IMPROVING CALIBRATION OF THERMAL STEREO CAMERAS USING HEATED CALIBRATION BOARD

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ABSTRACT

Calibration of stereo cameras is important for accurate 3D reconstructions. For standard color cameras there are many available tools and algorithms for accurate calibration, such as detecting corners of chessboard patterns on planar calibration boards. When viewed in thermal imagery, these chessboard patterns are difficult to detect due to uniform temperature between the white and black squares. Previous techniques involve creating a custom calibration board using multiple materials. One abandoned approach uses a printed chessboard heated by a flood lamp which results in blurry, hard to detect corners that are only visible for a short period of time. We propose improvements to this approach to make it more reliable by using an iterative pre-processing technique to enhance contrast and a glazed finish ceramic tile backing to retain heat longer. We present results which show our calibration board retains heat to reliably detect corners for over 10 minutes; our method performs well in real calibration trials.

1. INTRODUCTION

Camera calibration is the process of determining the camera parameters which map 3D scene points onto a 2D image plane. For stereo or multi-camera systems, the translation and rotation between each camera is also calculated. These parameters are important for many computer vision algorithms such as 3D metric reconstruction, feature matching, and localization, which are useful in military, entertainment, medical, and industrial domains. Thermal or long wave infrared (LWIR) cameras can be complementary or even advantageous when compared to standard color cameras. Thermal cameras can see a scene with no light, is invariant to lighting changes, and is robust to foggy conditions [1]. They are also useful for thermal analysis [2] and even for detecting hidden targets [3, 4].

With standard color cameras, the calibration process has effective methods of accurately determining the camera parameters. The most popular method applies the algorithm described in [5]. This requires reliably detecting corner points in a sequence of images, which is made easy by printing a chessboard calibration pattern with high contrast between the white and black squares. However, in thermal imagery the chessboard pattern is not visible due to a uniform temperature profile.

The purpose of this paper is to discuss a method for increasing the contrast between the squares of the chessboard pattern while not requiring a custom calibration object to be built. This also will allow standard off-the-shelf calibration toolboxes to be more reliably used. To achieve this we used a heat lamp to heat the calibration board. However, for this method to work we had to overcome a few problems:

- Retaining heat long enough to record calibration images
- Correcting for non-uniform heating
- Enhancing/sharpening corners

We use a ceramic backing to retain heat longer. To correct non-uniform heating, we use an iterative pre-processing technique combined with tophat filtering. Finally, to enhance contrast between the squares, we use gamma correction.

The paper is organized as follows. Section 2 gives related works and previous methods to calibrate thermal cameras. Section 3 details our setup and method for calibration. Section 4 explains our experiments and results, including how our calibration method performs in real calibration video sequences and how long it remains effective at successfully calibrating after cooling. Section 5 concludes the paper and gives direction to future work.

2. RELATED WORKS

Standard calibration patterns have uniform temperature in thermal imagery. To get around this problem, a few techniques have been proposed which generally use heated, novel calibration boards made of varying materials. [6] creates a calibration board by cutting out squares to expose the background temperature. [7] mills a chessboard pattern into a printed circuit board with a high emissivity base material and low emissivity copper squares. [2] uses a wire net that is heated with a heat gun. [8] uses a set of resistors mounted

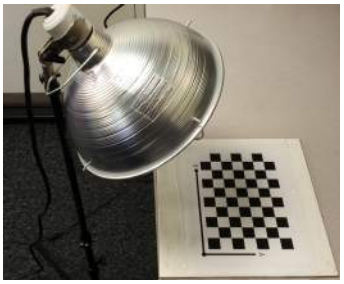

Fig. 1. Our setup includes a printed paper calibration pattern, a glazed finish ceramic tile backing to keep the pattern flat and retain heat, and a 250W heat lamp.

in the center of each square. [9, 10, 11] use a grid of lightbulbs. [12] uses circular thermostatic heaters in a cross-shape pattern. The drawback to many of these methods is that the calibration board needs to be custom made and can be time consuming or expensive to make.

One method that does not require any changes to the standard chess calibration board simply heats it with a flood lamp, as in [13, 14]. However, this method was argued against by [6], which shows that the corners were not sharp enough to reliably detect. The contrast between the squares also decreased quickly – 30 seconds after heating the corners were hard to detect. We propose improvements to the heat-based method that makes it viable for calibration. Our improvements allow calibration to be performed on a single sheet of printed paper instead of a custom made calibration object made of varying materials, and works with off-the-shelf calibration toolboxes.

3. METHOD

3.1. Physical Setup

Our setup can be seen in Figure 1. A printed calibration board is taped to the glazed finish ceramic tile backing in order to keep the pattern flat. ceramic is chosen because of its low thermal moment, which causes it to heat and cool slowly. We study this relationship between heating length, cooling time, and calibration quality in Section 4. The calibration pattern is then heated using a 250W heat lamp, which can reach temperatures up to 550°C, although at 2 feet away the calibration pattern reached 55°C. Next, our pre-processing is applied to a video sequence of calibration images. Finally, we detect corners and calibrate using [5]'s method which is implemented in many off the shelf toolboxes.

3.2. Correction of Non-Uniform Heating

Our processing can be summarized as: Mask out the calibration pattern → Iteratively fit a model to the image intensity and subtract the model from the intensity → Top hat filtering → Gamma correction. Each of these is described below.

Due to the size and position of the heat lamp, the center of the calibration object is heated more than the sides, as can be seen in Figure 3. Although off-the-shelf calibration toolboxes can find some corners, the corner detection is unreliable and inaccurate, as discussed in [6]. Moreover, with non-uniform lighting, standard contrast enhancement techniques fail. By correcting the non-uniform heating, we can increase the usefulness of standard contrast enhancement and reliably obtain more points.

To correct the non-uniform heating, we first mask out the calibration pattern from the rest of the scene. Conveniently, the heated calibration pattern is much warmer than the rest of the scene. This assumption is used to automatically threshold out the calibration pattern using Otsu's method [15].

Next, we fit a model to the intensity data that remains after the masking. Let $I_{mask} = chess\_pattern\_data + parametric\_heat\_model + noise$. Our goal is to model the non-uniform heat and noise, and subtract it out leaving only the chess pattern data. We chose to use a quadratic polynomial to model the intensity. That is

$$p\_h\_m(x,y) = p_{00} + p_{10} * x + p_{01} * y + p_{20} * x^2 + p_{11} * x * y + p_{02} * y^2, \quad (1)$$

where $p_{00}, p_{10}, p_{01}, p_{20}, p_{11}, p_{02}$ are the 6 parameters of the model. The fit is calculated using the Levenberg-Marquardt algorithm [16]. Next we subtract the model from the image $I'(x,y) = I_{mask}(x,y) - p\_h\_m(x,y)$. To account for noise, we repeat this process of fitting and subtracting until the change is under a threshold, $I'_n - I'_{n-1} < \alpha$.

Finally, after this iterative fitting process we perform top hat filtering. Top hat filtering is a morphological operation usually performed to remove non-uniform illumination and is defined as

$$I_{hat} = I - (I \circ S), \quad (2)$$

where $\circ$ is the morphological opening operator with structuring element S.

3.3. Contrast Enhancement

We use standard contrast enhancement via normalization and gamma correction. First, the intensity values are normalized to $[0, 1]$. Then the image is gamma corrected. This can be seen in Equation 3.

$$I_{gamma} = \left(\frac{I - min(I)}{max(I) - min(I)}\right)^{\gamma}. \quad (3)$$

The intensity values are then mapped again to $[0, 1]$, which, depending on gamma, can be a linear or non-linear mapping.

4. EXPERIMENTS AND RESULTS

In our experiments we used two Xenics Gobi 640 GigE uncooled long wave infrared cameras, which each have a resolution of 640x480 and a 50mC sensitivity. We also used two

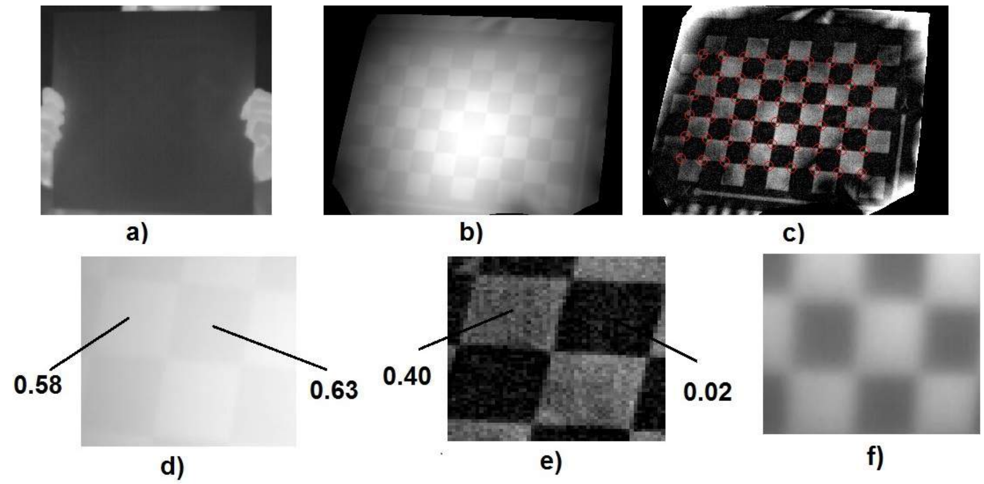

Fig. 2. Comparison of heating effects; note that white pixels denote high temperature. **a)** Unheated calibration board. The intensity is mostly constant. **b)** Heated calibration board. The squares are much more visible, but uneven heating makes corner detection difficult. **c)** Output of our method. Off-the-shelf toolboxes can now easily detect corners. **d)** Zoom in on b). A "white" square actually has a lower intensity than a "black" square, and also the corner is blurry. **e)** Zoom in on c). The light square is now much brighter than the dark square. **f)** The previous method's "best quality calibration image that could be produced using the heated chessboard method." [6]

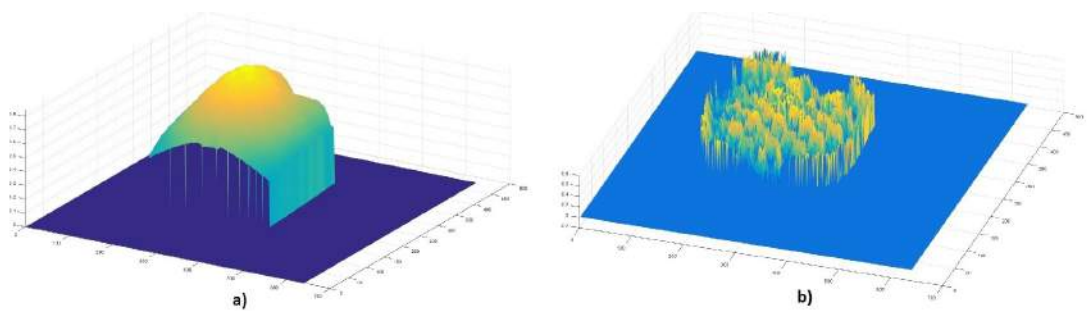

Fig. 3. Heating correction. **a)** A surface plot of the intensity values after heating but before correction. The white/black squares lie along a surface and only slightly perturb the surface. **b)** Surface plot after correction. The "white" squares rise up while the "black" squares stay close to 0. Note that white and black are inverted from color imagery because the black squares absorb and emit more thermal energy.

Point Grey Flea 2G 5MP color cameras, which used a resolution of 1600x1200. All four cameras were synchronized with software triggers and placed on a baseline of 0.25m focused at 1m away. We performed two experiments. The first experiment was to compare different pre-processing variations for enhancing the thermal calibration results. The second experiment was to study the quality of the calibration over time, due to the calibration board losing heat. All experiments were performed at room temperature ($22°C$). We used a disk shaped top-hat structuring element of size 10.

In the first experiment, we placed the calibration board under a heat lamp for 1 hour before recording a calibration video where the board was rotated to different orientations. We repeated this experiment 3 times with trial 1 having 61 images per camera, trial 2 having 46 images, and trial 3 having 63 images. Since each trial gave similar results, we averaged the results which are presented in Table 1. We measure the quality of the reconstruction by the percentage of image pairs with detected corners, the number of corners per image, and the root-mean-square (RMS) error. We tested a few variations of our method: shape fitting with and without iteration, higher order polynomial fitting, using bottom hat vs top hat, and different gamma values.

From Table 1 we noticed that when the number of detected pairs reached a certain threshold, the RMS error was similar between all methods. A more useful metric seemed to be the percentage of pairs of images with detected points. Typically, at least 6 different orientations are needed to give a robust, reliable calibration. In all of the trials, our method gave more than double what is needed for a reliable calibra-

Algorithm	% Pairs	#PtsPerPair	RMS (px)
Proposed (Quad iter fit, top hat, gamma=.8)	**31.40**	**54**	0.48
Quad non-iter fit, top hat, gamma=.8	12.94	48	0.45
No fit, top hat, gamma=.8	1.18	**54**	N/A
Quad iter fit, no hat, gamma=.8	3.53	20	17.01
Quad iter fit, bot hat, gamma=.8	29.40	**54**	0.44
Quad iter fit, top and bot hat, gamma=.8	3.53	20	13.10
Cubic iter fit, top hat, gamma=.8	30.80	**54**	0.45
Quartic iter fit, top hat, gamma=.8	24.70	**54**	**0.41**
Quad iter fit, top hat, no gamma	16.46	**54**	0.47
Quad iter fit, top hat, gamma=.5	29.40	**54**	0.45
Quad iter fit, top hat, gamma=1.15	6.40	**54**	0.46
Color imagery, no processing	50.56	54	0.38

Table 1. Comparison of variations of our pre-processing method averaged over 3 trials of 61, 46, and 63 pairs of images. % pairs measures the number of pairs with detected corners divided by the total number of pairs. The actual number of corners is 54. Note the RMS error is similar for most methods, and any value under 1 is typically acceptable.

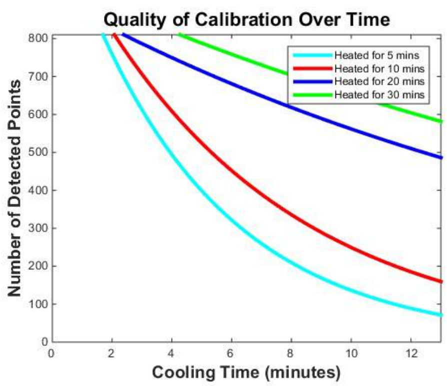

Fig. 4. Detected points over time in increments of 15 seconds. The calibration pattern was in a static, flat pose facing the camera for 15 minutes. The calibration results would become unreliable under 300 detected points. This means that when only heated for 5 mins, the corner detection is reliable for over 10 minutes.

tion. A visual comparison of the quality of our method versus the previous best heating method is shown in Figure 2.

The second experiment we performed was to measure how well our calibration board retains heat to enhance contrast between the squares. To do this we performed four different trials where we heated the calibration board for 5, 10, 20, and 30 minutes and then placed the calibration board in a static, flat angle facing the camera. The camera recorded 15 minutes of video where the calibration board was cooling over time. We plot the number of points detected over time in Figure 4. The number of detected points was measured in increments of 15 seconds. Note that we fit exponential curves to the raw data for visualization purposes.

We used 300 corner points as a cutoff for reliable calibration because it corresponds to about 6 image pairs where all corner points were detected. In the worse case of heating the calibration board for 5 minutes, the corner detection was reliable for over 10 minutes. This is significantly longer than the time calibration was reliable in other works (30 seconds in [6]). We note that our method relies on the assumption that the calibration pattern is much hotter than the rest of the scene from being heated. Thus, if other objects in the scene are of similar temperature or if the pattern cools off too much our method will fail. However, in all the data we recorded, even if humans or computers were in the scene, the calibration board was significantly warmer than the rest of the scene for at least 10 minutes.

5. CONCLUSION

In this paper, we described a physical setup and preprocessing technique to make calibration reliable for thermal cameras using off-the-shelf toolboxes. By taping a printed calibration board to a glazed finish ceramic tile backing, we were able to retain heat to reliably detect corner points for 10-20 minutes – much longer than other works reported [6]. Our pre-processing technique involved masking out the calibration pattern using Otsu's method, iteratively fitting and then subtracting a quadratic polynomial surface from the intensity, applying top hat filtering, and performing gamma correction to the image. We experimented with different variations of these pre-processing steps to come to our final technique. In three different trials, we were able to successfully and reliably calibrate the thermal cameras using our method."Future work includes testing different materials such as steel, aluminum, etc, instead of ceramic for backing the calibration board.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] Kurt Beier and Hans Gemperlein, "Simulation of infrared detection range at fog conditions for enhanced vision systems in civil aviation," *Aerospace Science and Technology*, vol. 8, no. 1, pp. 63 – 71, 2004.

[2] Yiu-Ming, Harry Ng, and R. Du, "Acquisition of 3d surface temperature distribution of a car body," in *Information Acquisition, 2005 IEEE International Conference on*, June 2005, pp. 5 pp.–.

[3] D.T. Anderson, K.E. Stone, J.M. Keller, and C.J. Spain, "Combination of anomaly algorithms and image features for explosive hazard detection in forward looking infrared imagery," *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of*, vol. 5, no. 1, pp. 313–323, Feb 2012.

[4] Philip Saponaro, Kelly Sherbondy, and Chandra Kambhamettu, "Concealed target detection with fusion of visible and infrared," in *Advances in Visual Computing*, George Bebis, Richard Boyle, Bahram Parvin, Darko Koracin, Ryan McMahan, Jason Jerald, Hui Zhang, StevenM. Drucker, Chandra Kambhamettu, Maha El Choubassi, Zhigang Deng, and Mark Carlson, Eds., vol. 8888 of *Lecture Notes in Computer Science*, pp. 568–577. Springer International Publishing, 2014.

[5] Zhengyou Zhang and Senior Member, "A flexible new technique for camera calibration," *IEEE Trans. Pattern Anal. Mach. Intell*, pp. 1330–1334, 2000.

[6] S. Vidas, R. Lakemond, S. Denman, C. Fookes, S. Sridharan, and T. Wark, "A mask-based approach for the geometric calibration of thermal-infrared cameras," *Instrumentation and Measurement, IEEE Transactions on*, vol. 61, no. 6, pp. 1625–1635, June 2012.

[7] V. Hilsenstein, "Surface reconstruction of water waves using thermographic stereo imaging," 2005.

[8] M. Gschwandtner, R. Kwitt, A. Uhl, and W. Pree, "Infrared camera calibration for dense depth map construction," in *Intelligent Vehicles Symposium (IV), 2011 IEEE*, June 2011, pp. 857–862.

[9] S. Lagela, H. Gonzlez-Jorge, J. Armesto, and P. Arias, "Calibration and verification of thermographic cameras for geometric measurements," *Infrared Physics and Technology*, vol. 54, no. 2, pp. 92 – 99, 2011.

[10] Rongqian Yang, Wei Yang, Yazhu Chen, and Xiaoming Wu, "Geometric calibration of ir camera using trinocular vision," *Lightwave Technology, Journal of*, vol. 29, no. 24, pp. 3797–3803, Dec 2011.

[11] A. Ellmauthaler, E.A.B. da Silva, C.L. Pagliari, J.N. Gois, and S.R. Neves, "A novel iterative calibration approach for thermal infrared cameras," in *Image Processing (ICIP), 2013 20th IEEE International Conference on*, Sept 2013, pp. 2182–2186.

[12] Zhang Yu, Shen Lincheng, Zhou Dianle, Zhang Daibing, and Yan Chengping, "Camera calibration of thermal-infrared stereo vision system," in *Intelligent Systems Design and Engineering Applications, 2013 Fourth International Conference on*, Nov 2013, pp. 197–201.

[13] S.Y. Cheng, S. Park, and M.M. Trivedi, "Multiperspective thermal ir and video arrays for 3d body tracking and driver activity analysis," in *Computer Vision and Pattern Recognition - Workshops, 2005. CVPR Workshops. IEEE Computer Society Conference on*, June 2005.

[14] Surya Prakash, Pei Yean Lee, Terry Caelli, and Tim Raupach, "Robust thermal camera calibration and 3d mapping of object surface temperatures," 2006.

[15] N. Otsu, "A threshold selection method from gray-level histograms," *Systems, Man and Cybernetics, IEEE Transactions on*, vol. 9, no. 1, pp. 62–66, Jan 1979.

[16] Donald W. Marquardt, "An algorithm for least-squares estimation of nonlinear parameters," *SIAM Journal on Applied Mathematics*, vol. 11, no. 2, pp. 431–441, 1963.