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Highly accurate geometric calibration for infrared cameras using inexpensive calibration targets

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A R T I C L E I N F O

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A B S T R A C T

Geometric camera calibration is affected by two sources of error: the lack of accuracy of the calibration target and the uncertainty in locating the control points in the images. Both issues are especially difficult to solve with infrared cameras because they require features that can be distinguished in terms of infrared radiation. In this work we propose a novel design for calibration targets for infrared cameras, easy to build, yet extremely accurate and also inexpensive. This work presents a far more cost efficient solution than previous works: calibration targets are printed on aluminum composite material with a continuous industrial flatbed printer used for advertising boards. This is an easy process that can be used to build calibration targets quickly and with the required size for each particular application. Two calibration targets with different calibration patterns are built and tested, including a thorough analysis of the emissivity and the consequences for the required calibration procedure. Extensive tests are performed to compare the calibration targets, the calibration indoors and outdoors, and the measurement accuracy. Results show excellent performance, with an average measurement error of less than 70 µm, below 0.09% of the real measurement value.

1. Introduction

Any object at a temperature above absolute zero emits infrared radiation. The intensity of the radiation and the wavelength at which it is emitted depend mainly on the temperature of the object [1]. Therefore, measuring the infrared radiation emitted by an object can provide accurate temperature measurements with proper calibration procedure [2].

Temperature measurement provides very useful information about the state of an object that is used in a wide variety of applications. In medical and veterinary applications it is used as a health indicator [3,4]. In mechanical and electrical applications it is used as an indicator of malfunction [5,6]. In non-destructive testing applications it is used to detect subsurface defects [7]. Many other applications use it for very different goals, such as bridge inspection [8], food safety and quality assessment [9], or pest detection [10].

Infrared thermography has many advantages [11]. One of the most important is that it provides two-dimensional infrared images that can be used to compare the radiation and temperature in different areas of the scene. Infrared images not only provide information about radiation and temperature, but also about an additional feature: the geometry of the scene. Geometrical information is generally neglected in infrared thermography. However, it can serve multiple purposes, such as measuring the size of objects in the image, establishing measurement regions in real world coordinates, or accurately aligning different types of images acquired from the same scene. There are two main reasons why geometric information is rarely used in infrared thermography: the relatively low resolution of the images (considerably lower than visible images) and the complexity of the required calibration procedure. Thus, when applications require geometrical information about the scene, they use visible cameras that provide much better resolution at a reduced cost. Moreover, extracting geometrical information from images requires geometric calibration. In infrared thermography this procedure is complex because it requires calibration targets with distinguishing features in terms of infrared radiation. In contrast, when using visible images, calibration targets are printed in inexpensive off-the-shelf printers. However, usually this type of targets cannot be used in infrared applications because infrared cameras cannot capture visible calibration patterns.

The popularity of infrared thermography in recent decades has brought major advances in most aspects of the technology [12]. Geometric calibration of infrared cameras is an active research field with

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numerous developments. The most common approach is the building of a flat calibration target with features that can be distinguished in the infrared images. The calibration target is observed with different orientations, and the features extracted are used to estimate the coefficients of the mathematical model that describes camera projection [13]. Some recent works have performed the calibration using the same visible calibration target used for visible cameras [14]. However this approach requires heating and an image preprocessing step to enhance and sharpen the corners of the images. No quantitative assessment is performed for the obtained measurement accuracy. One of the most popular solutions is the use of calibration targets based on burning lamps. These lamps are placed on a flat surface, such as a wooden plate, at specific positions. Lamps are clearly distinguished in infrared images because they emit more infrared radiation than the wood. Therefore, the positions of these lamps are easily calculated from the images, which are later used to fit the mathematical model. This approach is used in [15], where 64 burning lamps are placed on a wooden plate with a surface of $1\,m^2$. A similar approach is used in [16], where 57 small lamps are placed on a wooden plate of $1\,m^2$. More examples based on the same idea can be found in [17–19]. However, the same authors proposing this approach indicate severe drawbacks that make calibration difficult and inaccurate. One of the problems is that the center of the target lamps cannot be measured with precision [16]. Also, it is indicated that the calibration targets are heavy, require an external power supply and present diffraction effects because the burning lamps are generally placed in holes in the supporting plate [20].

An alternative solution when building calibration targets is the combination of materials with different emissivities. When the calibration target is heated, or when the reflected temperature on the target is different from the temperature of the target, the materials can be distinguished in the infrared image providing the required geometric features to fit the projection model. For example, in [21] a chessboard calibration target is printed and the white squares are covered with aluminum foil. In [20] a calibration target is proposed consisting of an aluminum sheet and a black card stuck on top of a wooden plate. In this case, the target is perforated so that the aluminum sheet is only visible in the required regions. A similar approach is presented in [16]. However, in this case rather than perforating the target, coded figures with self-adhesive foil are added to the surface. [22] presents two chessboard calibration targets that combine copper and high emissivity spray ink. [23] presents another calibration target anodized and coated with silver and black colors of very different emissivities. The problem with all these works is that few details are given about the construction of the calibration target. In some cases it is indicated that perforations are done manually. In other cases it can be assumed that the aluminum foil is also cut and glued using a manual procedure. However, no information is given about the accuracy of these procedures, which being manual, will be above 0.5 mm. This heavily affects the accuracy of the resulting calibration target, which plays a vital role in the geometric camera calibration as well as in all subsequent measurements based on that calibration. Moreover, manually made calibration targets not only limit calibration accuracy, they are also difficult and expensive to build.

The calibration accuracy can be affected by optical distortions produced by camera lenses, wide angle lenses in particular. Image distortion can be greatly reduced when working with camera lenses having long focal lengths. In this case, calibration targets are also much more simple, such as the calibration target presented in [24], which consists of scale bars with four reflective targets situated at the corners of the structure. A similar approach is used in [25], where the pose is estimated based on the coordinates of four points on the inspected object.

Camera calibration can even avoid using calibration targets, and use the shape of the inspected object as the required reference for calibration. This is the method proposed in [26]. This work also assumes a camera projection model not considering distortions. This method estimates the projection parameters iteratively based on features from objects in the image and the knowledge about their geometric properties. Thus, it does not require a specific calibration target.

Infrared camera calibration can be completely avoided when more visible cameras are available in the scene, such as in [27]. In this case the geometric information is obtained using a stereo camera setup. Then, 3D information and 2D infrared images are aligned and fused using automatically detected features. This approach requires significantly more resources to obtain geometric information from infrared images. Moreover, it assumes that features in the visible and infrared images can be matched, which is not always the case when only a partial view of the object is inspected.

This work proposes a novel calibration target that can be used to perform the geometric calibration of infrared cameras with high accuracy. Considering the problems associated with the reviewed proposals for infrared calibration targets, there is only one approach that can be used to build an accurate calibration target: printing. There are two main sources of error that affect camera calibration: the accuracy of the calibration target and the uncertainty in locating the control points in the images [28]. Therefore, since it is not possible to build manually a calibration target with high accuracy, a possible solution is to print the calibration target. However, as indicated before, this presents a major issue, as standard printed patterns cannot be distinguished in the infrared images. The proposed solution is to print the pattern, not on paper, but on Dibond®, an aluminum composite material. This material is excellent for digital printing and also extremely flat, another requirement for calibration targets. Printing on this material requires a specific printer. However, this type of printers are standard equipment used for printing advertising boards that are widely available nowadays. Printing the calibration targets not only provides the extremely accurate targets required for the most demanding applications, it is also an inexpensive process that can be used to build targets in the required sizes, quickly and easily. Based on this approach for building calibration targets, two different patterns are proposed: a circular pattern and a chessboard. The printed calibration pattern can be distinguished in the infrared images because the ink has a different emissivity from the aluminum panel. Methods to extract the control points from the infrared images are proposed, and the results are compared in terms of calibration accuracy. Extensive tests in controlled conditions are performed to compare the calibration targets and validate the accuracy of the proposed procedure.

The remainder of this paper is organized as follows. Section 2 introduces the fundamentals of camera calibration; Section 3 presents the proposed approach, including the description of the novel calibration target and the methods to extract the control points from the images; Section 4 discusses the results obtained; and finally, Section 5 reports conclusions.

2. Camera calibration

Camera calibration is a process used to estimate the parameters that control camera projection [29]. Once these parameters are known, distortions introduced by lenses and by the perspective projection can be removed. Thus, reliable geometric information can be extracted from the images. Calibration is divided into two phases: the definition of the theoretical model that approximates camera projection, and the estimation of the parameters of the model.

2.1. Camera projection

Camera projection can be interpreted as a series of consecutive transformations from 3D world coordinates in the scene to 2D pixel coordinates in the image based on the pinhole camera model. Generally, three transformations are considered:

1. Transformation from 3D world coordinates to 3D camera

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