Development of an algorithm for the calibration of optical and thermal cameras into a unified machine vision system and its software implementation

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Abstract. The analysis of thermal images is an urgent task for many areas of modern technology and technology, since thermal images are used in many areas of life. Disjointed systems do not allow you to quickly form a general idea of the ongoing processes, since they do not allow an analysis of all parameters. The combination of data spaces obtained in different ranges can increase the productivity and speed of decision making by automated systems. Most often, images obtained with only a thermal imaging camera are a set of spots that characterize the gradient of temperature change in space. These images do not have clear boundaries, which is associated with the physics of thermal energy transfer processes in space. Combination of data obtained by thermal imaging and a camera recording data in the visible range, which are familiar to perception and more understandable to humans.

Areas of application of combined images are: medicine, when making a diagnosis, identifying patients in a crowd (for example, a pandemic), searching for oncology or tissue death processes (as a result of hypothermia or burns); security systems and access control systems; chemistry, in the analysis of mixing processes and reactions; automated and autonomous control systems when building automatic driving systems; and etc.

The development of machine vision systems is based on the analysis of information received by light-sensitive matrices in the form of two-dimensional signals (images). Formation of images is associated with the imposition of distortions on them, which can affect the final result. It is possible to reduce the amount of distortion in different ways or a combination of them. One of the possible methods of primary data processing can be the use of an algorithm for combining data by means of their joint calibration, which will make it possible to achieve a relationship between a 3D point in the real world and the corresponding 2D image, a projection (each pixel) in the image taken by a calibrated camera. In this article, we will consider a thermal camera calibration algorithm based on the analysis of a test pattern.

1. Introduction

Modern systems for the analysis of three-dimensional space, find their application in many directions, such as: auto-control, when creating UAV devices or assistants to control a car [1, 2]; automated devices for object analysis, when creating systems for monitoring the accuracy and quality of operations [3]; energy audit of objects when creating systems for analyzing energy leaks [4, 5]; 3D analyzers for the creation and subsequent study of volumetric structures [6]; and etc. Combining the data obtained by sensors in various electromagnetic ranges allows you to expand the information field of data and improve the accuracy and speed of response to problems arising [7, 8]. The acquisition of data by sensitive matrices involves introducing noise into the data. The appearance of the noise component significantly complicates the process of subsequent analysis of information [9]. Optical systems have...
inhomogeneities and also affect the image formed on the matrix. The creation of a single sensitive matrix that allows recording information in various electromagnetic ranges is not yet possible. When forming a unified system, it is impossible to use completely identical optical systems and sensitive matrices, in connection with which it is necessary to carry out preliminary calibration of the systems [10].

Solving the problem of constructing a spatial representation of displaying object points on a sensitive camera matrix is associated with the need to determine the internal parameters of the system as a whole. As a result of calibration, the parameters of image distortion by the camera are calculated. They usually include two types of parameters: Internal parameters of the system (focal length, lens distortion coefficients and optical center), external parameters associated with the orientation (mixing) of the camera relative to the coordinate system. The second section of the article discusses one of the possible ways to calibrate a thermal camera.

2. Image model and types of camera calibration

The operation of finding the base points of anchoring the coordinate systems of the object and the camera, with the identification of the characteristics of such systems, is carried out using test setting fields. Figure 1 shows an example of a test image model of a tuning field.

![Figure 1. Model of the test checkerboard used to calibrate the camera system and its representation](image)

Figure 1 shows a model of a test image used to calibrate a thermal chamber. The model used has square cages (30x30 mm). The size of the field is 9 by 7 cells. The total field size is 270 x 210 mm. The image is binary.

A seek thermal pro thermal imaging camera will be used as a data capture system in the far infrared range. This camera captures images in 320x240 resolution, 8-bit color, in RGB format.

2.1 Camera Calibration Methods

The main methods of camera calibration include: template calibration - when the operator himself forms a set of images of an object or template of known sizes from different points of view. An example of this approach is the checkerboard method, which will be used in the future. Geometric primitives, straight lines, intersection points - can also be used for calibration. The method based on deep machine learning is the most complex among the presented methods, it is used when the possibilities of managing image settings are limited (single scene image).

2.2 Template Calibration

The checkerboard pattern calibration algorithm is quite simple compared to other calibration algorithms. First, you need to determine the real world coordinates of a 3D point of a checkerboard pattern of a known size, then capture several frames of images of a checkerboard from different observation points. Next, you need to find a 3x3 matrix K, a 3x3 rotation matrix R and a translation vector t using a set of known three-dimensional points (Xw, Yw, Zw) and the corresponding image coordinates (u, v).

To find the projection of a 3D point on the image plane, you first need to translate the point (Xw, Yw, Zw) from the world coordinate system into the camera coordinate system, taking into account external parameters (rotation R and offset t).
Next, using the internal parameters of the camera, we project the point onto the image plane. The equations that connect a 3D point \((X_w, Y_w, Z_w)\) in world coordinates with its projection in image coordinates \((u, v)\) are written below.

\[
\begin{bmatrix}
u' \\
v' \\
w'
\end{bmatrix} = P \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}
\]

\[u = \frac{u'}{w'}, v = \frac{v'}{w'}\] (1)

Where: \(P\) is a 3 \(\times\) 4 projection matrix consisting of two parts: an inner matrix \(K\) that contains the inner parameters and an outer matrix \(([R|t])\), which is a combination of a 3 \(\times\) 3 rotation matrix and \(R\) and a transformation vector 3 \(\times\) 1 t.

To determine the projection matrix, we will use the expression:

\[P = K \ast [R|t]\] (2)

The inner matrix \(K\) is upper triangular.

\[K = \begin{bmatrix} f_x & \gamma & cx \\ 0 & f_y & cy \\ 0 & 0 & 1 \end{bmatrix}\] (3)

Where \(f_x, f_y\) - focal lengths x and y; \(cx, cy\) - x and y coordinates of the optical center in the image plane. Using the center of the image is usually a good enough approximation. The \(\gamma\) factor is used to compensate for the rotation between the axes. Most often, this coefficient is taken equal to one.

3. Algorithm for the implementation of the thermal camera calibration

The main stages of solving the problem of finding the calibration values used to construct the transformation matrices consists of 4 main stages, presented in Figure 2.

![Figure 2. Block diagram of the thermal imaging camera calibration algorithm](image-url)
The algorithm presented in Figure 2 is implemented as follows:
1. At first, the thermal image is loaded into the device memory, image preprocessing [11-12];
2. Preparing images by adaptive thresholding and erosion to binarize the image [13];
3. Angle detection by Harris and Stephens detector [14]; calculation of the angle position with an accuracy of subpixels by the Forstner detector [15] with further verification of the field structure;
4. Calculation of transformations using analyzed images [16-17];
5. Saving the result to the device memory.

4. Results of processing test images used for template calibration
To implement the software part, the python 3.7 programming environment and a set of OpenCV libraries are used. Figure 3 shows an example of test field fixation obtained by the camera in the visible range. Due to physical limitations and peculiarities of information presentation by a thermal camera, the template is implemented on a reflective surface. The black squares of the grid of the calibration field are made of heat-absorbing material with a very different thermal conductivity (Figure 3).

Figure 3. Test image of the calibration field

In the role of the gauge field, a mirror is used, onto which the checkerboard pattern has been projected. Figure 4 shows examples of images obtained using a special template with a SEEK thermal imaging camera.
The images shown in Figure 4 were obtained by a SEEK camera with a resolution of 320x240, 8 bits, RGB. Images have superimposed errors in the form of noise and blurring of object boundaries. To eliminate this type of distortion, it is necessary to perform preprocessing operations.

Figure 5 shows an example of obtaining base points used for system calibration. The implementation relies on using the findChessboardCorners function and refining the pixel coordinates by using the cornerSubPix function.

Figure 4. Result of fixation the test field with a thermal imaging camera

Figure 5. An example of defining calibration points.

The result of applying the algorithm presented in Figure 2 is a matrix of calibration parameters. The calibration results are presented in the form of a set of matrices that can be used in the future when processing other images.

Camera matrix:
\[
\begin{bmatrix}
1.84797086e+03 & 0.00000000e+00 & 5.24688132e+02 \\
0.00000000e+00 & 1.94189324e+03 & 6.39504533e+02 \\
0.00000000e+00 & 0.00000000e+00 & 1.00000000e+00
\end{bmatrix}
\]
dist :
\[
\begin{bmatrix}
8.34184101e-02 & -8.80526974e+00 & -6.24683466e-02 & -1.32835998e-03 \\
7.23185407e+01
\end{bmatrix}
\]
rvecs :
array([[[-0.39578152], [-0.03193099], [0.01114664]]),
array([[[-0.4096448], [-0.02476508], [-0.00269565]]),
array([[-0.51810357], [0.0403355], [0.09284244]]),
array([[ -0.52356917, 0.27852244, 0.0544309 ]],
   [[ -0.51687125, 0.08388122, 0.01243067 ]],
   [[ -0.57325141, 0.02350688, -0.00275195 ]],
   [[ -0.49642191, -0.05533324, 0.00847312 ]],
   [[ -0.52324508, 0.08168122, -0.02882621 ]],
   [[ -0.56743925, -0.03712638, -0.43814614 ]],
   [[ -0.55891472, -0.02162395, -0.42731589 ]],
   [[ -0.52325972, -0.02392422, -0.19080487 ]],
   [[ -0.5768838 , 0.00793741, -0.0484419 ]])

tvecs :
   array([[ -0.06531274, -2.95832875, 19.74956693 ]],
   [[ -1.34221065, -3.32999454, 19.79044254 ]],
   [[ -0.36369084, -3.87407782, 19.43027185 ]],
   [[ -2.79939917, -0.98479288, 20.38672505 ]],
   [[ -2.92667901, -2.33987936, 20.01136028 ]],
   [[ -2.64989817, -0.45990177, 20.79921809 ]],
   [[ -3.13184814, 0.05431608, 21.06782548 ]],
   [[ -2.56100747, 0.35086869, 20.96202469 ]],
   [[ -3.20998941, 0.39733165, 20.81037048 ]],
   [[ -3.54589351, 0.17735444, 20.86647736 ]],
   [[ -3.22586516, -0.14395433, 20.25885156 ]],
   [[ -3.10566679, 0.7500399 , 20.33421666 ]])

As can be seen from the given example of the formation of calibration matrices, it was possible to identify the parameters of the system for fixing images obtained in the far infrared spectrum (thermal images) using a SEEK thermal imaging camera.

Camera matrix – matrix
\[
\begin{bmatrix}
  f_x & 0 & c_x \\
  0 & f_y & c_y \\
  0 & 0 & 1
\end{bmatrix}
\]

fx and fy – are focal lengths expressed in pixels.
Cx and Cy - describe the coordinates of the so-called main point.

dist - distortion factor.
rvecs – rotation vector.
tvecs – transfer vector.

Conclusion
As a result of the work, an algorithm for calibrating a thermal imaging camera was developed, which makes it possible to identify the parameters of image distortion. The parameters obtained during the operation of the algorithm can be used as image transformation coefficients and can be used to implement a system for integrating images obtained in the visible and far infrared ranges.

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