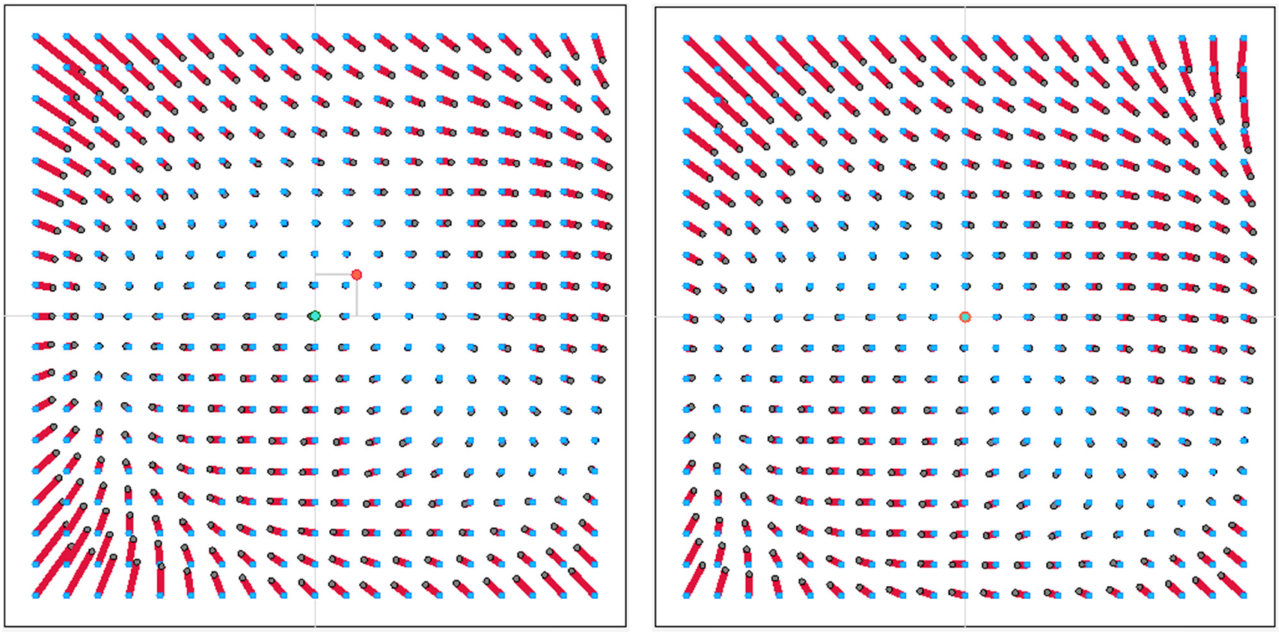

**Figure 6:** Combined distortion effects on the recorded image (lens distortion center is set to image center on the right).

$$Z_y = r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0), \quad (13)$$

$$N = r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0), \quad (14)$$

$$\ddot{x} = -c\frac{Z_x}{N}, \quad (15)$$

$$\ddot{y} = -c\frac{Z_y}{N}. \quad (16)$$

An important point here is to write down the equations that include all unknowns and exactly express the raw observation measurements used in calibration adjustments. In this case, observation measurements are $x$ and $y$ distorted image coordinates according to the image center so the collinearity equations should be expanded as equations (17) and (18), including all distortion corrections given in equations (9) and (10)

$$x = x_0 - c\frac{Z_x}{N} - \delta x_1 - \delta x_2 - \delta x_3, \quad (17)$$

$$y = y_0 - c\frac{Z_y}{N} - \delta y_1 - \delta y_2. \quad (18)$$

**Table 3:** List of camera interior orientation parameters as unknowns in least-squares adjustments

| Symbol | Description |
|---|---|
| $c$ | Focal length |
| $x_0$, $y_0$ | Location of principal point as distortion center according to the image center |
| $k_1$, $k_2$, $k_3$ | Coefficients of radial distortion |
| $p_1$, $p_2$ | Coefficients of tangential distortion |
| $b_1$, $b_2$ | Parameters of in-plane distortions |

The design matrix of adjustments should include first-degree derivatives of all unknowns (Taylor series expansion), and they should be resolved iteratively until the expected or determined convergence threshold is exceeded. At the end of every sequential iteration, convergence, and corrections for all unknowns should be analyzed, and incorrect observations should be eliminated. As there is no covariance matrix beforehand, the assumed covariance matrix

**Table 2:** Least-squares adjustment characteristics of self-calibration adjustments

| Symbol | Description |
|---|---|
| $n$ | Number of observations consists of $x$ and $y$ distorted image coordinates of each marker in every taken image of the calibration scene and offsets between camera locations as supportive conditions |
| $u$ | Camera interior parameters given in Table 3 and exterior orientation parameters of every taken image of the calibration scene |
| $s$ | Adjustment's degree of freedom ($n$ $u$) |

or given weight matrix should be re-scaled after the first iteration, and the final (a posteriori) variance should be taken into account for the health of adjustments.

## 5 Discussion

No matter whether the professional photogrammetric camera self-calibration adjustments give satisfactory results, the accuracies of calibrated coefficients and parameters depend on the adjustment's calibration model and reliable (accurate) observation inputs [44]. As all the camera distortions are modellable systematic errors, it is of vital importance to clearly understand the photogrammetric fundamentals and describe the digital camera's distinctive internal structure with enough parameters within the design of the calibration model [45]. All the healthy inputs should be taken into adjustment as observations for more accurate and reliable results.

For the importance of parameter effects on calibration adjustments, in case of any missing notable parameter definition because of assumptions in calibration adjustments exactly leads the calibrations to an unconverging situation because of the deficient definition of the present situation. Within the sequential iterations, undefined existing distortion corrections will be distributed to other unknowns, and this is the self-destruction of calibration adjustments depending on the given convergence thresholds. The distinctive characteristic of the principal point, which discriminates from distortion parameters, should be underlined that the principal point is an offset and affects every image coordinate on every side of the image with the same values. While performing stereo (3D) measurements or calculations by collinearity equations with calibrated camera parameters, unidentified or undetermined distortion values in different parts of the image will affect all the object space coordinates $X$, $Y$, and especially $Z$ depending on their size [45].

Although professional photogrammetric camera calibration has a big importance and necessity in photogrammetric productions and accurate measurements among images, the growing usage of non-metric cameras and the handling software solutions may cause some misunderstandings depending on their nature. It could be said that keeping the production accuracies at acceptable levels with a non-calibrated and non-metric camera can only be achieved by the abundance of accurate control points (e.g., UAV mapping solutions). A great number of control points are required for the camera self-calibration within the block adjustments. If we try to explain the subject over the UAV mapping example, this number can be decreased by the usage of real-time kinematic (RTK) or post-process kinematic solutions, but it should be underlined that they solve only the 3/6 of exterior orientation parameters of images precisely [46]. If there is no efficient IMU system on the UAV platform that is able to solve the other three rotation parameters precisely, all solutions will require again enough number of control points (GCPs).

The findings obtained in the study support the literature suggested in the past for digital camera distortion, and the application of visual effects, thanks to the developed software, makes it practical to understand digital camera distortion [16,18,41,43]. Nowadays, the development and widespread use of digital video cameras have paved the way for access to high-resolution and low-distortion images and increased their usability. At this point, digital photogrammetry is developing at an increasing rate, thanks to the high resolution of raster images. In addition to these, the increase in memory and processor performances in computer systems and their easy accessibility increase the interest in digital photogrammetry day by day [42]. The principles proposed in the study can be used, but not limited to, in analysis based on material properties and image processing [47], in surgical navigation applications [37], tunnel monitoring and displacement [48], remotely sensed images of temporal changes in water quality [49], measurements in industrial environments [36], and analysis of geotechnical properties of soils with geographic information systems and artificial neural network [50].

## 6 Conclusions

Defining the correct imaging geometry of a digital camera can be achieved by accurately determining the camera internal parameters and external orientation parameters. The camera internal parameters describe the exact shape and position of the lens and sensor planes, while the external orientation parameters describe the location and rotation of the imaging directions in a coordinate system. For this reason, these values must be known accurately in photogrammetric studies. This study explains the principles and foundations of computational theory for determining the causes of distortions in digital images. With the software developed in the study, camera distortions are visualized, and the process of obtaining camera parameters according to camera distortions and the theory of self-calibration in digital cameras are explained.

As a result, the most important fact that can achieve accurate and precise photogrammetric productions is the correct definition of central projection of space for every image, and for that reason, the correct definition can be achieved by the usage of accurate camera parameters which are calculated with professional photogrammetric camera calibrations.

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**Author contributions:** TD conceptualized, developed software, and implemented the methodology. EEM performed the verification and inspection. EEM and TD prepared the manuscript and made revisions.

**Conflict of interest:** Authors state no conflict of interest.

**Data availability statement:** The data used to support the findings of this study are included within the article. Additional information concerning the findings of this study is available from the corresponding author upon request.

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