3D Reconstruction of Thermal Images

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ABSTRACT

Infrared Thermography (IT) is an imaging technology aimed at the non-invasive measurement of the temperature distribution of the observed object. The capability to capture the temperature map of an object by an imaging device, makes IT an effective solution within Wind Tunnels systems, because it avoids the undesired drawbacks which are typically raised by intrusive diagnostics, like the alteration of the flowfield inside the facility testing chamber. Nevertheless IT, as with any other imaging system, is a bi-dimensional sensing technology unable to provide any direct information about the tridimensional structure of the observed scene. The purpose of this paper is to present both hardware and software components of a system built at the CIRA laboratories, in order to overcome this limitation and retrieve a 3D thermal texture for the observed object from the corresponding thermal images.

KEYWORDS

Thermography, Thermal Image, Camera Calibration, 3D Reconstruction, Computer Vision.

INTRODUCTION

In the Plasma Wind Tunnel SCIROCCO at CIRA, models representative of spacecrafts are tested in hypersonic regimes. At these Mach numbers (higher than 10) the heat fluxes acting on the surfaces are very high. Consequently the most important measurement is in terms of temperature. In the wind tunnels in general it is always a very important thing to have the possibility of not intrusive diagnostics, because intrusive diagnostics would change the field of view (and so the measured parameters) and it would also be dangerous for the instrumentation integrity. In this scenario Infrared Thermography (IT) plays a fundamental role for the data acquisition of the spacecraft models behaviour in hypersonic flow fields.

In the last years the research on spacecraft is going deeper, and particular aerothermodynamic phenomena are discovered and studied. In order to characterize these phenomena it is very important to have a spatial distribution of the temperature measurement as accurate as possible. In this frame the IT has an important limit, the bidimensional nature of the thermic maps. The present paper deals with the study of the upgrade of bidimensional information gained by means of thermographic measurements to three dimensional rebuilding of the models tested in the facility.
PERSPECTIVE PROJECTION MODEL

In this section a basic introduction of the projective geometry will be provided. The simplest representation of the image formation process in a perspective camera, is provided by the pinhole camera model, according to which any 3D point \( M \) is projected onto the focal plane by the ray passing through a unique point denoted as the projection center (Figure 1).

![Figure 1: Pinhole Camera Geometry](image)

Let us introduce the three reference frames (r.f.) which are used to model the geometry of the perspective projection, namely the world r.f., the camera r.f. and the focal plane (or image) r.f., denoted by the \( W \), \( c \), and \( i \) subscripts respectively. Using the homogeneous coordinate representation, a 3D point \( M_W = [x, y, z, 1]^T \) is projected onto the focal plane on the image point \( m_i = [u, v, 1]^T \), by the following transformation:

\[
m_i \sim K [R \ t] M_W
\]

where the 3x4 matrix \([R \ t]\) represents the rigid motion which transforms the point from the World r.f. to the camera r.f. and the 3x3 matrix \( K \), generally referred as Camera Calibration Matrix, models the perspective projection from the metric camera r.f. to the image r.f. In case of the pin-hole camera model, the matrix \( K \) has the following structure:

\[
K = \begin{bmatrix}
\alpha & \gamma & u_0 \\
0 & \beta & v_0 \\
0 & 0 & 1
\end{bmatrix}
\]

where \( \alpha, \beta \) represent the focal length expressed in adimensional pixel units, \((u_0, v_0)\) are the coordinates of the principal point \( p \) in the image-r.f. and \( \gamma \) is the parameter describing skewness of the pixels array and is zero for most of the cameras. These are generally referred as internal or intrinsic parameters since they model the internal geometry of an imaging system, while the parameters representing the rigid motion \([R \ t]\) are generally referred as external or extrinsic.
The estimation of the internal and external parameters of an imaging system is denoted as camera calibration and is usually performed by means of a known 3D calibration object. In this work it will be required to invert the perspective projection, that is given a thermal map and a 3D object, the task will be to estimate the 3D points corresponding to any image location and for this task the full calibration of the image acquisition system is needed.

SYSTEM OUTLINE
The flowchart shown in Figure 2 represents the design of the system aimed to the 3D texturing of CAD models with thermal maps.

![Figure 2: Block Diagram of the thermal texturing technique.](Image)

Each processing block will be described in detail below.

**Camera Calibration**

The processing block denoted as Camera Calibration (Figure 2) identifies a procedure aimed at estimating the parameters describing the geometrical model of the perspective projection, namely the intrinsic camera parameters. This task is unfailingly a preliminary operation for almost any 3D Computer Vision application; therefore the camera calibration field has kept a considerable interest among researchers with a resulting wide literature. The classic calibration methods require objects of known dimensions and position expressed in a coordinate system (world r.f.), equipped with visual features (corners, lines, etc.) that can be easily extracted from images with a common feature extraction algorithm. Usually a simple checkerboard can serve this purpose.

There are a large number of methods for camera calibration. The most classic methods were proposed by Tsai [2], Heikkila [4] and Zhang [3] and the source codes implementing these techniques are freely available on the web. The method of Tsai is based on the radial alignment constraint and requires accurate 3D coordinate measurement in a fixed reference. The method of Heikkila is based on a general direct linear transformation technique by making use of the prior
knowledge of intrinsic parameters; it also involves a more complete camera model for lens distortions. The method of Zhang is the most flexible one since it can be performed by means of a freely moving planar calibration pattern and the procedure can be easily repeated without redoing any measurement. An evaluation of the three calibration methods of Tsai, Heikkila and Zhang were performed by Sun and Cooperstock [5]. The influence of the measurement accuracy of the calibration patterns on the accuracy of the computed intrinsic and extrinsic camera parameters was analyzed by Lavest et al. [6].

In past years methods were developed that do not require any calibration pattern and are classified as self-calibration methods; these allow the computation of the intrinsic camera parameters using the point matches extracted across an image sequence of a rigid scene, captured by a single camera.

In this work we will use a thermal imaging system, anchored in a specific position within a controlled infrastructure, namely the Scirocco Plasma Wind Tunnel (PWT) and therefore self-calibration techniques are not really needed, instead a standard calibration technique using an a priori known calibration target is fully compliant with the normal system operations. Due to this reason we selected as a preferred solution the Matlab Camera Calibration Toolbox developed by the California Institute of Technology, which is based on the Zhang’s calibration method [7].

The Calibration Toolbox works in a semiautomatic way. The input is provided by a sequence of grayscale calibration images (at least three images) which are processed in order to extract with sub-pixel accuracy the location of the calibration points, provided by the internal corners of the calibration checkerboard. Finally the software determines the camera parameters as the solution to the following minimization problem on the overall Reprojection Error:

$$\min_{\mathbf{K}, \mathbf{R}, \mathbf{t}} \sum_{n=1}^{N} \sum_{b=1}^{B} \| \mathbf{m}_{jk} - \hat{\mathbf{m}}_{jk}(\mathbf{K}, \mathbf{R}, \mathbf{t}) \|^2$$ (3)

In the above equation $UT$ denotes the space of non-singular upper triangular matrices, $N$ is the number of calibration images, $B$ is the number of calibration points and $\hat{\mathbf{m}}_{jk}$ is the projection onto the retinal plane of 3D point $\mathbf{M}_j$ according to the camera model. This is a large nonlinear optimization problem that may be solved using Levenberg–Marquardt algorithm starting with the initial guess provided by the Zhang approach.

Once the intrinsic parameters are calculated, the software can calculate the extrinsic parameters using new images. The toolbox, also, allows analyzing the projection error and visualizing the results. The complete source and documentation of the calibration toolbox is available online (http://www.vision.caltech.edu/bouguetj/calib_doc/).

**Calibration Pattern for Infrared Camera**

The thermal imaging system used in this work is a thermal camera Thermovision 900 by AGEMA Infrared Systems with an angular Field of View 20° x 10° [1], and as any other thermal camera the captured imagery presents severe appearance differences with respect to the standard optical sensors. For this reason the calibration target has been realized with a checkerboard similar to the one used to calibrated optical cameras, but made with specifically selected materials in order to make it visible in the infrared images. In particular the support panel has
been realized with an aluminum sheet (80 × 60 × 2 mm) and the calibration texture with a vinyl film [8] shaped using a cutting plotter (Figure 3).

![Figure 3: Calibration checkerboard view by an optical and a thermal camera.](image)

It is understood that the thermal imagery of the unheated calibration checkerboard is not sharp enough for an accurate calibration process, therefore before capturing the image set, the checkerboard is heated by a silicon flexible heater (Figure 4).

![Figure 4: Silicon flexible heater with temperature controller (left) and an example of thermal image of the heated calibration checkerboard.](image)

It is clear from the visual inspection of the Figure 4 that the different emissivity of the aluminum sheet with respect to the vinyl guarantees a strong image sharpness making the captured imagery become suitable for the calibration purpose.

**Image Preprocessing**

The calibration methods require a preliminary step called feature extraction which is aimed at the identification at sub-pixel accuracy of the checkerboard corners in the target image. The feature extraction algorithms works on grayscale images and therefore the image set needs to be preliminarily converted into the grayscale color space. Furthermore, the calibration software used in this work requires for the most diagonal squares to be dark and therefore an inversion of the color space is also performed according to the following relation:

\[ I_{out} = (2^{nbit} - 1) - I_{in} \]  

(4)
where $n_{bit}$ is the number of bits used for the color quantization which is 8bit for most of the imaging systems.

In Figure 5 a sample of a calibration image after the preprocessing step is presented.

**Camera Pose Estimation**

In the most general case the estimation of the camera pose addresses the problem of determining the orientation and the position of an imaging system with respect to an observed object. In order to produce a result in the Euclidean space, where the transformation between the camera r.f. and the object r.f. is parameterized as a rigid motion, it is necessary to normalize the retinal plane coordinates with respect to the intrinsic calibration parameters. Therefore to solve the pose estimation problem the internal calibration is often assumed available and this also is the case of our system.

Indeed in this work the ultimate objective in order to realize the 3D thermal texturing, is the estimation of the camera pose with respect to the target object currently placed inside the testing chamber of the PWT. The direct computation of the camera pose from a single view of the test model captured from a long distance actually results in a complex and sometimes unreliable procedure, therefore we chose to estimate the camera pose by an indirect approach, taking an intermediate step the 3D pose of the calibration checkerboard.

Let us denote with $[R \ t]_{mdl\rightarrow cam}$ the estimation objective, namely the rigid motion between the target model r.f. and the camera r.f. needed to project the thermal map onto the 3D object model. This transformation can be factorized as a concatenation (denoted with the symbol $\otimes$) of two rigid transformations, namely the basis change from the model r.f. to the r.f. aligned with the calibration object and then from the latter to the camera r.f.:

$$[R \ t]_{mdl\rightarrow cam} = [R \ t]_{obj\rightarrow cam} \otimes [R \ t]_{mdl\rightarrow obj}$$  \hspace{1cm} (5)

The exploitation of this factorization, gives us the possibility to assume to be given as a system input the rigid motion between the calibration object and the target model, namely the transformation $[R \ t]_{mdl\rightarrow obj}$, indeed this information could be easily retrieved inside a controlled infrastructure since the calibration object may be accurately located in the same support of the target model.

Under this assumption, the only information which needs to be explicitly computed in the camera external calibration phase is given by the rigid motion between the camera r.f. and the calibration object r.f., namely the transformation $[R \ t]_{obj\rightarrow cam}$. Notice that the Caltech
Calibration Toolbox, used for the internal calibration process, provides as well the functionality for the pose estimation of the calibration object with respect to a calibrated camera, therefore we choose this solution for the purpose of camera pose estimation. Of course due to this choice, the images selected for camera pose estimation must undergo the same pre-processing step described in previous sections.

It is convenient to remark that in order to compute the overall geometrical pose of the thermal camera with respect to the target model, it is needed to place the calibration checkerboard in a known position relative to the target test model, and this operation requires a reliable and extremely accurate infrastructure where the calibration object and the test model may be accurately mounted different times in a repeatable geometrical configuration. In our system this support is provided by the Model Support System of PWT test chamber (MSS), which guarantees a sufficient accuracy for this purpose.

**Texturing**
The Texturing is the method that allows adding texture features, such as surface or color, to a computer generated 3D model, and in this work this procedure is aimed to map the features given by the thermal images to the 3D CAD model of the test object. For this purpose a preliminary version of the software module has been developed in Matlab, based on the following algorithm:

**Input:** thermal camera intrinsic and extrinsic parameters, thermal image of test object, surface mesh of test object.

1. Projection of model nodes on the image plane using the camera projection model estimated in the calibration and pose estimation phases (eq. 1);
2. Estimation of the thermal data associated to the projected nodes by 2D interpolation (Matlab function *interp2*);
3. Overall thermal texturing of the test model on the visible portion (Matlab commands *delaunay* and *trisurf*).

**Output:** 3D thermal image of test object.

**RESULTS**

**Preliminary test**
The preliminary test was performed in the workroom of Scirocco PWT. The test article consists of a slab of silicon carbide (SiC) in a sintered form, a cylindrical housing of silicon carbide, an insulating element of polycrystalline fibers and a copper flange (Figure 6).
The calibration images and the results of calibration process are shown below (Figure 7).

In this preliminary test the distortion parameters have been neglected because these parameters are in generally irrelevant for narrow lenses like the one commonly mounted on thermal cameras. Also the position of principal point was assumed coincident with the center of image and the value of the skew parameter that was assumed to be zero; these parameters therefore did not undergo the optimization process in the calibration phase.

After the calibration process the thermal camera was positioned on a tripod in the laboratory in order to make test article and the calibration checkerboard directly visible with an ideal visual
slant. The camera position in the workroom and the image adopted to estimate the camera pose estimation are shown in Figure 8.

Figure 8: Thermal camera position in the workroom, pose estimation image and thermal image of test article

The results of thermal camera pose estimation process are shown below.

<table>
<thead>
<tr>
<th><strong>Translation vector</strong></th>
<th>t</th>
<th>[-206.064942 -53.305475 1999.851725]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rotation Matrix</strong></td>
<td>R</td>
<td>[0.028619 0.999082 0.031872]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[0.962304 -0.018910 -0.271318]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[-0.270467 0.038435 -0.961962]</td>
</tr>
<tr>
<td><strong>Pixel Error</strong></td>
<td></td>
<td>[0.15005 0.30463]</td>
</tr>
</tbody>
</table>

Then a snapshot of the target object has been captured using an unchanged camera pose and the object exactly located in the center of one of the checkerboard squares. This actually guarantees that the geometrical transformation between the CAD object space and the calibration checkerboard r.f. can be assumed known and resembles the actual situation of the PWT-MSS. In Figure 9 the CAD model and the thermal image of corresponding test object are shown.

Figure 9: CAD model and thermal image of test article
Once camera intrinsic and extrinsic parameters are achieved and the CAD model of test article realized, we have adopted the texture mapping method to obtain the 3D thermal image of test article. The results of our method are shown in Figure 10.

![Figure 10: 3D thermal Image](image)

This preliminary result suggests that the method is actually effective and accurate, given that the pose of the test object with respect to the calibration checkerboard used for the pose estimation phase can be safely assumed known with sufficient accuracy.

**Experiment in the PWT Test-Chamber**

Encouraged by the results of the preliminary test we have performed a second test in the test chamber of the “Scirocco” PWT [9]. The thermal camera was placed in an optical access of the upper wall of the test chamber (Figure 11).

![Figure 11: Typical positions of thermal camera](image)

The test article in this second test was a flap developed for the EXPERT space vehicle [10]. The flap was connected to an additional support which serves as mechanical interface to the PWT-MSS of the test chamber (Figure 12).
In this test again the lens distortion and the skew parameter did not undergo the optimization process and the same internal calibration data estimated in the previous test has been used. The calibration image used for the pose estimation purpose has been captured placing the calibration checkerboard onto the PWT MSS and it is shown in Figure 13. Notice that due to the presence of the mechanical interface of the test model, the visibility of the calibration checkerboard is not as good as in the previous test, nevertheless this did not affect negatively the test result. The results of calibration process are shown below.

The CAD model and the thermal image of test article are shown below (Figure 14). Notice that in the thermal image it is visible thermal footprint of a hand, which has been introduced in order

![Figure 12: Test article and his support](image)

![Figure 13: Pose estimation image](image)

| Scale Factors | $(\alpha, \beta)$ | $(803.34149, 804.51160) \pm (34.90782, 35.01795)$ |
| Principal Point | $(u_0, v_0)$ | $(145.08839, 79.76240) \pm (18.25348, 11.72316)$ |
| Skew Parameter | $\gamma$ | $0.00000 \pm 0.00000$ |
| Pixel Error | | $[0.13481, 0.13350]$ |
| Translation vector | $t$ | $[-874.442271, 0.703361, 5090.096160]$ |
| Rotation Matrix | $R$ | $\begin{bmatrix} 0.019884 & 0.946772 & 0.321290 \\ 0.998247 & -0.036717 & 0.046416 \\ 0.055742 & 0.319804 & -0.945843 \end{bmatrix}$ |
| Pixel Error | | $[0.10650, 0.16110]$ |
to create a thermal discontinuity on the surface of the flap to evaluate the accuracy of the following 3D texturing without risking any damage due to the real operation of the PWT. Indeed the real test on this model was not scheduled before the preparation of this paper and therefore we used this simple artifact to simulate a temperature variation on the model surface.

![Figure 14: CAD model and thermal image of test article](image1.png)

The back-projection of the thermal map on the CAD model, obtained by using the proposed technique, are presented in the in Figure 15.

![Figure 15: 3D Thermal image](image2.png)

**CONCLUSION**

A technique for the 3D texturing of thermal imagery on CAD models has been presented. The proposed method makes use of standard 3D video processing algorithm like camera calibration and camera pose estimation, and provides a preliminary version of the final system which will be integrated within the technological equipment of the Scirocco PWT at CIRA. The obtained results confirm the validity of the approach but at the same time have highlighted the need for a further improvement of the technique. In particular the assumption of known pose of the target model with respect to the calibration object, needed for the pose estimation phase, can be valid and accurate only in certain circumstances and in particular they are only partially achievable within the PWT test chamber where the optical access is quite far for the MSS. The future work will be addressed towards the improvement of the pose estimation throughout the exploitation of
a model based tracking algorithm in order to refine the numerical accuracy of the camera pose with respect to the target object place in the test chamber. On the other hand the importance of this system for the improvement of the testing capabilities of the Plasma Wind Tunnel surely confirm the need to proceed towards the realization of an accurate and reliable 3D mapping of thermal maps, which will provide a great benefit for the overall completeness of the services offered by the PWT test facility.

Bibliography
