Thermo Vision Camera Space Calibration Method in Area of Mobile Robots Observation

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Abstract: The existing popular methods of thermo vision camera calibration are for temperature range adjustment using reference temperature sources and test thermal images. Correct temperature calibration of a thermal or infrared camera allows the inspector to be certain of the temperature measurements presented in the thermal images given from a calibrated thermal or infrared camera. Also in each thermo visual images processing method is very important to use temperature calibration of thermo and infrared cameras as sources of thermal images. Here is proposed a space calibration method for the thermal or infrared camera. The space calibration is of superior importance in applications where thermal or infrared cameras are applied for 2D or 3D thermal objects localization and their position calculation, for example when a mobile robot detect and determine the position of thermal objects in area of observation. The proposed in this article space calibration method for thermal or infrared camera is presented first with a theoretical model, described as algorithm and then tested for a concrete mobile robot application.

Keywords: Thermo Vision, Space Camera Calibration, Mobile Robots Thermal Objects Detection

1. Introduction

Thermal and infrared cameras are sensitive to temperature and are used as sensors or sources of thermal or infrared images [1]. Thermal imaging technologies are now suitable for wide range of applications such as thermal monitoring industrial systems, thermal imaging systems for use in research, medicine, security, night vision, surveillance, rescue, etc. [2, 3]. There are methods of temperature calibration for thermo vision cameras [4, 5, 9]. The calibration in these methods (Fig.1.) is based on temperature range measurements and adjustment using reference temperature sources and test thermal images [6]. Temperature calibration of a thermal or infrared camera allows to extend the precision of the the temperature measurements presented in thermal images given from a calibrated thermal or infrared camera. Also in each thermo visual images processing method is very important to do temperature calibration of thermo and infrared cameras as sources of thermal images. This happen for example, when is needed to known, with a suitable precision, the temperature of an object find in thermal image.

Fig.1. Temperature calibration for thermo vision cameras

The goal of this article is to propose a space calibration method for the thermal camera. The space calibration is of superior importance in applications where thermal or infrared cameras are applied for 2D or 3D thermal objects localization and their position calculation, for example when a mobile robot detect and
determine the position of thermal objects in area of observation. The proposed in this article space calibration method for the thermal or infrared camera is presented first with a theoretical model, described as algorithm and then tested for a concrete mobile robot application.

2. Model description of the proposed space calibration method for thermal or infrared camera

The coordinate systems used in thermal camera calibration procedure is presented in Fig.2 [7,8].

![Coordinate systems used in thermal camera calibration procedure](Image)

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

In Fig.2 is presented a three dimensional coordinate system in which is placed the thermal or infrared camera. The origin of this coordinate system is at the centre of projection and whose Z axis is along the optical axis. An object in the area of thermal or infrared camera observation is considered in Fig.2 with their mass of gravity M have a relevant point M with coordinates (X,Y,Z). Regarding to the centre of the projection point or mass of gravity M have a relevant point m with coordinates (x, y) in the thermal image plane. These coordinates are with respect to a coordinate system (c,x,y) whose origin is at the intersection of the optical axis and the image plane, and whose x and y axes are parallel to the X and Y axes of coordinate system (C,X,Y,Z):

\[
x = \frac{Xf}{Z}, \quad y = \frac{Yf}{Z},
\]  

(1)

where \( f \) is the focal length.

The relationship between the two systems of coordinates (c,x,y) and (C,X,Y,Z) is given by linear transformation in homogeneous coordinates:

\[
\begin{bmatrix}
s_x \\
s_y \\
s
\end{bmatrix} =
\begin{bmatrix}
f & 0 & 0 & 0 \\
0 & f & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix},
\]  

(2)

where

\( s \) is the scale factor.

The equation (2) can be rewritten for the actual pixel coordinates (u,v), defined with respect to an origin in the top left hand corner of the image plane (Fig.2.):

\[
\begin{bmatrix}
su \\
sv \\
s
\end{bmatrix} =
\begin{bmatrix}
f / k_x & 0 & 0 & 0 \\
0 & f / k_y & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix},
\]  

(3)

where

\( k_x, k_y \) are scaling factors.

Following this method of coordinate transformations is possible to define the thermal or infrared camera calibration matrix:

\[
C =
\begin{bmatrix}
\alpha_x r_1 + u_x r_3 \\
\alpha_y r_2 + v_y r_3 \\
r_3
\end{bmatrix},
\]  

(4)

where

\( r_1, r_2, r_3 \) are row vectors of rotation matrix \( R \);

\( t = (t_x, t_y, t_z) \) - the homogeneous vector of homogeneous transformation matrix \( K \) capturing the thermal camera displacement from the world frame origin:

\[
K =
\begin{bmatrix}
R & t \\
0^T & 1
\end{bmatrix},
\]  

(5)

\( R \) - a 3 x 3 rotation matrix \( R \) and encodes the camera orientation with respect to a given world frame;

\( \alpha_x, \alpha_y, u_x, u_y, t_x, t_y, t_z \) - parameters which do not depend on the position and orientation of the camera in space, and are called the intrinsic parameters of thermal or infrared camera.

The matrix \( K \) has six degrees of freedom, three for the orientation, and three for the translation of the thermal or infrared camera. These parameters are known as the extrinsic thermal or infrared camera parameters.

The space calibration of thermal or infrared cameras is the process of estimating the intrinsic \((\alpha_x, \alpha_y, u_x, u_y)\) and extrinsic \((r_1, r_2, r_3, t)\) parameters of a thermal or infrared camera. Therefore, the equation (4) of thermal or infrared camera calibration can be rewritten in the following form:
where
\[ q_i^T = q_{i1} + q_{i2} + q_{i3} + q_{i4}, \] for \( i = 1, 2, 3, 4 \).

If it is assumed that scale factor \( s=1 \), then for each point \( M_i \) (Fig 1) with space coordinates \((X_i, Y_i, Z_i)\) and a relevant point \( m_i \) with coordinates \((x_i, y_i)\) in the thermal image plane is possible to define:
\[
q_i^T M_i - u_i q_{i1} M_i + q_{i4} - u_i q_{i4} = 0,
\]
\[
q_i^T M_i - v_i q_{i1} M_i + q_{i4} - v_i q_{i4} = 0,
\]
or in matrix form:
\[ Lq = 0, \] (8)
where
\[ L \] is a \( 2N \times 12 \) matrix;
\[ q \] is a \( 12 \times 1 \) vector.

Using a set of point \( M_i \) for \( i=1, 2, 3, \ldots N \) with space coordinates \((X_i, Y_i, Z_i)\) is possible to build up a matrix with \( 2N \times 11 \) dimension. There are 11 unknowns and each point providing 2 constraint equations, therefore it is need at least six points from thermal images to solve the system equation (7) or matrix equation (8).

It is seen than the equation (7) or (8) is just a system of linear equations, which must be solve for \( q \). Constraints must be imposed upon \( q \), to avoid the trivial solution \( q = 0 \). It is natural to use the constraints given by the structure of the matrix \( C \):
\[
\| q_3 \|^2 = 1 \text{ and } (q_1 \wedge q_3). (q_2 \wedge q_3) = 0 \] (9)

This is a method of constrained optimization, which leads to a closed form solution. There are three possible cases:
- the rank of matrix \( L \) is \( \text{rank}(L) = 12 \), in then the nullspace has dimension 0, and there is only one solution to the system, namely \( q = 0 \), which is not very meaningful;
- the rank of matrix \( L \) has dimension 1 and there is a unique solution (up to a scale factor);
- \( \text{rank}(L) < 11 \), which means that now there is an infinite number of solutions to linear equation system (7) or (8), therefore one way in which this can happen is if all the reference points \( M_i \) are in a plane. It is possible to conclude, that to achieve a unique solution to the system (7) or (8), is need to guaranty, that the reference points \( M_i \) are in general position. This means that in practical applications of this method is necessary to chose points, which not lie in a certain configuration. If six or more points are chosen at random, and do not lie on a plane, then it can be confident that this situation will not occur.

The described above solution of equation system (7) or (8) is an existing possible simple linear solution for estimation of the intrinsic \((\alpha_u, \alpha_v, u_c, v_c)\) and extrinsic \((r_1, r_2, r_3, t)\) parameters of a thermal or infrared camera in process of their calibration.

The solution of equation system (7) or (8) can be treated also as a non-linear minimization problem, where the attempt is to minimize the distance in the image plane between the points \( m_i \) in thermal or infrared camera plane and the real points \( M_i \) for \( i=1, 2, 3, \ldots N \). this minimization can be done by defining the quantity:
\[
E = \sum_{i=1}^{N} \left( \| q_i^T M_i + q_{i4} - u_i \|^2 + \| q_i^T M_i + q_{i4} - v_i \|^2 \right) \]
\[ (10) \]
The constrained minimization is applied to equation (10) assumed from (9) that \( \| q_3 \|^2 = 1 \).

It is necessary to declare that in general, non-linear method using constrained minimization of equation (10) lead to much more robust solutions.

2. Algorithm of the proposed space calibration method for the thermal or infrared camera

The presented above model of the proposed space calibration method for thermal or infrared camera is arranged as a practical algorithm possible to prepare the space calibration method for a concrete model of a thermal or infrared camera. This algorithm is shown in Fig.3. First a sequence of thermal images is chosen. Usually for the conventional visible image camera calibration are used checkerboard images. For the case of thermal or infrared camera space calibration also is possible to apply a sequence of images similar to the checkerboard visible images, but their pseudo colors or pseudo intensity must correspond to different temperature values. Then is applied an the interactive procedure to input the essential for the calibration points usually a set of points manually chosen as corners of each applied test thermal images similar to checkerboard. The corners are then extracted using appropriate thermal image processing methods. After that the automatic calibration is follow, which can be arranged using the linear system equations (7) and
or non-linear method using constrained minimization of equation (10).

Start

Input a sequence of test thermal images similar to checkerboard

Interactive input a set of point chosen from the set of test thermal images similar to checkerboard

Extract grid corners

Calibration using linear or non-linear methods for intrinsic and extrinsic parameters of thermal camera calibration

Visualization and analysis of the results from thermal camera calibration

Using the results from thermal camera calibration in thermal objects localization from a mobile robot

End

Fig. 3. The flowchart of space calibration algorithm for a thermal or infrared camera

5. Experimental results

The algorithm for space calibration of thermal camera is tested with a sequence of thermal images like checkerboard (Fig.4.). The results of tests for estimation of the intrinsic \( (\alpha_u, \alpha_v, \nu_u, \nu_v) \) and extrinsic \( (r_1, r_2, r_3, t_1) \) parameters of a thermal camera are summarized as follow:

**Focal Length:** \( f_c = [630.40895, 645.27611] \pm [8.63489, 7.58383] \)

**Principal point:** \( c_c = [300.35182, 172.93238] \pm [8.13332, 10.62623] \)

**Skew:** \( \alpha_c = [0.00000] \pm [0.00000] \Rightarrow \) angle of pixel axes = 90.0000 ± 0.0000 degrees

**Distortion:** \( k_c = [-0.16438, 0.17498, 0.00439, -0.00809, 0.00000] \pm [0.03009, 0.09368, 0.00283, 0.00308, 0.00000] \)

**Pixel error:**

\( \text{err} = [1.15961, 1.27301] \)

8. Conclusion

In conclusion it is possible to claim the satisfactory results of testing the space calibration method of thermal camera.

Fig. 4: Sequence of thermal images like checkerboard sequence of captured with thermal camera

The results of proposed thermal camera space calibration will be applied in thermal objects localization and position calculation, when a mobile robot detect or find thermal objects in area of observation. The future researches will be directed to combine proposed thermal or infrared camera calibration method with the laser range finder calibration to extend the calibration precision.

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