Virtual camera calibration using optical design software

Anne-Sophie Poulin-Girard,[1] Xavier Dallaire,[1] Simon Thibault,[1,*] and Denis Laurendeau[2]

[1]Centre d'optique, photonique et laser, Département de physique, de génie physique et d'optique, Université Laval, 2375, rue de la Terrasse, Québec G1V 0A6, Canada

[2]Laboratoire de vision et systèmes numériques, Département de génie électrique et de génie informatique, Université Laval, 1065, avenue de la Médecine, Québec G1V 0A6, Canada

*Corresponding author: Simon.Thibault@phy.ulaval.ca

Received 12 February 2014; revised 20 March 2014; accepted 22 March 2014; posted 24 March 2014 (Doc. ID 206332); published 24 April 2014

Camera calibration is a critical step in many vision applications. It is a delicate and complex process that is highly sensitive to environmental conditions. This paper presents a novel virtual calibration technique that can be used to study the impact of various factors on the calibration parameters. To highlight the possibilities of the method, the calibration parameters' behavior has been studied regarding the effects of tolerancing and temperature for a specific lens. This technique could also be used in many other promising areas to make calibration in the laboratory or in the field easier. © 2014 Optical Society of America

OCIS codes: (150.1488) Calibration; (080.2208) Fabrication, tolerancing; (080.3620) Lens system design.

http://dx.doi.org/10.1364/AO.53.002822

1. Introduction

Vision systems are increasingly used in scientific and industrial applications. For 3D-depth estimation tasks, a variety of systems and techniques exist: plenoptic systems [1], stereoscopic imaging [2–4], structured light [5], and many others. The precision of those devices often relies on adequate and accurate camera calibration. Ideally, the calibration process should be performed at operating conditions to avoid physical changes in the system causing variation in the calibration parameters. While it is widely admitted that this method ensures the reliability of calibration parameters, it is often difficult or impossible to actually calibrate in those exact conditions.

When designing a vision system, engineers pay attention in selecting an adequate camera that presents the right sensor type and size, spatial resolution, frame rate, and pixel pitch but usually end up choosing an optical system with limited knowledge of its internal characteristics except for its focal length and field-of-view (FOV). With so little information, the physical changes that can be caused by a number of factors such as temperature, storage, transportation, or vibration are difficult to predict and so is their impact on calibration parameters. However, this is a topic of interest, and experimental studies have been conducted on the impact of environmental conditions on the calibration parameters [6,7].

Optical design software is a powerful tool that enables optical designers to create, optimize, and evaluate the performances of an optical system. The design file contains all of the system's information such as types of glass, thickness, and radius of curvature and can also be used to analyze the effects of temperature and tolerancing on optical design performances. Traditionally limited to optical designers, optical design software tools are accessible to more

1559-128X/14/132822-06$15.00/0

people now that some optical systems suppliers have given access to the design file of their products to customers to enable them to carry out simulations and performance analysis.

This paper proposes a new technique to use Zemax and an existing calibration toolbox running on MATLAB to assess the theoretical impact of temperature and tolerancing on calibration parameters. This technique could be applicable to many other situations, but specific cases have been chosen to highlight the possibilities of the procedure. The characteristics of the optical system used are given, and the calibration model and associated existing toolbox are described. The virtual calibration technique is detailed, and the results for tolerancing and thermal simulation are given. The sensor and camera are not taken into account in this paper, which focuses on the optical system only.

2. Lens and Calibration Algorithm

To perform the analysis, a fisheye camera lens and the OCamCalib toolbox for MATLAB were used. Similar work could be performed with any other combination of lens and calibration technique.

A. Lens Specification

The lens chosen to perform the simulation has a FOV of 170 deg and an f-number of 1.8. This design was originally published in Milton Laikin's *Lens Design* [8] at Fig. 9.4 in the "Very-Wide-Angle Lenses" chapter. The complete prescription can also be found in the Zemax Zebase 6 under number F_006 [9]. Figure 1 shows the system layout as displayed in Zemax.

B. Omnidirectional Camera Model

There are many existing calibration models for wide-angle lenses. Some of them are relatively close to the traditional pinhole camera model while others are different, but all of them deal with high distortion. In this paper, the omnidirectional camera model for catadioptric and fisheye lenses that have a FOV up to 195 deg [10–12] was used. This model is based on the three following assumptions. First, the optical system is a central system (or a quasi-central system).

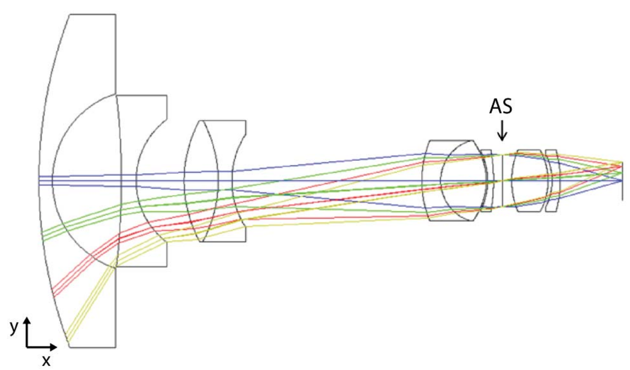

Fig. 1. Zemax design layout for a 170 deg FOV and F/1.8 camera lens (F_006). The effective focal length is 5.2 mm. The position of the aperture stop (AS) is indicated above.

Second, the system presents a perfect alignment between all of its optical components, and, finally, it is rotationally symmetrical around its optical axis. Wide-angle lenses, like fisheye lenses, that exhibit an entrance pupil displacement [13] can be considered quasi-central systems. Also, in this model, distortion is not considered in the traditional way by the focal length and distortion coefficients but is taken into account in a projective function $f(u,v)$.

If the first two above conditions are met, the relation between a vector in object space $[x,y,z]^T$ and its corresponding image point $[u,v]^T$ can be written as

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} u \\ v \\ f(u,v) \end{bmatrix}. \quad (1)$$

With the third condition also being satisfied, the projective function f only depends on the distance ρ from the image point to the principal point and can be modeled as a polynomial:

$$f(\rho) = \boldsymbol{a}_0 + \boldsymbol{a}_2\rho^2. \quad (2)$$

The degree of the polynomial projective function $f(\rho)$ can be chosen by the user. Even if the author of the toolbox suggests employing a fourth-order polynomial, the second-order polynomial is a better choice in this paper because the optimization process is not able to cope with higher-degree polynomials with the lens chosen.

Since real optical systems do not have a perfect alignment between their components, an affine transformation is introduced to account for misalignments resulting from the manufacturing process and tolerancing where $[u',v']^T$ are the distorted coordinates and $[u,v]^T$ are the ideal ones:

$$\begin{bmatrix} u' \\ v' \end{bmatrix} = \begin{bmatrix} \boldsymbol{c} & \boldsymbol{d} \\ \boldsymbol{e} & 1 \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} \boldsymbol{xc} \\ \boldsymbol{yc} \end{bmatrix}. \quad (3)$$

Seven calibration parameters will be used and are indicated in bold in Eqs. (2) and (3). The projective function and the principal point coordinates xc and yc are expressed in pixels. The parameters c, d, and e are dimensionless.

C. OCamCalib Toolbox for MATLAB

OCamCalib toolbox for MATLAB [14] uses the omnidirection camera model and is based on Bouguet's Camera Calibration toolbox [15], making it very easy to use. Images of a known checkerboard at different positions and orientations have to be taken in order to calibrate a camera [16]. In the toolbox tutorial, the author suggests acquiring between eight and 10 images to cover the entire FOV and also to bring the checkerboard as close as possible to the camera for better results.

To mimic a realistic calibration, a set of simulated calibration data representing nine random positions and orientations of 11×11 control points checkerboard in object space was designed, as shown in Fig. 2. The horizontal and vertical distance between two consecutive points on one checkerboard is 40 mm.

3. Simulation Using Optical Design Software

In order to calibrate a camera virtually, the image position of each control point on each checkerboard has to be obtained with Zemax. For each control point, the field angles, obtained with direction cosines, are used to calculate the position of the chief ray by ray tracing. The centroid position of the rays passing through the entrance pupil could also be employed to perform calibration. However, centroid determination takes much more computation time than chief ray determination for similar results. Figure 3 shows image points corresponding to object points in Fig. 2 for the nominal design. The image points are used as inputs for the calibration toolbox.

Since there are no real pixels, the virtual images were sampled with 1 μm square pixels to allow the algorithm to perform calibration as if real images were used. Any other pixel pitch value could have been chosen.

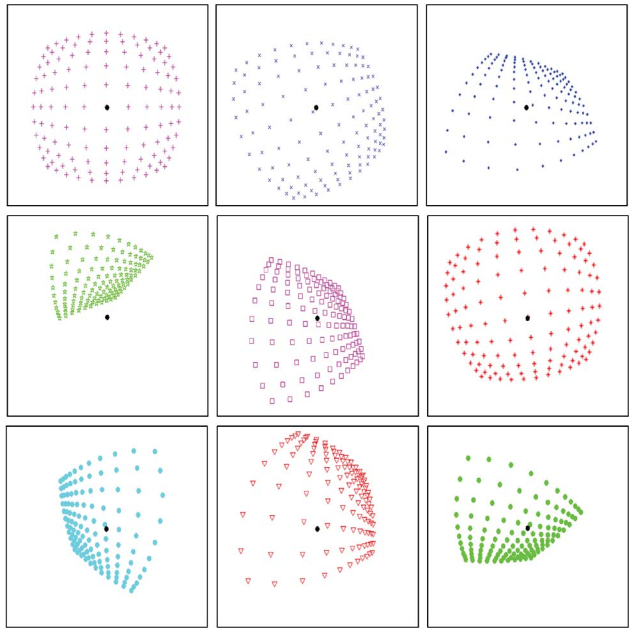

Fig. 3. Image points corresponding to the simulated calibration targets. The black dot represents the position of the optical axis (also the center of the image and the principal point).

4. Results

This paper focuses on the individual and combined impact of tolerancing and temperature on calibration parameters. It would have also been possible to study pressure or polarization impact and recreate almost any operating conditions for a specific application. All the calibrations were made with the same nine simulated targets and exhibit a similar mean reprojection error.

A. Temperature

Using the nominal design, 21 configurations with operating temperatures from −250°C to 250°C were generated in the multiconfiguration mode. Each temperature variation induces a perturbation on certain sensible parameters (glass index, surface curvature, thickness, and diameter) [17]. The thermal coefficient of expansion of aluminum was used in air spaces to account for the mount. There was no refocusing involved between the different operating temperatures. That way it was possible to compare the total effect of the perturbations on the system. Considering the physical meaning of the calibration parameters, no variations were expected to be observed except in the projective function. Figure 4(a) shows parameters a_0 and a_2 as a function of the temperature.

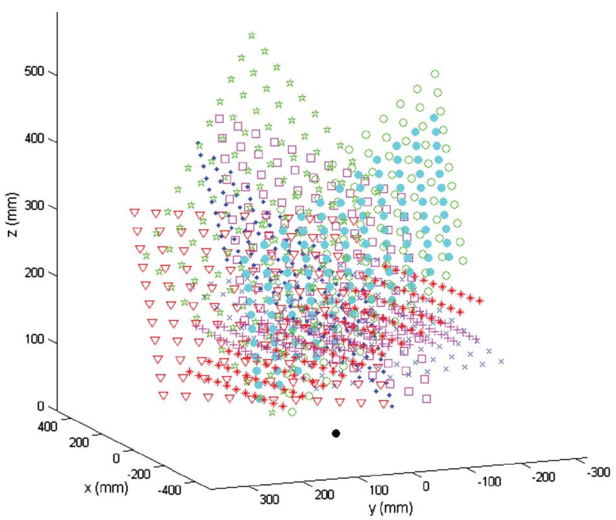

Fig. 2. Simulated calibration targets in object space representing nine checkerboards with 11×11 control points. The black dot marks the camera position.

As shown in Fig. 4(a), the coefficient a_0 dominates the projective function for every temperature. Its value grows as the temperature rises, exhibiting a zoom-like behavior as expected and observed in [7]. All the other calibration parameters are stable. Parameters xc and yc, representing the principal point, vary from less than 0.2% with respect to the mean. Parameters c, d, and e exhibit absolute variation in the order of 1×10^{-3} between the minimum and the maximum value.

Another interesting example of the advantages of using Zemax for calibration simulation is temperature gradient, a situation that occurs frequently in real-life applications. A discrete gradient shaped by the optical system elements was created from 10°C at the front lens to 30°C at the last lens. Figure 4(b) presents the difference between the nominal and the gradient projective functions. The difference doubles between the center of the image and the edges. Even if only the projective function were to be modified, all the other parameters would show minor changes as a result of the optimization process.

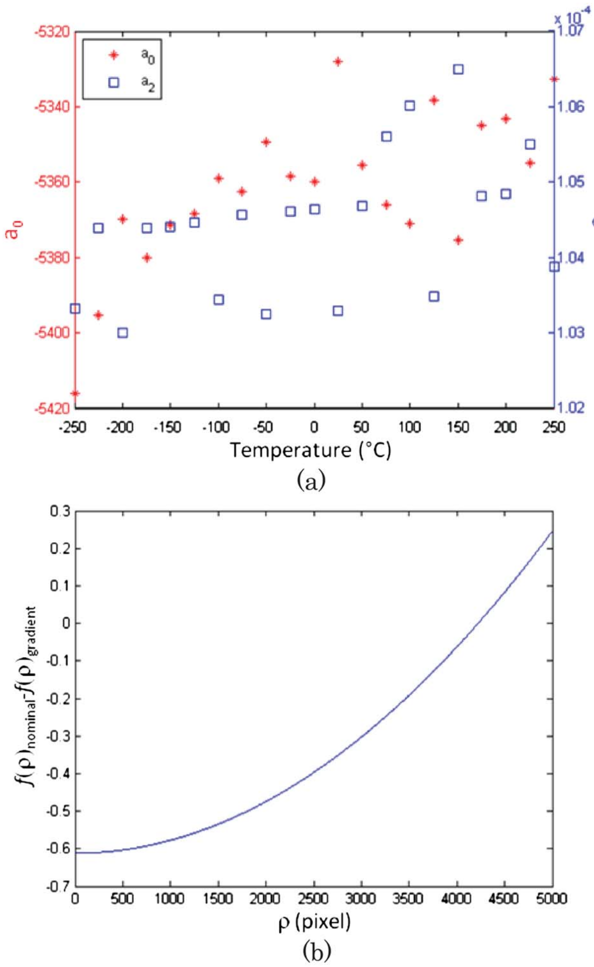

Fig. 4. Influence of temperature on the projective function. (a) Variation of projective function coefficients a_0 and a_2 depending on the temperature. (b) Difference between nominal and gradient (10°C at front lens to 30°C at last lens) projective functions.

Those changes were more important than with uniform temperature.

B. Tolerancing

Tolerancing is a key step in the production of an optical design. Its goal is to allow fabrication of an optical system while keeping the specifications and image quality in an acceptable range. For the same optical system, every sample will have different values of radius of curvature, spacing, and thickness, always within the tolerancing limits. This will cause small variations of focal length, FOV, image quality, etc. from one sample to the other. Since every sample is different, it is also expected to cause small variations in the calibration parameters. Starting with the nominal design, two different optical elements, the front lens and the element after the aperture stop (AS), were submitted in turn to a 50 μm decentering. A tilt was added to the decentering for the element after the AS. The position of the AS is indicated in Fig. 1. Table 1 shows the calibration parameters for the three modified designs. More significant figures were available but are not included in the tables for clarity.

Decentering of the front lens seems to have a negligible effect on the calibration parameters as opposed to the same decentering value of the optical element located right after the AS. In this case, parameters xc and yc are different from the nominal design values. As shown at Table 1, keeping the same decentering value and adding a tilt of 0.15′ to this lens induces small additional modifications to the parameters d and e while xc and yc remain similar to the case with decentering only. This example illustrates that there are elements that can be identified as the ones that have the most significant impact on the calibration parameters compared to the nominal design. In the same way as the worst offender for image quality can be identified during tolerancing, the same type of study could be made to find the physical parameters that are the worst offenders for camera calibration, opening new ways for stable calibration prescription.

A more general tolerancing analysis has been made to evaluate how the calibration parameters vary for different builds of the same lens. The different versions of the design were generated using a Monte-Carlo process to select, within the defined tolerance values, a small perturbation for each of the variables (surface curvature, glass index, tilt, etc.). The range of tolerance used was chosen to emulate a realistic tolerance budget [18]. Table 2 lists the maximum, minimum, and mean value of each calibration parameter as well as the standard deviation of each distribution.

The standard deviation for the coefficients of the projective function (a_0, a_2) and the coordinates of the principal point (xc, yc) account for less than 0.6% of the mean value in each case. For the parameters of the affine transformation (c, d, e), the standard deviation values are very similar. It suggests that

Table 1. Calibration Parameters for Decentering and Tilt of Two Different Optical Elements

	Nominal Design	Front Lens 50 μm Decentering	First Element after AS 50 μm Decentering	First Element after AS 50 μm Decentering and 0.15′ Tilt
a_0	−5354.2	−5360.7	−5360.2	−5357.7
a_2	1.0465×10^{-4}	1.0455×10^{-4}	1.0457×10^{-4}	1.0455×10^{-4}
xc	5013.1	5012.7	5080.8	5083.6
yc	5002.5	5008.0	4938.9	4946.6
c	1.0009	1.0003	1.0003	1.0005
d	-9.0022×10^{-4}	-2.3648×10^{-4}	-2.6079×10^{-4}	5.6461×10^{-4}
e	2.9109×10^{-4}	3.2150×10^{-4}	3.3789×10^{-4}	-8.2840×10^{-4}

Table 2. Range of Calibration Parameters for Perturbed Designs

	Maximum	Minimum	Mean	Standard Deviation σ
a_0	−5315.0	−5380.1	−5359.3	14.5
a_2	1.0546×10^{-4}	1.0299×10^{-4}	1.0442×10^{-4}	6.35×10^{-7}
xc	5054.9	4975.7	5016.2	27.7
yc	5063.7	4959.6	5016.0	27.3
c	1.0023	1.0001	1.0006	4.76×10^{-4}
d	1.0439×10^{-3}	-7.7906×10^{-4}	7.6737×10^{-5}	4.04×10^{-4}
e	5.0974×10^{-4}	-1.1522×10^{-3}	-3.1242×10^{-4}	4.60×10^{-4}

variations in the calibration parameters are bounded and that, if this optical system were produced with such tolerances, the calibration parameters of the optical system itself are more likely to have a behavior represented by the data in Table 2. It also shows that the optimization is stable for small variations associated with the tolerancing process.

C. Temperature and Tolerancing

Both effects can be combined to study the variation of the calibration parameters. Using one of the 20 toleranced designs, simulations ran between 10°C and 30°C for each 0.5°C increment. Figure 5 shows all the calibration parameters for this simulation.

The results of the toleranced system calibration parameters as a function of the temperature shown in Fig. 5 display a possible jump in the optimization process at 16°C. This change can be observed in the projective function parameters [Fig. 5(a)] and possibly in parameter c of the affine transformation [Fig. 5(c)]. The coordinates of the principal point (xc, yc) undergo the same type or variations around the mean value of 5022.7 pixels for xc and of 4998.9 pixels for yc. This behavior is a specific case and cannot be generalized for other fisheye lenses. Parameters d and e of the affine transformation [Fig. 5(d)] do not show any specific behavior.

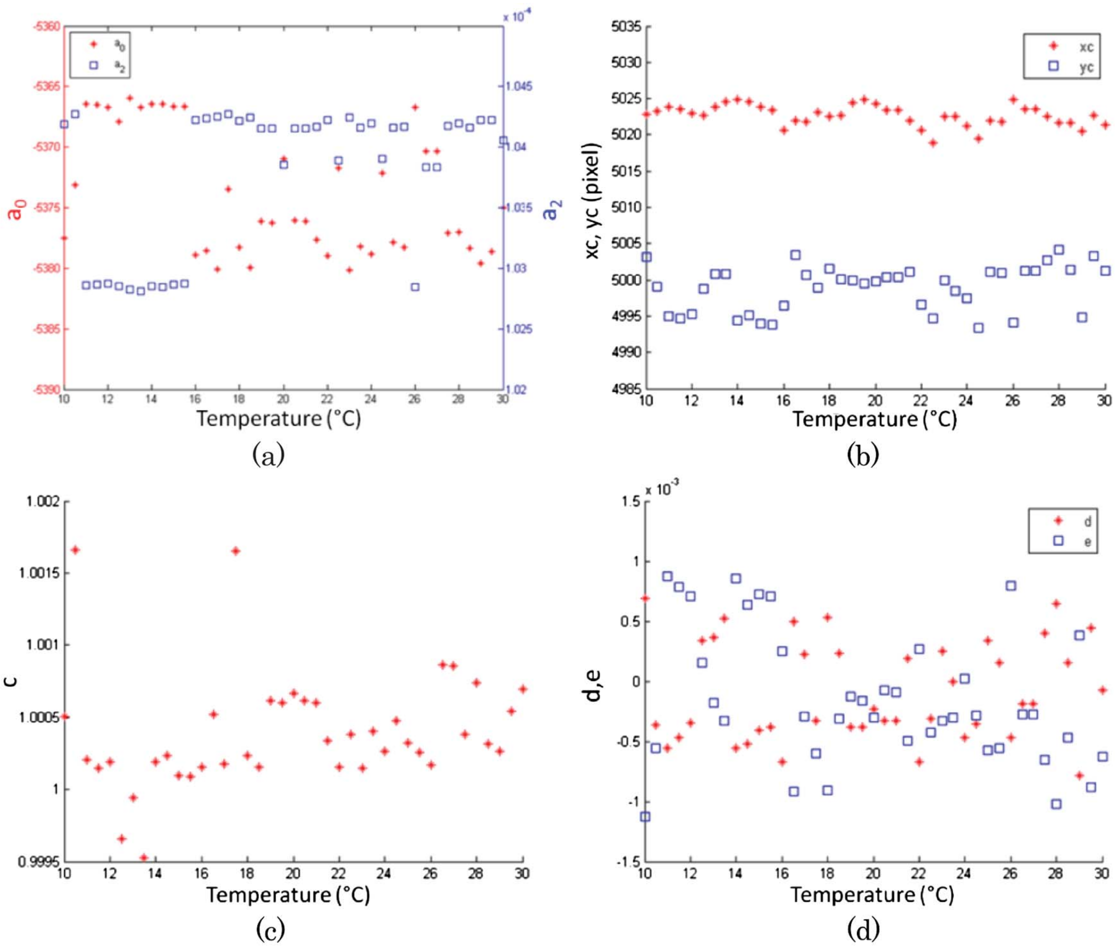

Fig. 5. Calibration results for a toleranced design as a function of the temperature between 10°C and 30°C. The calibration parameters are (a) the projective function coefficients a_0 and a_2; (b) the principal point coordinates xc and yc; (c) parameter c of the affine transformation; (d) parameters d and e of the affine transformation.

5. Conclusion

In this paper, a new technique for virtual camera calibration was presented. Using the Zemax design file of a fisheye camera lens and the MATLAB toolbox OCamCalib for calibration of fisheye and catadioptric lenses, many virtual calibrations were performed at different temperature conditions and also on several toleranced designs using the same set of nine calibration targets. The chosen cases showed that it is possible to study the calibration parameters' behavior in virtual settings. Experimental camera calibration of a known optical system could be performed in order to validate this technique.

There are many other interesting aspects of virtual calibration that were not addressed in this paper. A study could be made to find the range of temperature for which a specific set of calibration parameters achieves acceptable results for 3D reconstruction. Implemented within the lens design process, it could enable the designer to produce lenses that are more robust to calibration parameter changes. Used with a different calibration model, this technique could be employed to develop a better procedure for zoom calibration, which is known to be difficult to perform. Also, it would be possible to theoretically determine the best calibration target number, number of control points, size, orientations, and positions for a specific lens, a task that would be tedious to perform in the laboratory. Environmental conditions could be taken into account, making real-life calibration easier and more accurate.

This work was supported by the NSERC Industrial Research Chair in Optical Design.

References

1. E. Adelson and J. Wang, "Single lens stereo with a plenoptic camera," IEEE Trans. Pattern Anal. Mach. Intell. **14**, 99–106 (1992).
2. Z. Kiraly, G. Springer, and J. Van Dam, "Stereoscopic vision system," Opt. Eng. **45**, 043006 (2006).
3. A. Ude, C. Gaskett, and G. Cheng, "Foveated vision systems with two cameras per eye," in *Proceedings of IEEE International Conference on Robotics and Automation* (Institute of Electrical and Electronics Engineers, 2006), pp. 3457–3462.
4. T. Nishimoto and J. Yamaguchi, "Three dimensional measurement using fisheye stereo vision," in *Proceedings of 46th SICE Annual Conference* (Institute of Electrical and Electronics Engineers, 2007), pp. 2008–2012.
5. Y. Caulier, "Inspection of complex surfaces by means of structured light patterns," Opt. Express **18**, 6642–6660 (2010).
6. D. Fiedler and H. Müller, "Impact of thermal and environmental conditions on the kinect sensor," in *Proceedings of International Workshop of Advances in Depth Image Analysis and Applications*, Lecture Notes on Computer Vision (SpringerLink, 2012), Vol. **7854**, pp. 21–31.
7. M. J. Smith and E. Cope, "The effects of temperature variation on single-lens-reflex digital camera calibration parameters," in *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Commission V Symposium (International Society for Photogrammetry and Remote Sensing, 2010), Vol. **XXXVIII**, Part 5, pp. 554–559.
8. M. Laikin, *Lens Design*, 4th ed. (CRC Press, 2006).
9. Zebase 6 Optical Design Database (ZEMAX Development Corporation, 2007).
10. D. Scaramuzza, "OCamCalib: omnidirectional camera calibration toolbox for MATLAB," https://sites.google.com/site/scarabotix/ocamcalib-toolbox.
11. D. Scaramuzza, A. Martinelli, and R. Siegwart, "A flexible technique for accurate omnidirectional camera calibration and structure from motion," in *Proceedings of IEEE International Conference of Vision Systems* (Institute of Electrical and Electronics Engineers, 2006), pp. 45–52.
12. D. Scaramuzza, A. Martinelli, and R. Siegwart, "A toolbox for easy calibrating omnidirectional cameras," in *Proceedings to IEEE International Conference on Intelligent Robots and Systems* (Institute of Electrical and Electronics Engineers, 2006), pp. 5695–5701.
13. J. Parent and S. Thibault, "Tolerancing panoramic lenses," Proc. SPIE **7433**, 74330D (2009).
14. D. Scaramuzza, *Omnidirectional Vision: From Calibration to Robot Motion Estimation*, (ETH Zurich, 2008).
15. J.-Y. Bouguet, "Camera calibration toolbox for MATLAB," http://www.vision.caltech.edu/bouguetj/calib_doc/index.html.
16. Z. Zhang, "Flexible calibration by viewing a plane from unknown orientations," in *Proceedings of 7th IEEE International Conference on Computer Vision* (Institute of Electrical and Electronics Engineers, 1999), pp. 666–673.
17. "Thermal analysis," in ZEMAX User's Manual, (ZEMAX Development Corporation, 2013), pp. 667–672.
18. Optimax Systems, Inc., "Manufacturing tolerance chart," http://www.optimaxsi.com/innovation/optical-manufacturing-tolerance-chart/.