Geometric Calibration in Active Thermography Applications

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Abstract. The application of active thermography such as Lock-in or pulse thermography has been widely used in aerospace and other industries. Over the last decade, the level of automation has increased by using various manipulators like classical NC machines or even industrial robots. Meanwhile integration of measurement systems and automated manipulators achieved industrial standard. It is therefore possible to cover a large range of geometrical complex parts even on larger dimensions. Manipulators like a robot can be used for the positioning of the thermography camera and delivers the location of the robot flange coordinate system at the time of measurement automatically. Or one can think of having a stationary camera and the part is moved around. In principle thermography cameras used in NDT applications as well as other fields can be handled as standard photogrammetric cameras. According to the longer wavelengths of the measured infrared spectrum the lenses of thermography cameras are mainly made of Germanium. Although the high cost for these lenses, they are optimized for radiometric resolution, thus geometric precision or minimal distortion had not been targeted especially in the field of NDT.

The approach at DLR Augsburg of a robot based measuring system for industrial thermography applications in the context of CFRP production technology including a hand-eye-calibration procedure for a thermography end-effector has been presented in previous papers. In order to achieve higher accuracy in terms of geometric precision a number of distortion parameters have been evaluated. An automated procedure has been developed to compare different calibration strategies as well as different camera characteristics e.g. focal length. Within this paper DLR’s Center for Lightweight-Production-Technology in Augsburg will give insight into current work in the area of geometric calibration for thermography cameras for a high resolution camera, results derived from experiments and applications for such calibration procedure.
1. Introduction

Earlier studies have demonstrated how important it is to optimize the method of calibrating your optical quality management device for measurements. One of these, the calibration of the intrinsic and extrinsic parameters of the camera, was explained in the previous publication [1]. The following step, which is the Hand Eye Calibration (HEC), was basically explained in a previous paper [2] but needed much more improvement. They key aspect for the automation is the accuracy that this calibration can deliver. Errors in the HEC influence the working distance, which yield to false sizes of measured pictures and wrong parameters for the Optical excited Lock-In Thermography, but they also yield to a wrong position from where the picture was taken. If this position isn’t correct, the place where possible failures in production appear gets detected wrong and could possibly yield to failure of the whole part.

Since we investigated the method in the previous paper [2], this research should increase the accuracy of the HEC and also should lead to a determination of the actual error and its sources. Excellent work in the field of accuracy had been done by Bianchi, although following a different approach his paper [3] had been a valuable source and needs to be mentioned in this context.

1.1 Main issues

The main issue of the used method lies in its output of accuracy. The method itself delivers a so called “back projection error” which describes where the picture was taken and where the picture would be after the calibration. This error does not provide real information where the actual calculated tool centre point (TCP) lies and which orientation it has. It is also a relative value which cannot be compared with the actual absolute error. Another aspect we had to investigate on was the stability of the software for the HEC itself. There are several factors like for example the pattern location that influence the accuracy of the computation. Also the error which will be calculated should be minimized to a certain amount that lies within a tolerance band that has also should be researched.

2. Experiments

2.1 Experimental Setup

Since the HEC is almost exactly executed like the camera calibration described in the previous paper [1] a point pattern with exactly sized points on a flat surface is needed. Therefore a point pattern was printed with a precise industrial plotter and then glued to an AluDibond plate. The plate was put on a table within the reach of an industrial robot. The difference from the camera calibration is that the camera is mounted to the robot. In this setup the camera is mounted on an end-effector that can turn the camera around the X-axis and translate along the Y-axis. That makes it possible to manipulate the camera for different experiments and test different angles. To enable the robot to position over the pattern with a constant distance an offline programming (OLP) had been used. This allowed to manage tool data and to generate robot programs easily and correct. To generate the pictures the Lock-In Thermography was used and therefore two spotlights were placed next to the table. A number of ten images per run had been acquired and fed in to the HEC toolbox [4], [5]. The complete experimental setup can be seen in picture Fig. 1.
In order to achieve high accuracy in positioning the robot controller can take loads in its hand as well as the arm into account. For a proper compensation it needs the exact values for the mass and the moments of inertia around each axis. Therefore a program called “load-detect” was used to determine both. That delivered a weight of approximately 55 kg. Since the single components of the end-effector only weigh about 36 kg the cable carrier which is mounted on it adds additional weight. But since the force that is put on the end-effector from the cable carrier is related to the position of the robot this has to be further inspected.

2.2 Concept to prove the accuracy of the HEC

The concept of getting more information about the accuracy of the HEC is to compare the positions of the taken pictures with the calculated ones. This still does not lead to an absolute error but gives a good indication about the characteristics within the computations.

2.3 Experimental execution

The first run of the HEC was performed while the pattern laid flat on a table and the camera positions where all taken with the same orientation around the Z-axis of the camera. With this setup a first row of iterations were done. Also a statistical measurement with one robot motion program was done to ensure the stability of the toolchain and the computations.

In the second setup the robot program was calculated with mixed orientations around the Z-axis of the camera. With this approach we wanted to measure if these varying positions of the robot and the pictures taken from different angles make a difference in the outcome of the TCP, hence the quality of HEC computations.
After these iterations some other aspects where investigated. At first the influence of robot velocity on positioning accuracy had been investigated. Also the pattern had been placed at a different location within the reach of the robot. Here again the influence of robot pose on positioning accuracy had been investigated. Since the toolbox calculates with Euler angles and the corresponding translation and rotation matrixes, there are some positions of the pattern where the arcsine can jump between its limitations. Therefore the pattern was tilted around the horizontal axes to ensure the arcsine limitation does not influence the toolbox. In the last campaign the camera was tilted some degrees around the X-axis of the end-effector, therefore the TCP had changed, to see if this new position generates different values.

3. Discussion of Results

The statistical measurement over six runs to ensure the stability of the toolbox as well as the repeatability of the robot delivered excellent values. The standard deviation in translational direction is not higher than 0.22 mm and for the rotatory components not higher than 0.03 degree and again smaller than in previous campaigns with a similar setup. For more details see Fig. 2.

![Fig. 2 Statistical data from HEC](image)

By comparing the first and second iterating measurements (constant and mixed orientation of camera view on pattern) the pose, in which the robot is while taking pictures, obviously has some influence on the accuracy of the HEC. Although having slight variations over six runs, there was no clear trend visible as shown in Fig. 3.
Having a closer look on each run it comes clear that certain camera locations respectively robot poses produce higher errors. Observing these errors, both components, translational and rotatory, had been investigated separately. Especially the errors in orientation had been under strong surveillance. This becomes clear when looking at the effect. Using the camera at some distance to the object, any misalignment around the camera’s X- or Y-axis would cause a large deviation in image location. Let’s call this “pointing error” for later use. Table 1 demonstrates this par excellence. At point 4 we can see the largest error sum of the absolute angle delta.

<table>
<thead>
<tr>
<th>Point 1</th>
<th>Point 2</th>
<th>Point 3</th>
<th>Point 4</th>
<th>Point 5</th>
<th>Point 6</th>
<th>Point 7</th>
<th>Point 8</th>
<th>Point 9</th>
<th>Point 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.579</td>
<td>0.588</td>
<td>0.657</td>
<td>0.696</td>
<td>0.614</td>
<td>0.601</td>
<td>0.609</td>
<td>0.657</td>
<td>0.640</td>
</tr>
<tr>
<td>B</td>
<td>-0.04</td>
<td>-0.053</td>
<td>-0.086</td>
<td>-0.056</td>
<td>-0.065</td>
<td>-0.044</td>
<td>-0.017</td>
<td>-0.043</td>
<td>-0.034</td>
</tr>
<tr>
<td>C</td>
<td>0.290</td>
<td>0.276</td>
<td>0.263</td>
<td>0.300</td>
<td>0.289</td>
<td>0.282</td>
<td>0.332</td>
<td>0.328</td>
<td>0.339</td>
</tr>
<tr>
<td>Σ Abs (A,B,C)</td>
<td>0.915</td>
<td>0.918</td>
<td>1.007</td>
<td>1.052</td>
<td>0.969</td>
<td>0.927</td>
<td>0.958</td>
<td>1.03</td>
<td>1.014</td>
</tr>
</tbody>
</table>

This strongly correlates with the robot pose and the effect on its accuracy. Especially the points that are the furthest away from the robot and with the most rotating components at the sides of the pattern deliver the largest errors. In such case a slight deviation from the masses mounted on the robot would cause a wrong compensation by the robot. Additionally these points also collide with the tension that the cable carrier is acting on the end-effector and therefore on the robot’s wrist at these positions as shown in Fig. 4. As the cable carrier is a moving mass the robot controller cannot take this into account correctly. The problem becomes more severe when the tension of the cable carrier comes into play. Due to the offset fixture of the cable carrier on the end-effector platform it causes high momentum on the wrist. By nature the robots wrist is one of the weakest joints, such momentum would therefore cause an inaccurate positioning as well as a misalignment of the TCP.
The influence of the different velocities can be neglected as they show almost no change in the relative error but maybe there is a dependency to the absolute error, see Fig. 5. Also the change of the pattern position did not influence the stability or outcome of the HEC.

The positioning around critical axes for the algebra used in the toolbox showed that the Y-axis of the TCP is very sensitive around 0 degree since this is the point where the arcsine is not defined and therefore sometime jumps for 360 degree. This can be negated by implementing a crosscheck within the toolbox. Also the last change with varying the orientation of the camera didn’t change the outcome of the HEC. This again speaks for the stability of the toolbox.

Finally it is up to summarize the HEC effort. With the described experimental set up the best result that had been achieved allows a geometrical calibration with the following values implying very small pixel error, see Table 2. The numbers in brackets are representing values in horizontal and vertical direction including their uncertainties.

<table>
<thead>
<tr>
<th>Focal Length:</th>
<th>( fc = [792.35514, 791.89987] \pm [1.98918, 1.98444] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal point:</td>
<td>( cc = [310.91202; 252.17727] \pm [0.86609; 0.68516] )</td>
</tr>
<tr>
<td>Skew:</td>
<td>( alpha _c = [-0.00037] \pm [0.0001] \Rightarrow \text{angle of pixel axes} = 90.02114 \pm 0.00577 \text{ degrees} )</td>
</tr>
<tr>
<td>Distortion:</td>
<td>( kc = [-0.26355; 0.16009; 0.00004; -0.000180] \pm [0.00542; 0.03374; 0.0002; 0.00018, 0] )</td>
</tr>
<tr>
<td>Pixel error:</td>
<td>( err = [0.06461; 0.0634] )</td>
</tr>
</tbody>
</table>
With such a set of calibration data and the HEC results at a working distance of 400mm it was possible to achieve a mean HEC magnitude error (translational) of 1,7384mm. In fact, the translational component is only one aspect. By adding the rotatory errors to our TCP we obtain a pointing error in two directions. This means an error of -1,0168mm in the camera’s Y-direction and 2,9882mm in the camera’s X-direction. Both effects can be seen in Fig. 6 where the difference from the pattern center to the picture center is shown in pixel. For this working distance the 17,28 pixel are 10,31 mm and the 4,87 pixel are 2,87 mm. Here it can be seen that the absolute error is still higher than we can assume out of our relative error.

The image to the right is nicely rectified but also shifted towards the bottom and towards the left. We can state that the geometrical calibration works fine but the image localization has still room for improvement.

4. Conclusions and prospect

4.1 Conclusion

After these series of experiments the Hand Eye Calibration method has been deeply understood and optimized. Errors like the tilting between 0° borders, temperature and velocity of the robot, orientation between camera and pattern could be further investigated. The main success was to test a method that defines a value for the error in translational and rotatory parts of the TCP that was calculated in the HEC. Also the decrease in the error while iterating over the method is great improvement. The camera resolution and therefore the pattern representation definitely have some limitation on the overall accuracy. Also the amount of change between each of the camera positions has great impact as mentioned in [6]. Additionally the usage of Euler angles has drawbacks in some cases. Although they are easier to understand and interpret for humans, their ambiguity and phenomena like gimbal lock can trick your results.

4.2 Prospect

To further increase the accuracy of the HEC additional tests have to be made. One aspect is to enhance the precision of the pattern location. This could be done with a plate that is dowelled into the basement of the robot cell or a device standing on it. Then this defined location has to be measured in the most accurate way so that the OLP and therefore the HEC gets more precisely.
The other inaccurate part in the method is the absolute accuracy of the robot. There are two options imaginable. Since the toolbox compares robot poses from the OLP with the camera pictures, a comparison between the poses of the OLP and the real poses from the end-effector have to be done. This could be realized by tracking the poses with third party devices while the robot program is running, e.g. laser tracker. Alternatively it is possible to improve the accuracy in positioning in general. This can be done by performing an enhanced calibration of the robot or at least the prevention of robot poses that are not beneficial to its positioning accuracy. This seems to be applicable on a short term perspective.

Since the method only generates single parts for translational and rotatory components relative to the system a way to generate those parts in absolute reference have to be investigated. This also has to be done to guarantee the position the measurement was taken. When these errors are calculated, the number of iteration steps that are needed to bring the rotatory parts beneath a certain level must be found. The rotatory components generate a drastically higher error in absolute values because of the pointing so these have to be minimized.

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**References**


