CALIBRATION OF A STRUCTURED LIGHT SYSTEM FOR 3D ACQUISITION

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ABSTRACT

This paper presents a calibration approach for 3D acquisition systems based on structured light. The objective of calibration is to adapt parameters so that 3D measurements are as accurate as possible. In a first step, camera parameters are determined thanks to several presentations of a reference object. In a second step, the whole system (including a camera and a projector) is calibrated thanks to 3D coordinates of reference points obtained during the first step. The main advantage of this two-step approach is the separation into two simpler calibration problems. Moreover, the adopted method for camera calibration (step 1) can account for imperfect manufacturing of the reference object. The presented calibration scheme has been used for a structured light prototype developed for 3D facial surface capture and recognition.

1. INTRODUCTION

Coded structured light is one possible approach to capture 3D surfaces [1]. It consists of a camera and a projector. The projector projects a specific light pattern on the scene that is captured by the camera. This solution has retained our attention for facial surface acquisition because it is eye-safe, it quickly grabs the face and requires only off-the-shelf components.

Many structured light systems have been developed [2]. Their main difference lies in the projected pattern. Our own developments started when only a few and expensive systems were available [3]. We later refined our prototype [4] to improve the quality of reconstructed surfaces.

The 3D precision of a structured light acquisition system depends on the camera, the projected pattern, the scene to capture and the image analysis software. A calibration phase is necessary to achieve accurate measurements.

The next section introduces the structured light acquisition approach. Section 3 describes the calibration procedure, presenting the reference object, the image processing tasks and the parameter optimisation procedure. Section 4 gives calibration results. Section 5 concludes the paper.

2. STRUCTURED LIGHT ACQUISITION

3D acquisition with structured light consists (Figure 1) in the projection of a particular light pattern on the 3D scene that is captured by a camera. The difference between the camera and projector points of view allows for triangulation, leading to 3D position estimation of illuminated points of the scene.

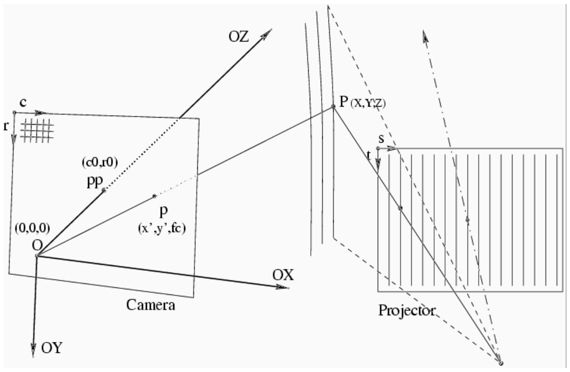

Figure 1: *structured light principle*

In our developments [3,4], we designed patterns consisting of parallel stripes (Figure 2). These provide a continuous and precise localisation in one direction. Each stripe is identified from a property (thickness or colour) that is uniquely distributed among several stripe neighbours.

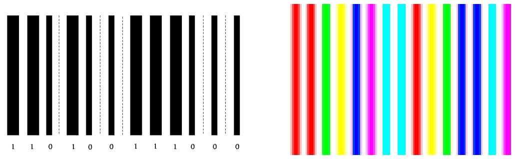

Figure 2: *Partial pattern for prototypes of [3] and [4]*

According to Figure 1, the 3D localisation of an object point 'P' is the intersection of a line of sight from the camera, passing through point 'p' detected in the image, and a plane corresponding to the stripe projected on 'P'.

3. CALIBRATION

3.1. Objective

Calibration aims at determining system parameters to achieve 3D measurements as accurately as possible. For a structured light system, these parameters concern the camera sensor and optics, the projected pattern and projector optics, and the camera/projector arrangement.

The calibration approach consists in acquiring with the system images of a reference object of known characteristics. An optimisation algorithm adapts the parameters to minimise the error between coordinates of points from the reference object and coordinates of the same points measured by the acquisition system.

The success and quality of the approach depend on the:

- Quality of the model which is used to approximate the acquisition system;
- Quality of the reference object, in terms of design (type of marker, density) and physical realisation;
- Localisation of reference points in the image;
- Algorithm optimising the parameters.

3.2. Model

In the case of structured light with stripe projection, and referring to Figure 1, the 3D coordinates (X,Y,Z) of a point P are obtained as the intersection of the line defined by the focal point O and the image point p, and the plane corresponding to the stripe illuminating P. This intersection is conveniently computed in the 3D axis system centred at the camera focal point O, with X and Y axes parallel respectively to the pixel column (c) and row (r) axes of the image plane, and with Z along the optical axis, perpendicular to the image plane.

An image point (c,r) gives the coordinates (x',y') relatively to the principal point (c0, r0) and according to a distortion compensation function DistortionFct (sufficiently precise in our tests with one radial term) :

$$x' = \mathrm{DistortionFct}(c - c0,\ r - r0)$$
$$y' = \mathrm{DistortionFct}(c - c0,\ r - r0)$$

The 3D line Op (with p = (x',y',fc) and fc, the camera focal length) passes through 'P'.

The planes of the projected stripes are written in the practical form:

$$a\,X + b\,Y + c\,Z + d = 0$$

where the normalised vector (a,b,c) gives the direction normal to the plane and 'd' is the (signed) distance of (X,Y,Z) to the plane. From the alignment of O (0,0,0), p and P, we arrive at the following equations:

$$\left.\begin{aligned} X &= d\,x' / (-a\,x' - b\,y' - c\,fc) \\ Y &= d\,y' / (-a\,x' - b\,y' - c\,fc) \\ Z &= d\,fc / (-a\,x' - b\,y' - c\,fc) \end{aligned}\right\}\ \text{(Equations 1)}$$

In our approach (see section 3.5), camera parameters (referring to c0, r0, fc, DistortionFct) are first calibrated by the Lavest technique [5]. This algorithm delivers refined 3D coordinates of the reference points which are used in a second step to estimate the projection plane coefficients a, b, c, d of all the stripes.

3.3. Reference object

The reference object provides points of known geometry used to accurately determine system parameters.

3.3.1. Design constraints

The reference object should:

- be precise enough to satisfy calibration accuracy expectations;
- contain enough reference points;
- lead to correct and precise point localisation;
- not interfere with the projected light pattern.

3.3.2. Selected design

Among planar and volumetric objects typically involved in calibration, we opted for a planar solution, which is low cost, precise and easily manufactured. Although circular patterns seem to give a more precise localisation [5,6], we preferred crossing edges that offer better visibility of stripes projected near reference points.

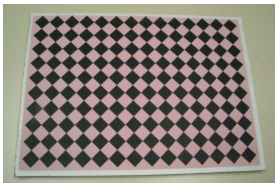

Figure 3: *Calibration object*

The calibration object consists of a planar chessboard (Figure 3), printed in A3 format (42 x 29.7 cm) and stuck on a rigid plate. It nearly covers the whole field of view at 1 m and provides one reference point every 3 cm in both directions. These reference points are the corners situated between two horizontal bright squares. The chessboard has good contrast for edge detection and bright squares are pink to offer an intensity range close to facial images with the same camera settings. To reduce interferences between the projected stripes (nearly vertical) and square edges, the chessboard is printed diagonally.

3.4. Reference point localisation and indexing

Reference point extraction necessitates image analysis tasks to deliver corner image positions with stripe indices. Corner indexing follows the regular corner arrangement of the reference object.

3.4.1. Corner localisation

For each possible corner, square edges are detected as vertical gradient maxima, weakly affected by projected stripes that are nearly vertical. Detected points are classified as rising or falling edge points. A line is fitted to each category of points. The intersection of the two lines gives a precise estimation of the corner position.

To detect the grid of corners, a first corner C1 is looked for near the image centre. Corners above (C2) and right (C3) to C1 are then localised in the vertical and horizontal directions respectively. The grid of corners is derived from C1, C2 and C3.

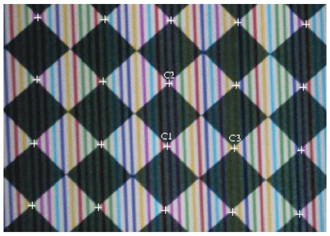

Figure 4: *Corner localisation in partial image*

Corner coordinates in the space of the reference object are derived from corner indices and the known distance between corners.

3.4.2. Stripe indexing

Around each corner (Figure 5), twelve edges along horizontal profiles in the red, green and blue fields allows for the localisation of stripe edges and for the determination of the stripe colour. Stripe indices are obtained by colour matching of consecutive stripes with the colour sequence of the pattern.

Using the local linear dependence between stripe indexing and horizontal position, the decimal stripe index at the corner position is obtained by interpolation from the position and index of detected stripe edges.

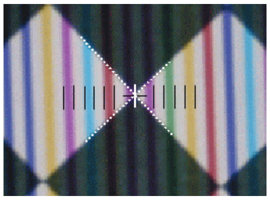

Figure 5: *Stripe localisation and indexing near a corner*

Stripes and corners appear rather regularly spaced in images of the reference object. Corner positions and their associated stripe index should exhibit a nearly linear dependence from which erroneous corners can be identified.

3.5. Parameter optimisation

Our parameter optimisation approach first calibrates camera parameters, based on the localisation of the reference points (corners). Adopting the technique developed by Lavest [5], the algorithm delivers refined 3D positions of the reference points. These are used in a second step (*system calibration*) to find the planes corresponding to each stripe edge of the projected pattern.

3.5.1. Camera calibration

For each presentation of the reference object, the position of each reference point is predicted into the camera sensor coordinates thanks to the pinhole camera model and compared to detected image positions. Optimisation consists in adapting camera intrinsic parameters (section 3.2) and rotation - translation matrices ((R-T)j, projecting reference object on the camera image plane) to minimise the function φ, which is the global error between coordinates of reference point projected on the camera sensor plane and coordinates of points detected in calibration images:

$$\text{Error} = \varphi\,(\text{camera intrinsics},\ (R\text{-}T)j,\ Xi,Yi,Zi)$$

Calibration results depend on the quality of the coordinates of the reference points. In our case, the critical point is the planarity assumption of the object. Lavest suggests to take advantage of the numerous data points (in our case, 10 images containing each 100 corners) to incorporate the reference point coordinates (Xi,Yi,Zi) in the list of parameters to be optimised. We refer to [5] for implementation details concerning this approach.

3.5.2. System calibration

Once the camera has been calibrated, an image position p specifies a 3D line containing the object point P. The

3D localisation of P still requires the *system calibration.* This estimates the projected planes corresponding to stripe edges, based on the 3D position of corners (estimated during camera calibration) and the decimal stripe indices obtained by image analysis (3.4.2).

To rely on a sufficient number of 3D positions for plane estimation, we enlarge the set of available points. Each corner of each calibration image provides six left and six right 'synthetic' points thanks to interpolation with respectively left and right immediate corners (Figure 6). 3D coordinates of the synthetic points are obtained by interpolation at stripe edges, supposing local linearity (supported by the weak distortion). The coefficients of the least mean square plane are evaluated thanks to reference and synthetic points associated to each stripe edge.

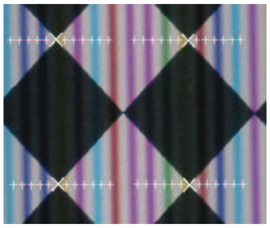

Figure 6: *Synthetic points obtained by interpolation*

Individual plane coefficients must follow a global constraint. Neglecting the moderated distortion of the projector, all planes cross along a line passing through the projector focal point, with a constant normal vector increment due to the regular spacing of stripes. This model helps deriving planes for which there were few or no points collected.

4. RESULTS

The average error of 3D point localisation for a plane at a distance of 1.2 m amounts to less than 1 mm, which fulfils our needs for face acquisition. Other error values interesting for system investigation were considered. For instance, an average error of point localisation per image was estimated to identify images of doubtful quality. An average error per projection plane was also computed to identify where the system is more precise.

The calibration procedure was tested on a few sets of calibration data. In comparison with a previous calibration approach [4], the new results were improved when the calibration object was not planar or when the object only occupied a reduced volume of the capture space.

5. CONCLUSION

An approach adapted to the calibration of structured light 3D acquisition systems has been presented. In a first step, camera parameters are calibrated with Lavest's approach, refining the knowledge about point coordinates of the calibration object. In a second step, the projection planes are estimated.

In comparison with our previous developments, the new calibration scheme performs better, especially when the reference object deviates from its specifications or when calibration captures occupy similar positions. An average error distance of 1 mm at 1 m has been judged as acceptable for 3D facial acquisition according to visual inspection and 3D face comparison experiments.

6. REFERENCES

[1] R. Jarvis, "Range Sensing for Computer Vision", In *Three-Dimensional Object Recognition Systems, Advances in Image Communication*, Vol 1, A.K. Jain and P.J. Flynn, Elsevier Science Publisher, pp 17-56, 1993.

[2] J. Battle, E. Mouaddib, "Recent progress in coded structured light as a technique to solve the correspondence problem: a survey", *Pattern Recognition*, Vol 31, No 7, pp. 963-982, 1998.

[3] C. Beumier, M. Acheroy, "Automatic Face Authentication from 3D Surface", In *British Machine Vision Conference BMVC 98*, Univ. of Southampton UK, pp. 449-458, September 1998.

[4] C. Beumier, "Facial Surface Acquisition with Colour Striping", *ICANN/ICONIP 2003*, Istanbul, Turkey, pp. 548-551, June 2003.

[5] Lavest JM, Viala M, Dhôme M, "Do we really need an accurate calibration pattern to achieve a reliable camera calibration", in *Proc. of the 5th European Conf. on Computer Vision*, Freiburg, Germany, June 1998.

[6] A. Redert, E. Hendriks, J. Biemond, "Accurate and robust marker localization algorithm for camera calibration", *1st Int. Symp. On 3D Data Processing Visualization and Transmission (3DPVT2002),* Padova, Italy, June 2002.