# Geometric Thermal Infrared Camera Calibration for Target Tracking by a Mobile Robot

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**Abstract.** Geometric calibration of thermal cameras is an important primary step in applications where thermal vision is employed for the localization of thermal objects within the field of view of the camera. The geometric thermal camera calibration method proposed in this paper provides camera parameters used for the transformation of the thermal objects coordinates from the 3D world reference frame to 2D image frame and vice versa based on a low cost test pattern prepared for thermal camera calibration. The accuracy and functionality of the suggested method in real world applications are verified by applying it to a mobile robot equipped with a thermal camera for tracking a human target.

**Keywords:** Thermal Imaging, Geometric Camera Calibration, Thermal Object Localization and Tracking.

## 1. Introduction

Thermal infrared cameras are sensitive to objects thermal radiation, which is not visible by human eye (Fig.1).

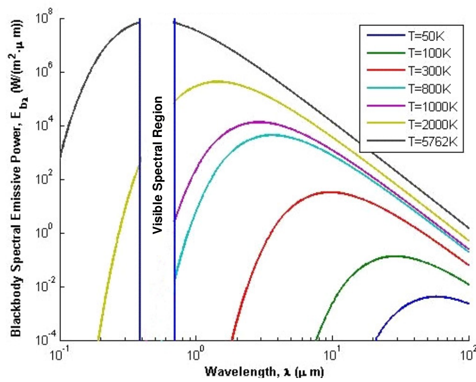



**Fig. 1.** Spectral blackbody emission power

Thermo visual technology is employed in a wide range of applications such as thermal monitoring of industrial systems, thermal imaging systems used in research, medicine, security, night vision, surveillance, rescue, etc. Thermal cameras capture thermal information from the surrounding environment and visualize the scanning results often in a 2D color map image in which the intensity of the infrared radiation emitted by objects is mapped using different colors. Geometric calibration of thermal cameras is an important primary step in thermal vision applications especially for the localization of thermal objects within the field of view of the camera, for example in mobile robotics, thermal images are used for people recognition and tracking [1, 2, 3, 4, 5, 6]. In this paper is proposed a special geometric thermal camera calibration method based on a low cost test thermal pattern and suitable in real world mobile robot algorithms for tracking a human as target.

## 2. Model Description of the Proposed Geometric Calibration Method for Thermal Infrared Camera

The coordinate systems used for thermal camera calibration is presented in Fig.2. $P_O=(x_0,y_0,z_0)$ and $P_C=(x_C,y_C,z_C)$ are object coordinates with respect to its local frame and camera frame, respectively. $P_I=(u_i,v_i)$ is object coordinates in the image plane in pixels.

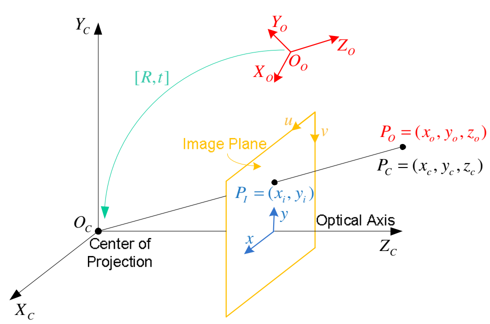



**Fig. 2.** Coordinate systems used in thermal camera calibration procedure.

If $f$ is the focal length of the camera, then the object local frame with respect to the camera reference frame is represented by a 3 x 3 rotation matrix $R$ and a 3 x 1 translation vector $t$ (equation 1).The coordinates of the corresponding point projected to the image plane and projected point in the image plane is represented in pixels $(u_i^{'},v_i^{'})$ using equations 2 and 3:

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \underbrace{\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}}_{R} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} + \underbrace{\begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix}}_{t} \quad (1) \qquad \begin{bmatrix} x_i \\ y_i \end{bmatrix} = \frac{f}{z_c} \begin{bmatrix} x_c \\ y_c \end{bmatrix} \quad (2) \qquad \begin{bmatrix} u_i' \\ v_i' \end{bmatrix} = \begin{bmatrix} D_u s_u x_i \\ D_v y_i \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \end{bmatrix}, \quad (3)$$

where $s_u$ the scale factor, $D_u, D_v$ are coefficients for conversion from metric units to pixels, $[u_0\ v_0]^T$ is principal point. Here, only two coefficients are considered for each distortion. The radial and tangential distortions are modeled by equation (4) and equation (5), respectively.

$$\begin{bmatrix} \Delta u_i^{(r)} \\ \Delta v_i^{(r)} \end{bmatrix} = \begin{bmatrix} x_i (k_1 r_i^2 + k_2 r_i^4) \\ y_i (k_1 r_i^2 + k_2 r_i^4) \end{bmatrix} \quad (4) \qquad \begin{bmatrix} \Delta u_i^{(t)} \\ \Delta v_i^{(t)} \end{bmatrix} = \begin{bmatrix} 2 p_1 x_i y_i + p_2 (r_i^2 + 2 x_i^2) \\ p_1 (r_i^2 + 2 y_i^2) + 2 p_2 x_i y_i \end{bmatrix}, \quad (5)$$

where $k_1, k_2$ are radial distortion coefficients, $r_i = \sqrt{x_i^2 + y_i^2}$ and $p_1, p_2$ are tangential distortion coefficients.

Therefore, using the distorted coordinates $(\tilde{u}_i, \tilde{v}_i)$ , the general camera calibration model is obtained by combining the pinhole model and radial and tangential distortions:

$$\begin{bmatrix} u_i \\ v_i \end{bmatrix} = \begin{bmatrix} \alpha_u \tilde{u}_i \\ \alpha_v \tilde{v}_i \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \end{bmatrix} = \begin{bmatrix} D_u s_u (x_i + \Delta u_i^{(r)} + \Delta u_i^{(t)}) \\ D_v (y_i + \Delta v_i^{(r)} + \Delta v_i^{(t)}) \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \end{bmatrix} \quad (6)$$

The camera calibration parameters can be estimated linearly using Direct Linear Transform (DLT) method [7]. In this approach nonlinear radial and tangential distortions are ignored and transformation from object local frame to image frame is assumed to be linear using the homogeneous 3 x 4 matrix, *M* (equation 7). Equation 8 is valid if eliminating the depth value, $w_i$ , for each control point $(x_i, y_i, z_i)$ and $j = 1,2,\ldots N$ .

$$\begin{bmatrix} u_i w_i \\ v_i w_i \\ w_i \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ 1 \end{bmatrix} \quad (7) \qquad L_j m = 0;\ j = 1,2,\ldots,N \ , \quad (8)$$

where $m = [m_{11}, m_{12}, m_{13}, m_{14}, m_{21}, m_{22}, m_{23}, m_{24}, m_{31}, m_{32}, m_{33}, m_{34}]^T$ ;

$$L_j = \begin{bmatrix} x_j & y_j & z_j & 1 & 0 & 0 & 0 & 0 & -x_j u_j & -y_j u_j & -z_j u_j & -u_j \\ 0 & 0 & 0 & 0 & x_j & y_j & z_j & 1 & -x_j v_j & -y_j v_j & -z_j v_j & -v_j \end{bmatrix}$$

By replacing $(u_j, v_j)$ with the coordinates of the observed points $(U_j, V_j)$, the values of $m_{11},\ldots,m_{34}$ can be estimated using the least squares method. In order to avoid singularities, in [8] is proposed to use the constraint $m_{31}^2 + m_{32}^2 + m_{33}^2 = 1$ .

## 3. Algorithm of the Proposed Geometric Calibration Method for Thermal Infrared Camera

The chessboard pattern is a very popular pattern for geometric camera calibration. Therefore, the suggested pattern is a planar chessboard pattern containing two materials with different emissivity properties (Fig.3.(a) visual and Fig.3.(b) thermal camera view).


(a) (b)

**Fig. 3.** (a) Test pattern Visual view. (b) Thermal image view

The main steps of the thermal camera calibration process are:

- Capture a sequence of test thermal images representing chessboard patterns with varying depth and angle;
- Initialize grid corner extraction interactively (The user inputs grid corners and information about grid cell dimension;
- Extract all grid corners;
- Initialize camera calibration. (Initial guess values are computed using DLT method);
- Nonlinear optimization of camera calibration parameters;
- Visualization and analysis of the results of thermal camera calibration;
- Thermal image correction based on computed calibration parameters for tracking a human target by a mobile robot.

Assuming that during image observation only Gaussian noise is present and systematic measurement noise is compensated, camera calibration parameters are computed by minimizing the least square error between the observed coordinates and the coordinates computed based on the calibration model (equation 6). Considering N corner observations $\{(U_1,V_1),...,(U_N,V_N)\}$, least squares method is used to minimize equation (9).

$$E^2 = \sum_{i=1}^{N}(U_i - u_i)^2 + \sum_{i=1}^{N}(V_i - v_i)^2 \qquad (9)$$

Because the calibration model is nonlinear, calibration parameters are estimated iteratively by minimizing equation (9) using the Levenberg–Marquardt algorithm (LMA). In order to avoid the local minimum problem during the iterative optimization process, the initial values of the parameters are computed using the DLT method. Computed camera calibration parameters are used for image correction. Below is presented the image correction Algorithm 1. First, a 40 x 40 grid with tie-points $(x_i, y_i)$ is generated, covering the entire image. Distorted coordinates $(\tilde{u}_i, \tilde{v}_i)$ of the corresponding tie-points are calculated. Then, parameters $a_1,\ldots,a_8$ of equation (10) are estimated iteratively using the least squares method in order to calculate the undistorted coordinates.

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = \frac{1}{N} \begin{bmatrix} \tilde{u}_i\left(1 + a_1 r_i^2 + a_2 r_i^4\right) + 2a_3 \tilde{u}_i \tilde{v}_i + a_4\left(r_i^2 + 2\tilde{u}_i^2\right) \\ \tilde{v}_i\left(1 + a_1 r_i^2 + a_2 r_i^4\right) + 2a_3 \tilde{u}_i \tilde{v}_i + a_3\left(r_i^2 + 2\tilde{v}_i^2\right) + 2a_4 \tilde{u}_i \tilde{v}_i \end{bmatrix}, \quad (10)$$

where $N = \left(a_5 r_i^2 + a_6 \tilde{u}_i + a_7 \tilde{v}_i + a_8\right) r_i^2 + 1$ and $r_i^2 = \tilde{u}_i^2 + \tilde{r}_i^2$.

**Algorithm 1. Image correction algorithm**

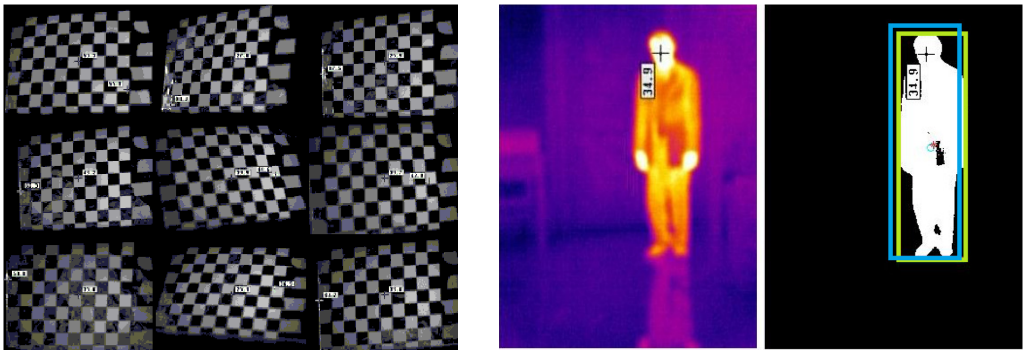
1. Generate a $40\times40$ grid with distorted and undistorted tie-points $(x_i, y_i)$ and $(\tilde{u}_i, \tilde{v}_i)$, covering the entire image.
2. Calculate the corresponding distorted coordinates $(\tilde{u}_i, \tilde{v}_i)$.
3. Estimate parameters $a_1,\ldots,a_8$ for calculation of the undistorted coordinates iteratively using the least squares method.
4. Compute the corrected undistorted coordinates $(x_i, y_i)$ based on the estimated parameters.
5. Calculate all actual coordinates of the image by interpolation based on $(\tilde{u}_i, \tilde{v}_i)$ and the new $(x_i, y_i)$.

Once the parameters are estimated, equation (10) can be employed for the computation of the corresponding undistorted coordinates. Actual coordinates of the points of the image are calculated by interpolating the computed distorted and corresponding undistorted results.

## 4. Experimental Results

The proposed algorithm for geometric calibration of thermal camera is tested with a sequence of thermal images from the proposed planar chessboard pattern. Based on the estimated calibration results (Table 1), image correction is performed on the images captured by the thermal camera for tracking the human target. On Fig.4 are shown comparative results of human detection without and with correction.

A thermal image and target detection results with and without image correction are displayed.



(a) (b) (c)

**Fig. 4.** Sequence of test pattern for calibration (a). Input thermal image (b). Results of human detection without (in blue) and with correction (in green)

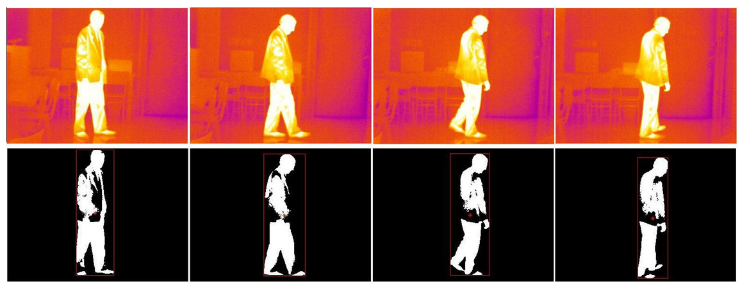
Table 1 presents the intrinsic parameters of the thermal infrared camera EasIR™-9.

| Parameter | $f_u(pixels)$ | $f_v(pixels)$ | $u_0(pixels)$ | $v_0(pixels)$ | $k_1^{(r)}$ | $k_2^{(r)}$ | $k_1^{(t)}$ | $k_2^{(t)}$ |
|---|---|---|---|---|---|---|---|---|
| Value | 1100.45 | 1116.10 | 300.22 | 306.93 | -0.08 | -0.01 | 0.02 | 0.03 |
| Standard deviation | 19.54 | 19.88 | 0.0 | 0.0 | 0.05 | 0.263 | 0.003 | 0.002 |

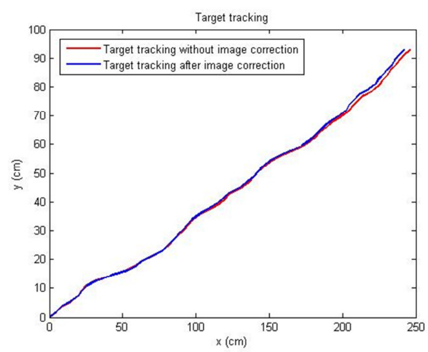
**Table 1.** Results of thermal infrared camera EasIR™-9 geometric calibration

The intrinsic parameters are $\{(f_u, f_v), (u_0, v_0), (k_1^{(r)}, k_2^{(r)}), (k_1^{(t)}, k_2^{(t)})\}$, in which: $(f_u, f_v)$ is the focal length in pixels; $u_0, v_0$ are the coordinates of the principal point in pixels; $k_1^{(r)}, k_2^{(r)}$ present radial lens distortion coefficients and are related to the radial distortion coefficients described by $k_1^{(r)} = f^3 k_1$ and $k_2^{(r)} = f^5 k_2$ ; $k_1^{(t)}, k_2^{(t)}$ present tangential lens distortion coefficients and are related to the tangential distortion coefficients described by $k_1^{(t)} = f^2 p_1$ and $k_2^{(t)} = f^2 p_2$ .

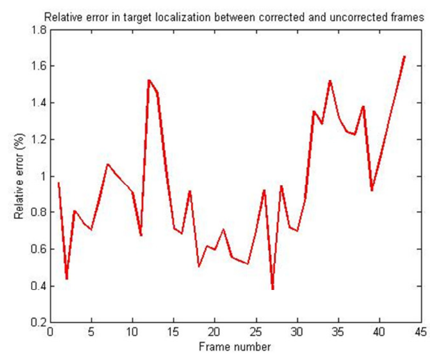
In Fig. 5 is show an example of human target detection and tracking with the resultant paths and relative error from target tracking with and without correction.



(a)




(b)




(c)

**Fig. 5.** (a) Four frames of the video captured by the thermal camera and target detection applied on the corrected images. (b) Resulting paths from target tracking with and without image correction. (c) Relative error between the two paths.

The experimental results prove the effectiveness of the calibration method based on the proposed test pattern for thermal camera calibration in real world applications like target tracking by a mobile robot. The relative error between two paths from target tracking with and without image correction is sufficient small (approximately 1.6% maximal error as is seen from Fig.6. c).

## 5. Conclusion

The proposed in this article geometric thermal camera calibration method with low cost test pattern provides distinct and well defined corners in the set of thermal images. The calibration method based on this pattern extend considerably the results of human target tracking by a mobile robot equipped with a thermal camera. Future researches will be directed to combine the proposed thermal infrared camera calibration method with the laser range finder calibration.

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