Multiple Methods of Geometric Calibration of Thermal Camera and A Method of Extracting Thermal Calibration Feature Points

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Abstract—**The thermal camera riches the sensing information by providing temperature features in the environment that visual camera cannot detect. Therefore, accurate geometric calibration for thermal cameras is a crucial step in the thermal geometry-based computer vision applications. Unlike visual cameras, thermal cameras detect temperature, thus the popular checkerboard calibration target cannot be used directly. Additionally, due to the heat transfer between high-temperature area and low-temperature area, region edges and feature points will be blurred and more noises will be on thermal images; thus, existing algorithms cannot detect features as efficiently as on visual images. The paper, in the first part, presents three methods of implementing thermal geometric calibration based on Zhengyou Zhang's [3] calibration method and OpenCV toolkit. The proposed techniques can provide well-organized thermal patterns that consistently and accurately correct the lens distortion. In the second part, the paper propose a template-matching method for extracting the calibration feature points and the target pattern. The evaluation of each calibration target method contains MRE(Mean Re-projection Error) and undistorted images. Both evaluation criteria revealed that the proposed methods accurately and consistently corrected the geometric lens distortion.**

I. Introduction

Geometric calibration is required in existing monocular and multi-view geometry-based computer vision algorithms and applications. Due to the manufacturing process, distortion is introduced to the cameras, making objects appear distorted on the image. Lens distortion increases as the pixel approach to the border of the image. Such optic distortion leads to inaccurate transformation map between 3-dimensional object points and 2-dimensional image points. In the geometry-based vision, an accurate 3D to 2D mapping is required. Therefore, geometric calibration is a crucial step that directly influences the accuracy and performance of algorithms and applications.

This paper introduces three different calibration targets that provide heat pattern for thermal cameras. With these targets, Zhang's [3] algorithm, implemented in OpenCV toolkit, can be performed with thermal cameras. In addition, we propose a template matching method to extract the thermal feature points as the prerequisite for using the existing OpenCV calibration toolkit. The paper then compares the MRE(Mean Re-projection Error) from each calibration target along with the MRE from visual camera calibration with conventional chessboard target to evaluate the quality of the calibration. The proposed calibration methods make the thermal calibration process more convenient and feasible, as well as provide high-quality and accurate thermal geometric calibration results.

II. Problem

Zhengyou Zhang's [3] calibration method is an existing convenient and popular approach to calibrate optic lenses. The conventional Zhang's method uses the cross-points on a chessboard target for geometric calibration. The calibration target performs considerably well with visual cameras; however, it is not suitable for thermal cameras. Since thermal cameras generate images according to the temperature, the chessboard, without temperature variation, cannot be detected by the thermal camera. Therefore, a calibration target with thermal pattern should be used to calibrate thermal cameras.

In addition, visual images have sharp and clear features since color changes sharply. However, due to heat transfer, features are not always clear, making it not feasible to adopt conventional feature detect algorithms. Thus, a robust and efficient thermal feature detection method should be performed to calibrate thermal cameras.

III. Proposed Solutions

We divide this problem into three sub-problems and propose solution for each of the sub-problems:

1) Generate temperature difference that is visible to the thermal camera. We propose three methods to achieve desired thermal patterns.
2) Detect feature points from the feature pattern generated by above methods. We propose a template matching solution to extract accurate features.
3) Geometrically calibrate the intrinsic parameters and distortion coefficients using the feature points got from the previous step. We use Zhang's method [3] to calculate the intrinsic parameters of the thermal camera.

A. Temperature difference generation

1) Hot Wire Method: This method uses the thermal property of electric conductive wires. We can get desired feature points by arranging the wires in a net pattern so that the cross points of the wires can be recognized as features.

We then apply a voltage difference at the ends of the wire so that the current will heat up the wire and generate a visible pattern for the thermal camera.

See appendix A for hardware setup details.

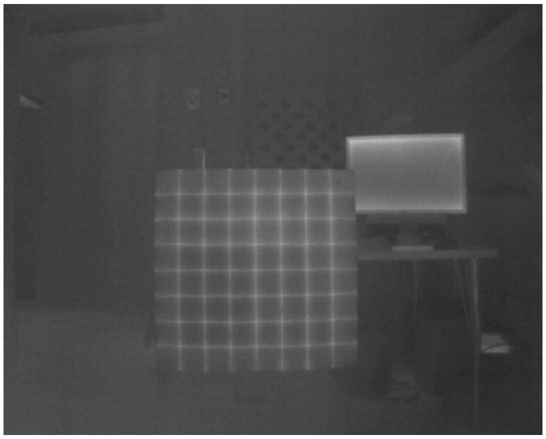


Fig. 1: Wired Board Thermal Image

2) Foam Metal-Plate Method: This method generates temperature pattern by inserting cold aluminum metal disks into normal temperature foam board.

Both the foam and aluminum disks are CNC machined to ensure the accuracy of the circle grid pattern. The foam was machined to have suitable slots to put the aluminum disks into the desired pattern. Thanks to Joseph Bartels [1] who designed the calibration board and Chuck Whittaker [2] who fabricated the device.

The aluminum disks are painted to black, and the foam is pink, making this calibration board compatible with RGB cameras, thus, making it easier to calibrate the extrinsic parameters between the thermal camera and RGB camera if needed.

By cooling the aluminum disks and place them in the slots on the foam sheet, we can generate temperature patterns that enable us calibrate the intrinsic parameters based on an asymmetric circle calibration board.

See appendix A for hardware setup details.

3) Light Heating Normal Calibration Pattern: This method uses light to heat up a normal calibration board, a checkerboard in our case. It utilizes the property that the black part of the checkerboard would absorb more heat from light and thus make the temperature of the black blocks higher than that of white blocks. We tested this method with both lamp and sunlight as light source to heat up the checkerboard. Results will be shown in the following part.

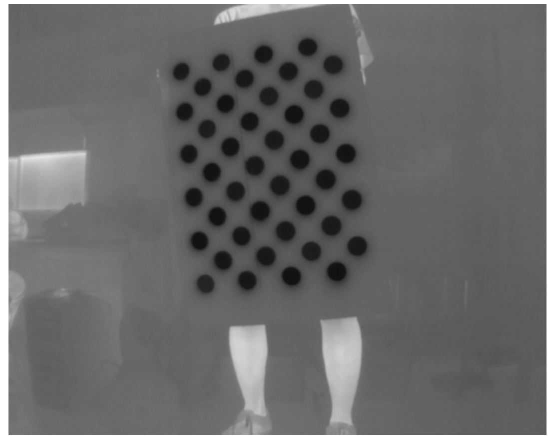


Fig. 2: Foam-Metal Board Thermal Image

Depending on the material of the calibration board, the valid recording time (the duration that the temperature difference remains obvious to the thermal camera) is different from board to board. If the calibration board uses materials with small heat capacitance, then the valid recording time would be shorter.

Since this method directly uses a normal calibration board, the board is also compatible with RGB camera calibration. This method also doesn't require any additional mechanical design and also accurate.

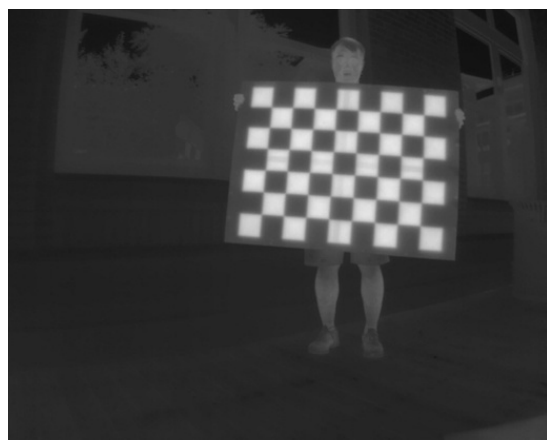


Fig. 3: Checkerboard Thermal Image

B. Template Matching Feature Detection

Motivation: Temperature information does not change as sharply as color information, thus, the edges in a thermal image are blurred. In addition, heat radiation makes the thermal image noisy. Therefore, the existing feature detecting algorithm performs poorly. We propose a template-matching method to accomplish correct and accurate feature points extraction and pattern detection on thermal images.

Methodology: We propose a template-matching method to extract the features on the thermal calibration target.

1) Assumption:

- We have the assumption that the feature points are the same type.
- Only one feature point in a given patch.

2) Procedure:

- Extract template: Select the features we intend to use in the calibration process. Use the selected features as the template patches.
- Template matching: Traverse the thermal image and locate the patches that match with the extracted templates.
- Locate feature point: In a found patch, first, sharpen and threshold the patch. Then, apply a cross-point filter to locate the feature point. If more than one point is found, take the average pixel coordinate.
- Detect pattern: Form the found feature points into the desired rectangular pattern.

See Figure 4.
See appendix B for software details.

C. Geometric Calibration

Zhengyou Zhang's [3] calibration algorithm is a widely-used method in current applications. It is advantageous since it is convenient and easy to use as well as able to achieve accurate calibration results. The thermal geometric calibration in this paper is using the Zhang's [3] calibration method which is implemented in the OpenCV.

Methodology: In Zhang's [3] method, pixels in the pixel-coordinate have the coordinates

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix}$$

and feature points on the calibration board are in the world-coordinate and have the coordinates

$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

Since the calibration board is a flat board, $Z = 0$. Therefore, the projected image pixels and the calibration board have the following relationship:

$$s \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = K[R|T] \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

where RT is the rotation matrix and translation matrix from world-frame to pixel-frame, and K is the camera matrix. In the implementation of OpenCV, the distortion is solved as:

$$x_{corrected} = x * (1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \tag{1}$$

$$y_{corrected} = y * (1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \tag{2}$$

$$x_{corrected} = x + [2p_1 xy + p_2(r^2 + 2x^2)] \tag{3}$$

$$y_{corrected} = y + [p_1(r^2 + 2y^2) + 2p_2 xy] \tag{4}$$

From at least 10 test patterns, the OpenCV is able to solve for the $Distortion\ coefficients = (k_1, k_2, p_1, p_2, k_3)$, and

$$camera\ matrix = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

as well as the rotation matrix, R, and translation matrix, T, for each test pattern.

IV. Results and Analysis

For each setting,

- Wired Board Target
- Foam-metal Board Target
- Chessboard Target(Sunlight)
- Chessboard Target(Lamp)
- Visual Camera with Chessboard

we collected multiple sets of images and used the OpenCV toolkit with the template-atching method to calibrate the thermal camera. Undistorted images were saved and MREs have recorded as well as the intrinsic parameters from each set.

A. Algorithm Performance

The template-matching method successfully and accurately extracted the feature points on thermal images. The proposed algorithm formed the extracted points into a rectangular pattern for later calibration using the OpenCV. See Figure 5. 6. 7.

B. Calibration Quality

We used the undistorted image and the MRE to assess the quality of calibration by each target.

1) Undistorted Image: The undistorted images for all settings, Figure 15. 16, showed reasonable undistorted borders. We compared the original image and the undistorted image to examine the correction. Due to the nature of camera imaging, pixels nearer to the image border experience more distortion. Thus, we focused on lines near the border. We marked red straight lines on the images in order to see the lines were curved.

- The door frame was severely distorted in the original image of the wired board setting. It is back to a straight frame in the undistorted image. See Figure 8 (a)(b).
- The window frame was curved in the original image of the chessboard setting. It is a straight frame in the undistorted image. See Figure 9 (a)(b).

According to the undistorted images, all geometric calibration targets performed considerably high-quality calibration.

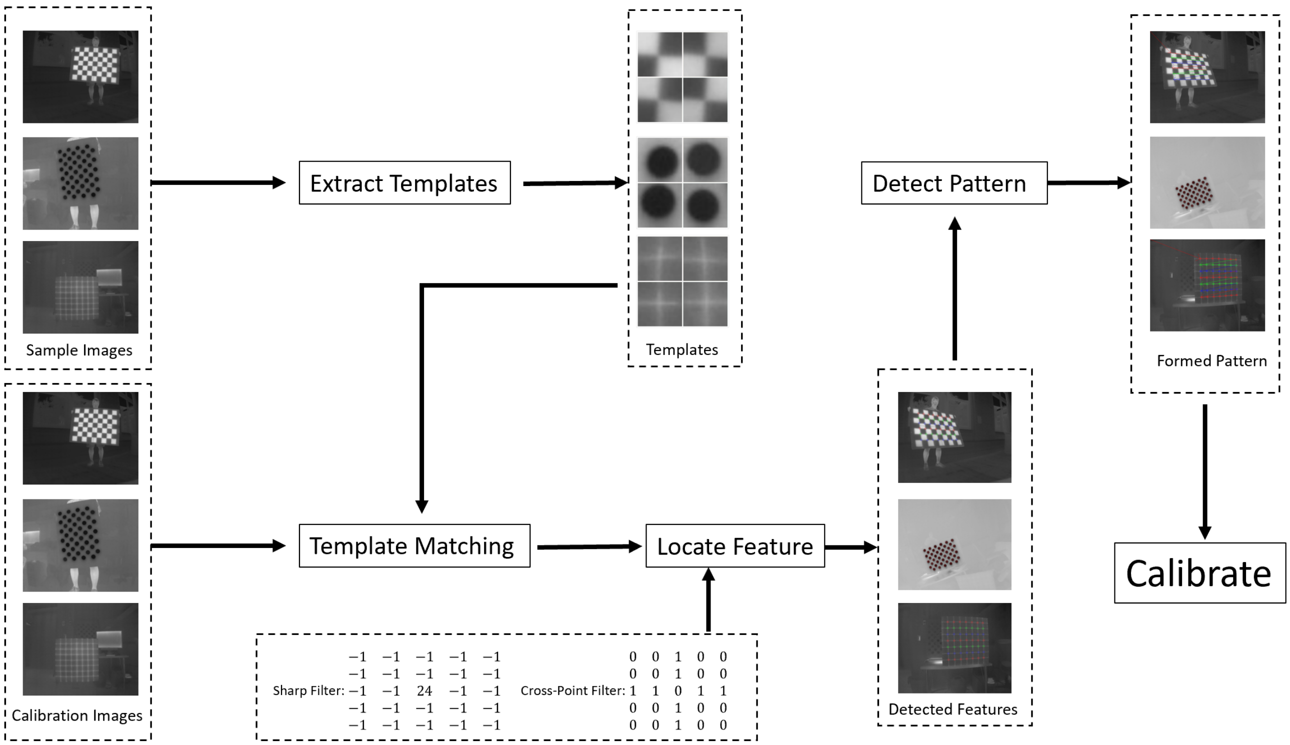
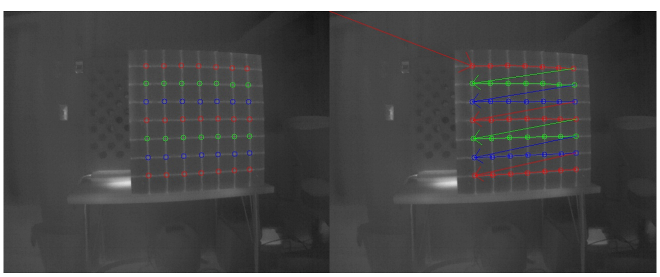
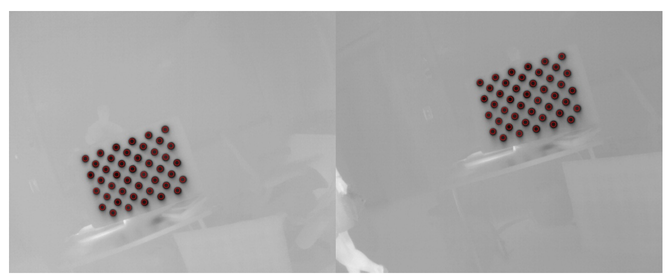


Fig. 4: Template Matching Framework



(a) Extracted Features (b) Ordered Features

Fig. 5: Wired Feature Points



(a) Extracted Features (b) Extracted Features

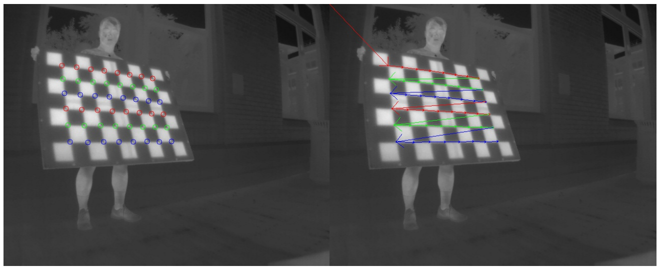
Fig. 6: Circle Feature Points

2) MRE: MRE is the most commonly used criteria to assess the result of a calibration. After we checked the undistorted images, we evaluated the MRE from each calibration result.

Table 1, 2, 3, 4 show the calibration result and the MRE for all sample sets for each calibration set. For each setting, the standard deviation is small for each intrinsic parameter, which indicates that the certain target board works consistently as a geometric calibration target for the thermal camera. The comparison in Table 4 between chessboard heated by sunlight and lamp shows that the results varied significantly. This indicates that the quality of calibration using chessboard depends heavily on the heating source. The chessboard target will perform better if the heating source is able to provide even and strong heat radiation.

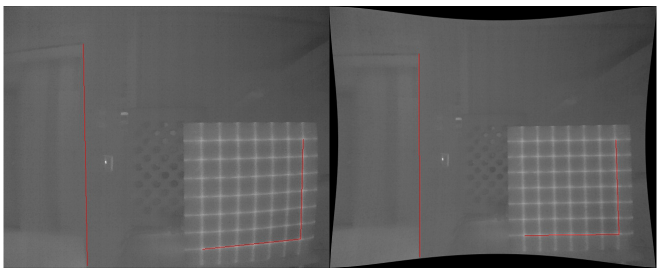
In terms of MRE, the MRE for each sample of each setting was below than 0.2. From Table 5, the visual camera calibration can achieve an MRE value of 0.02485. The MREs achieved by the wired board and chessboard with sunlight was close to the visual camera calibration result, lower than 0.1. Table 6. The result indicates a high-quality geometric calibration was accomplished.

Comparing the results from the different settings, the chessboard target with sunlight achieved an average MRE of 0.0325, which was lower than that of the wired board target, 0.0695 and



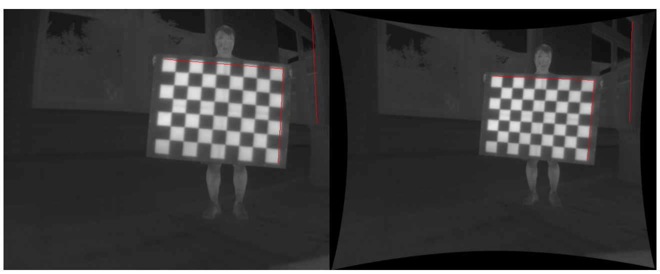
(a) Extracted Features (b) Ordered Features

Fig. 7: Chessboard Feature Points



(a) Original (b) Undistorted

Fig. 8: Wired Board Target



(a) Original (b) Undistorted

Fig. 9: Chessboard Target

that of the foam-metal target, 0.198. The lower MRE represents that the chessboard target accomplished a better quality of the geometric calibration.

V. Conclusions and Recommendations

The report presents a template-matching method for extracting the calibration target feature points and three geometric calibration targets for the thermal camera. The method presents a reliable and accurate way to extract feature points in thermal images, providing the prerequisite to accomplishing high-quality geometric calibration. Based on the proposed algorithm, the three proposed geometric calibration methods presented high-quality calibration. In terms of MRE, the value

TABLE I: Wired Calibration Result

Sample Img Set	**1**	**2**	**3**	**Avg**	**Std**
fx	529.960	526.196	528.913	528.356	1.943
fy	530.557	526.079	528.668	528.435	2.248
cx	332.462	328.386	325.665	328.838	3.421
cy	263.000	254.681	265.239	260.973	5.563
k1	-0.333	-0.327	-0.334	-0.331	0.004
k2	0.106	0.089	0.123	0.106	0.017
p1	0.001	0.001	0.001	0.001	0.000
p2	-0.001	0.0004	0.004	0.001	0.003
k3	0.042	0.088	0.031	0.054	0.031
MRE	0.0624	0.0728	0.0734	0.0695	0.0062

TABLE II: Foam-metal Calibration Result

Sample Img Set	**1**	**2**	**3**	**Avg**	**Std**
fx	531.404	524.461	530.632	528.832	3.107
fy	530.642	523.928	529.233	527.934	2.890
cx	324.194	323.846	323.531	323.857	0.270
cy	266.504	261.785	265.105	264.464	1.979
k1	-0.359	-0.348	-0.357	-0.354	0.004
k2	0.172	0.150	0.165	0.162	0.009
p1	-0.0006	0.0001	0.0001	-0.0004	0.0003
p2	-0.001	0.0004	0.004	0.002	0.002
k3	-	-	-	-	-
MRE	0.197	0.195	0.204	0.198	0.003

TABLE III: Chessboard(Sunlight) Calibration Result

Sample Img Set	**1**	**2**	**3**	**Avg**	**Std**
fx	532.081	534.649	532.470	533.067	1.384
fy	533.173	536.718	534.010	534.633	1.853
cx	319.687	319.252	321.726	320.222	1.321
cy	265.597	259.871	267.387	264.285	3.926
k1	-0.364	-0.353	-0.367	-0.362	0.007
k2	0.224	0.239	0.257	0.240	0.016
p1	-0.001	-0.001	-0.001	-0.001	0
p2	0.002	0.002	0.002	0.002	0
k3	-0.084	-0.200	-0.147	-0.144	0.058
MRE	0.0319	0.0333	0.0324	0.0325	0.0007

TABLE IV: Chessboard Lamp vs Sunlight

Sample Img Set	**Lamp**	**Sunlight**	**Abs Diff**
fx	559.002	533.067	25.935
fy	558.695	534.633	24.062
cx	342.591	320.222	22.369
cy	264.795	264.285	0.510
k1	-0.277	-0.362	0.085
k2	-0.279	0.240	0.519
p1	0.001	-0.001	0.002
p2	-0.001	0.002	0.003
k3	0.833	-0.144	0.977
MRE	0.1085	0.0325	0.0760

TABLE V: Visual Camera Calibration with Chessboard

Sample Img Set	**1**	**2**	**3**	**4**	**Avg**
MRE	0.0222	0.0231	0.0297	0.0244	0.02485

TABLE VI: MRE Comparison

Sample Img Set	Wired	Foam	Chessboard Sunlight	Visual
MRE	0.0695	0.198	0.0325	0.02485

of MRE for each sample set of each calibration setting was smaller than 0.2. The values of MRE for wired board and chessboard with sunlight were lower than 0.1, which indicated a high-quality geometric calibration.

The chessboard target heated by sunlight achieved the lowest MRE, 0.0325, among all settings. The discrepancy in MREs between the different settings might be caused by the inaccuracy in manufacturing, heat radiation, and indirect feature points.

For the foam board target, the pattern was clear; however, the feature points were indirect. Indirect feature points may lead to inevitable error in feature extraction. For example, for the asymmetric circle pattern, the feature points are the center of the circles. When the target was no longer parallel to the image plane, circles became ellipses and the extracted feature points may deviate since the center points were not directly viewable.

For the wired board target, it is possible that tightened wires could intersect slightly away from the cross-point locations we desired, which could potentially cause higher MREs.

Even though the chessboard target achieved the best MRE, each calibration target has advantages and disadvantages in terms of feasibility, consistency, and manufacturing difficulties.

Wired Board:

- Advantages: The wired board target showed high consistency. The target consistently achieved low MRE. It doesn't affect by the environment or weather.
- Disadvantages: The manufacture process is relatively complicated. In addition, since the target was heated by electrical power, it would be unsafe to move the target during the calibration process.

Foam-metal Board:

- Advantages: The foam-metal target achieved consistent results. It is convenient and easy to use.
- Disadvantages: The manufacturing process is relatively complicated, requiring CNC machining to achieve high precision. In addition, indirect feature points lead to relatively high MRE.

Chessboard:

- Advantages: The chessboard target is easy to build and easy to use.
- Disadvantages: The quality of calibration depends heavily on the heating method, which leads to potentially inconsistent quality of the calibration. It is vulnerable to the light source.

In conclusion, the report propose a reliable and accurate template-matching method, which could be used to extract feature points in thermal images, and three thermal camera geometric calibration methods, which could provide high-quality geometric calibration. The report also recommends using the wired board and the chessboard with uniform light heating, sunlight in our case, since it presented the best performance in our experimentation and provided a convenient and feasible thermal geometric calibration.

APPENDIX A
MECHANICAL DESIGN FILES

A. *hot wire method*

In this section, our goal is to construct crosses of the wires and use them as features to calibrate the thermal camera. To reveal the wires in the thermal images, we set up an electrical current and thus heating up the wire.

We fabricated the device shown in the following pictures. Here is some information about this device:

- We used nickel-chromium wire as the heating resistance wire because nickel-chromium has suitable resistance for heating application. And we chose a 24*24 inch acrylic board as the baseboard for the calibration target.
- We used a laser cutter to cut small channels on the acrylic board to outline the pattern, which also helped to deploy the wire.
- We used a 30V/5A power supply to power the wire, and the wire has total resistance around 100 ohms. The temperature rise is not obvious but can be detected by the thermal camera.
- When building the target, make sure to insulate the wire at the cross point. We used tape to insulate the wire both at the front and back. The tape also helped to align the crossing wire with the pattern.

See Figure 1. 2. 3. 4.

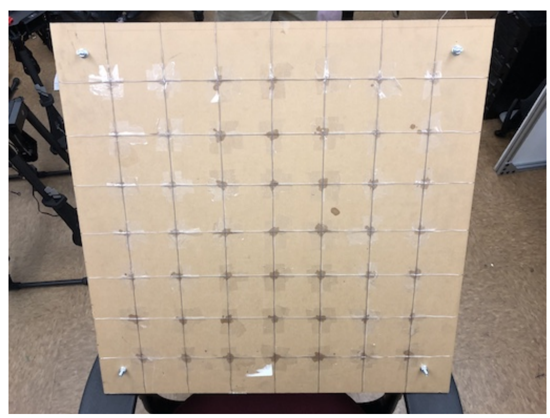


Fig. 10: Wired Calibration Target Front

B. *Foam-Metal Plate Method*

In this section, our goal is to construct an asymmetric circle grid calibration pattern that can be recognized by the thermal camera. Here are the steps for hardware setup:

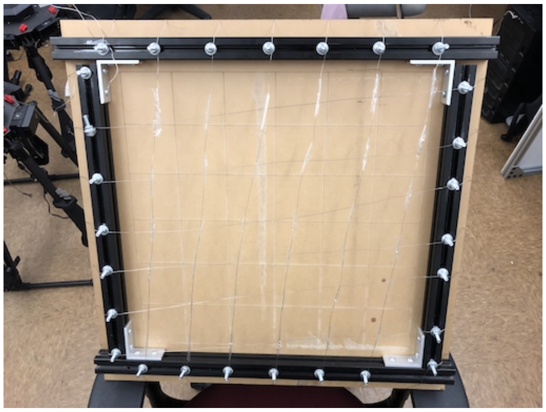


Fig. 11: Wired Calibration Target Back

Fig. 12: Wired Calibration Board Setup

1) Put the aluminum disks in a refrigerator or cold water to cool down the plates. Usually a duration of 5 minutes is sufficient for the calibration.
2) Wipe the water on the aluminum plates to ensure good temperature pattern.
3) Insert the aluminum disks into the foam sheet.
4) Start calibration.

See Figure 15. 16.

C. *Light Heating Normal Calibration Pattern*

Here are the steps for hardware setup:

1) Put the checkerboard under sunlight for 10 minutes. See Figure 17.
2) Start calibration.

Note: When exposing the calibration board to the light, try to make the light evenly distributed over the board surface, so that the temperatures of the same color blocks are relatively same. Using the sunlight is our option here and it worked well.

Fig. 13: Foam-Metal Calibration Target Setup

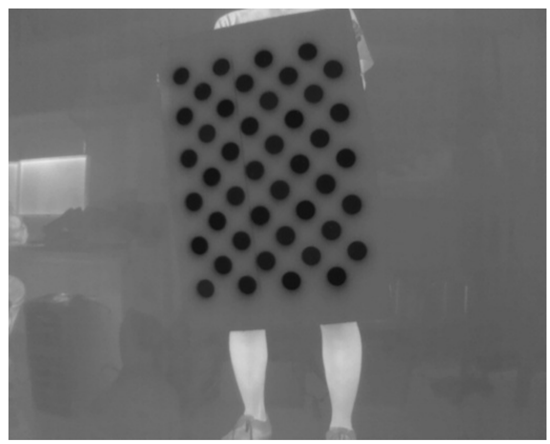


Fig. 14: Foam-Metal Board Thermal Image

D. *CAD files*

https://grabcad.com/library/hot-wire-thermal-camera-calibration-board

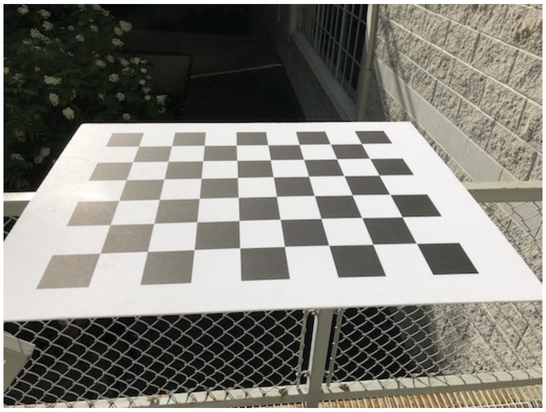


Fig. 15: Exposing Checkerboard Under Sunlight

APPENDIX B
SOFTWARE

- Thermal Calibration Pipeline: https://bitbucket.org/castacks/flir_thermal_camera_calibration/src/master/
- See the README.md for detail instruction on using the calibration tool.

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[2] Chuck. Whittaker, manufacturing of the foam-metal calibration board. Staff, the Robotics Institute, Carnegie Mellon University.

[3] Z. Zhang, "A Flexible New Technique for Camera Calibration" in *MSR-TR-98-71* Available: https://www.microsoft.com/en-us/research/wp-content/uploads/2016/02/tr98-71.pdf.