IMAGE PROCESSING BASED CALIBRATION OF HIGH PRECISION LASER PROJECTION SYSTEMS

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ABSTRACT:

Large-scale laser projection systems used in industrial environment, e.g. for the projection of CAD drawings onto large work pieces, require external calibration to ensure constant precision and hence quality. Basically, each different projected pattern has to be calibrated at least once, to account for temperature-induced variations in the laser scanning systems, relative displacements due to variable distances and shifts between projector and projection target.
The calibration system consists of 4 to 10 standard machine vision B/W cameras or alternatively less expensive modified USB or 1394 cameras, depending on the specific requirements of the factory. Specific calibration patterns are projected at given positions, acquired by spatially calibrated cameras, image processed and compared with the default coordinates. Evaluation algorithms perform error minimisations between the actual data and the set point data, involving different parameter models accounting for offset, rotation, scaling and perspective distortion. The resulting correction routines are fed back into the laser projection control software, thus facilitating an automated re-calibration and error correction. Difficulties with the nature of the projection surface that result in parts of the patterns to be indistinct or entirely missing are encountered by projecting dedicated, stable calibration patterns and using suitable image processing algorithms, in particular sub-pixel methods, for the laser line detection and subsequent computation of calibration data points. This procedure ascertains, even in difficult environmental conditions, a projection accuracy of 2 x 10^{-4} relative to the total projection area, both in position and scaling even with simultaneous or sequential use of several projectors.

1. INTRODUCTION

For the automated or automation-assisted assembly of large parts, typically larger than 1 m x 1 m, it is generally preferable to project the CAD construction onto the work area, rather than manually measuring the position of every single part and compare it with a paper drawing. The best solution for this is to use large-scale high-precision laser projection systems. The relevant designs are fed into the laser projection system and projected onto the work surface, which can be either stationary or a moving table. A typical application would be the production of pre-fabricated house parts, e.g. cellar walls and the like, reaching dimensions of up to 3,5 m x 12 m. The projection of CAD information onto the worktable is highly helpful in different phases of this production. In a first step, the outer contours are displayed. Subsequently, the exact positions of the iron reinforcements, of windows, doors, electrical cable channels and pipes, etc. are projected, which can be positioned now with high precision and without necessitating individual measuring. Additionally, text information, e.g. assembly instructions, can be displayed

For such an application, a typical accuracy of ± 1 - 2 mm over the length of the part is required to avoid problems during instalment at the building site. To achieve this accuracy, the laser projection system has to be calibrated. The recalibration frequency of the projection system depends on the operation mode and the precision requirements. Calibrations are performed either (i) in regular time intervals, (ii) prior to each projection or (iii) following every movement, either of the projector(s) or the worktable(s). Especially in modern high-throughput production lines, where the tables and the projector(s) move relative to each other, thus increasing the danger of severe misalignments, the calibration has to be repeated frequently. The system can be calibrated in a number of different ways. Manual calibration is a possibility, but is time-consuming and labour-intensive, especially when frequent re-calibrations are necessary. A second possibility is to use optical sensors or reflection marks on the worktable for the calibration. Here, the laser scans a given area until the target is found and the optical sensor gives a signal back to the system. The drawback of this system is for one the attenuation of the optical signal in the production environment, e.g. by dust and dirt, and secondly the danger of damaging or shifting the reference points / sensors. Hence, a contact-free imaging system, working from the ceiling of the production hall, would be preferable.

An image-processing based calibration system has to be capable of correcting (i) linear shifts, caused by relative misalignments between (moving) tables and the projectors, (ii) rotation, also caused by movements of the projector or the table during production, and (iii) scaling, due to changes in the distance between projector and projection area, the projection area size and changes of the ambient temperature. The system must be quick, mechanically robust, deliver stable results and fully automated. Such a system should be presented in this paper in detail.

2. SETUP OF A TYPICAL PROJECTION AND CALIBRATION SYSTEM

A typical projection system consists of two to four projectors, plus automated linear slides, control software and different other components. The integration of the proposed imaging based calibration systems requires the addition of the camera system and the necessary image processing, calibration and compensation routines. In the integrated system, the projectors are mounted together with the cameras and the electronic system in a rigid frame, which is in turn attached to a ceiling crane system or mounted stationary in the ceiling. Figure 1 illustrates this system.

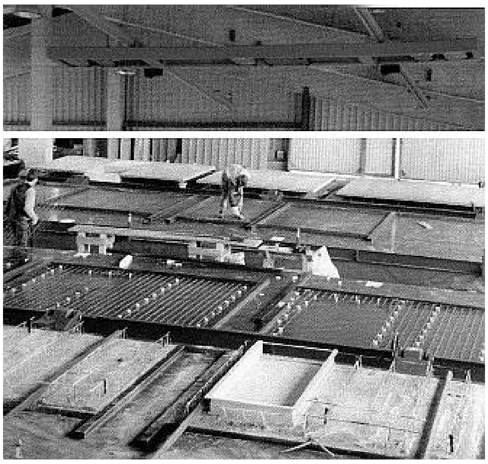

Figure 1. Integrated laser projection and calibration system in an industrial environment. The projection system is attached to the crane, looking down onto the worktables.

The *projectors* are high-precision laser projectors, based on diode pumped green solid-state lasers (532 nm) with 10 – 50 mW power and galvanometric laser scanners. The projection systems are hermetically sealed and temperature stabilised. To achieve the necessary resolution, four *cameras* looking onto the corners of the projection area are required per laser projector. However, it is possible to “share” cameras located between adjacent projectors, thus e.g. reducing the number of cameras required for two projectors to six. In the first prototypes, standard CCIR video cameras were used, connected to commercial frame grabber cards. In the present system, modified USB or FireWire (IEEE 1394) web-cams were used, with modified housings accepting c-mount standard accessories. Attached to the cameras were c-mount lenses with focal lengths matched to the distance between the camera and the projection area, each camera viewing an area of approximately 50 cm x 50 cm. An interference filter optimized to the laser wavelength gets installed between lens and camera, that only the laser light and little background light are visible to the camera sensor. The images are captured using WDM drivers and imported through DirectX 8 filters (Microsoft, 2000) into the software. This is possible as the timing structure of the imaging system is not a critical fact. More critical is the number of laser scans during the integration time of the camera. Due to the limited number of scans during integration, significant differences in luminosity may occur, as well as missing lines in interlaced half images.

3. COORDINATE SYSTEMS AND TRANSFORMATIONS

The basic mechanism for the calibration procedure is to apply different coordinate systems to all parts of the systems and generate mathematical transformations from one to each other.

(i) The world coordinate system (x, y, z) has a fixed relationship to the projection and camera system and moves together with the crane.
(ii) The table coordinate system is given by the Cartesian coordinate system of the worktable (xt, yt, zt). This coordinate system, which is applied to each work area, is identical to the system used in the design process of the CAD model in the construction bureau. Provided no distortions, etc. occur, the computer model should correspond exactly to the projected image.
(iii) The third coordinate system is the individual coordinate system of the projectors (r, s). Each projector has an underlying, individual coordinate system to transform 3D projection information to electrical signals for the scanners and laser.
(iv) Each camera has its own camera coordinate system (u, v) for rows and columns of pixel.
Goal of all calibrations is to find a transformation (xt, yt, zt) -> (r, s), so that the projected pattern in the work area matches exactly the CAD-drawing, independent from influences like positioning errors, drift, etc.

Due to easy integration in the production process, all calibrations have to be done with 2D-targets or 2D-patterns projected onto the work area respectively. To extend transformations to 3D-space, the camera height above the work area is measured manually and input to the system. This is sufficient, because the required height range of the projection volume is rather small (app. 20 cm) compared with the camera distance (app. 6 m). The transformation from the world coordinate system to pixel coordinates uses a homomorphic transformation taking into account translation, rotation, scaling and perspective distortions between the coordinate systems:

$$u = \frac{a_k \cdot x + b_k \cdot y_k + c_k \cdot z + d_k}{i_k \cdot x + j_k \cdot y + k_k \cdot z + 1} \qquad (1)$$

$$v = \frac{e_k \cdot x + f_k \cdot y + g_k \cdot z + h_k}{i_k \cdot x + j_k \cdot y + k_k \cdot z + 1} \qquad (2)$$

The transformation parameters $a_k - k_k$ are determined within the camera calibration routines. An initial camera calibration is done upon system installation. Inverse transformations from camera coordinates to real word coordinates can be derived by inverting equations (1) and (2). The inverse transformation requires that a fixed z coordinate is known.

The transformation between world coordinates and the production area (table) coordinates is described by:

$$xt = \frac{a_t \cdot x + b_t \cdot y + d_t}{i_t \cdot x + j_t \cdot y + 1} \qquad (3)$$

$$yt = \frac{e_t \cdot x + f_t \cdot y + h_t}{i_t \cdot x + j_t \cdot y + 1} \qquad (4)$$

$$zt = z \qquad (5)$$

The parameters $a_t - j_t$ are calculated during a table calibration procedure. The height z can be neglected, because the possible change is small and only expands or reduces the area, which can better be compensated for by adapting other parameters. The transformation between the coordinate systems of the work area (table) and the projection system(s) can be described by:

$$r = \frac{a_l \cdot x + b_l \cdot y + c_l \cdot z + d_l}{i_l \cdot x + j_l \cdot y + k_l \cdot z + 1} \qquad (6)$$

$$s = \frac{e_l \cdot x + f_l \cdot y + g_l \cdot z + h_l}{i_l \cdot x + j_l \cdot y + k_l \cdot z + 1} \qquad (7)$$

The parameters $a_l - k_l$ for this transformation get calculated during the laser calibration procedure. In the practical implementation, at first the characteristic coordinate points of the projected images have to be detected, using image processing routines. Afterwards, standard minimising procedures involving the algorithms and transformations outlined above can be applied to determine the calibration correction set.

4. CALIBRATION PROCEDURE

Calibration of the system comprises three steps – camera calibration, table calibration and laser calibration.

(i) *Camera calibration* is usually done during the installation of the system, or in regular service intervals. In this calibration step, the relationship of the cameras to the world coordinate frame is calculated. For this procedure, a calibration target with a typical array of 5 x 5 light spots – usually a fibre optic bundle illumination arrangement with a central light source - is positioned on a production table with known world coordinates and table coordinates. A picture of such a calibration before and after the automated search algorithm is shown in figure 2. An automated search algorithm detects the light spots in the image(s) and calculates the transformation parameters using a least-square minimising algorithm. This procedure yields a fixed relation of the pixel coordinate system to the world coordinates by means of an inverse coordinate system transformation, following equations (1) and (2). The individual transformation parameters for each camera are stored in the software and only have to be changed when cameras or other parts of the system have to be readjusted.

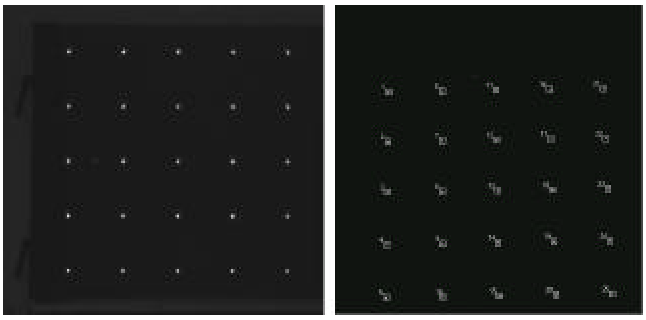

Figure 2. Typical camera calibration picture (left) with automated calculation of the positions (right).

(ii) The *table calibration* determines the relative position and orientation of the worktable in respect to the world coordinate frame. The edges of the table itself, which has a known size, is used as calibration target. The laser projection is used only to make the edges visible to the camera system. During this calibration step, groups of six lines are projected onto the edges of the production table (Fig. 3, top). The lines get projected in each camera view area and typically start in the planar production field to get stable line detection. The images are processed using line-following image processing algorithms, which yield the coordinates of the end points of the lines. The end of line points correspond to points on the edges of the worktable due to different positions of projector and cameras and therefore viewing angles, when a shift of the line in the picture is detected from the height difference of the production area and the floor of the production site. The edges are transformed back to world coordinates using the calibrated cameras. Comparison with the table coordinates delivers the parameters $a_t - j_t$ of (3) and (4) using least square fit algorithms.

(iii) The transformation parameters between the world coordinate system and the laser coordinate systems are determined during the *laser calibration*. In this procedure, each laser projector projects an optimised calibration pattern with several squares into the corresponding camera view fields (Fig. 3, bottom). A line following algorithm is applied to automatically detect the intersections and corners of the pattern(s). To determine these points with the necessary precision, sub-pixel line detection algorithms in combination with least-square-fit line intersection detection are used. Similar to the table calibration, the corners and intersection points of these patterns are transformed back to world coordinates using the camera calibration result. Laser calibration is then performed by comparing the achieved world coordinates with the corresponding commanded laser position (r, s).

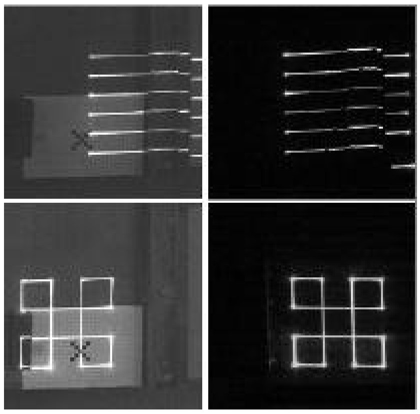

Figure 3. Projection patterns for table calibration (top row) and laser calibration (bottom row), with (right column) and without (left column) background subtraction.

The parameters for the two transformations – *table calibration* and *laser calibration* are calculated during the actual in-process calibrations. The order of these two calibrations is depending on the production system. In systems where the projection system is moving, the table calibration is done prior to the laser calibration. In systems where the laser system is stationary and the worktables are moving, and where in most cases already work pieces obscure parts of the work area, the laser calibration is performed first, followed by the table calibration. The order also depends on the expected tolerances in both calibration tasks. In critical situations, where only a very small area for calibration is possible, a precalibration procedure is used. This procedure is described later. Figure 4 illustrates the layout of the projection patterns, both for table and laser calibration, on a typical worktable.

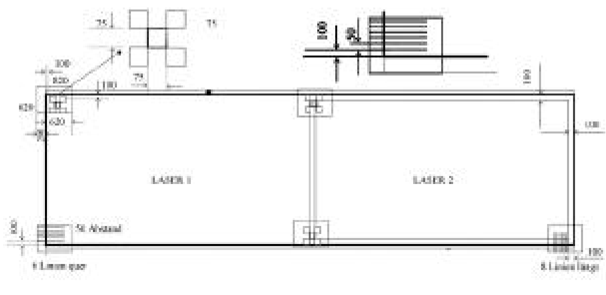

Figure 3. Characteristic calibration pattern layout for laser and table calibration on a worktable

The images are acquired twice, once with and once without the projected patterns. The subtraction of the pictures reduces the background stray light influence even further, resulting in an increased stability and consequently better results of the image processing routines. This step is essential especially when sunlight illuminates the worktable or other light is reflected directly on the steel surfaces. Figure 3 illustrates these images, also showing the importance of the background subtraction. The upper images show the table calibration pattern, while the lower images illustrate the pattern used for the laser calibration.

The result of laser- and camera calibration can be described with matrixes as follows:

$$X_l = M_l * X_w \quad (8)$$
$$X_t = M_t * X_{w,} \quad (9)$$

With X_l, X_t and X_w being the coordinate vectors in table, laser resp. world coordinates, and M_l and M_t being the transformation matrixes. Goal of the calibration is to find a transformation M_c

$$X_l = M_c * X_t \quad (10)$$

with which the coordinates of the CAD-drawing can transformed for use as control commands of the projector, so that the resulting projection matches X_t again. From (8) and (9) M_c can easily be calculate with.

$$M_c = M_l * M_t^{-1} \quad (11)$$

In many cases, the laser calibration is complicated by work pieces and other constructional parts already located on the worktable. To circumvent problems related to this, the calibration system is supplemented by a software routine taking into account the information provided about these parts by the CAD drawing and the information of the worktable contour stored in the system to determine optimal areas for the projection of the calibration patterns. As a direct result of this, the calibration patterns are not projected in a fixed array, but onto the determined optimal positions. A typical software display is shown in figure 5.

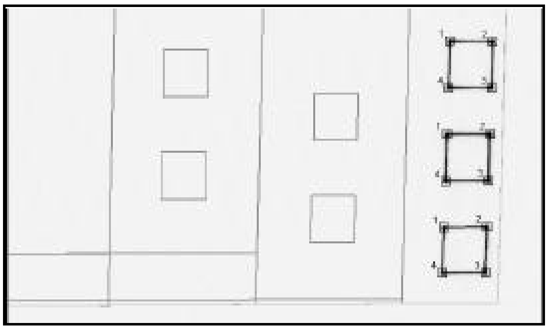

Figure 5. Typical maintenance view with inverted gray values for an enhanced laser calibration.

In this computer figure the contours of the production area and the already positioned parts are shown. As background of the figure the original camera picture with the three optimized positioned squares is used in world coordinates. Also the theoretical position of the squares is drawn and the found intersections are marked and numbered corresponding to the initialization in the software. This visualization tool makes system analysis during installation and inspection with remote maintenance very easy, because a mishandling of coordinates is visible directly on the computer screen during the calibration procedure.

In special applications, where the production area cannot be used for calibration tasks, because metal-mats or isolation material is already on the surface, a special, offset compensated calibration procedure is performed. The calibration can be performed on small areas at the corners of the movable production table, because it uses smaller calibration patterns. In order to precisely project the patterns at the wanted positions, a simple, preliminary laser-calibration, which compensates for the offset between actual and nominal positions in the laser projection, is carried out. In this case a simple pattern, i.e. a cross is projected. The position of the crossing point, as detected by the camera, is used to calculate the initial offset. Then a modified calibration routine is used, which combines table and laser calibration in one step. Within this modified routine offset compensated lines, vertical and horizontal, are projected as calibration patterns. Usually only 2 to 4 lines can be projected because of reduced projection area. The table calibration is performed on the detected lines with the standard table calibration routine. For the laser calibration the virtual intersections between the sequentially projected vertical and horizontal lines are used. All intersection points from one projector are used for the fitting in the final laser calibration. This modified calibration procedure usually gives slightly less accurate calibration results since a minor number of calibration lines can be used. Also the procedure to overcome faults in the detection is more difficult than in the normal laser calibration procedure.

With the calibrated transformation parameters a transformation from CAD data to the actual corrected projection data can be performed and accuracy of normally less than 0.5 mm to the hand measured data can be achieved. Normally the largest discrepancy from projected and hand measured distances is based on a not flat surface of the production area or changes in the outer contour of the production area due to dirt or changes due to material deformation.

5. CONCLUSIONS AND OUTLOOK

The calibration of high precision technical laser projection systems with image processing stated as a sophisticated and useful tool for production processes. The automated calibration with minimizing actual coordinates found by digital image processing with saved system coordinates made a calibration with high stability and accuracy possible. It has been shown from different systems and for longer work periods, that the automatically calibrated projection is normally more accurate than the typical positioning by manual measuring. In production facilities the faults due to missing or manually wrong positioned parts decreases to a low percentage.

The whole calibration system can be easily adapted to other projection tasks. With small changes the calibration system could also be applicable to color projection systems like LCD systems. In this case only the line detection algorithms, which are nowadays available in standard machine vision libraries, have to be adapted to get the mandatory input coordinates for the calibration system. With other adaptations the system also could handle real 3 dimensional projection tasks. In this case the transformations and projection data have to be handled in a complete 3 dimensional system, which only would be a minor expansion of the software system.

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