# Automatic Geometric Projector Calibration
## *Application to a 3D Real-time Visual Feedback*

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Abstract: In this paper, we present a fully automatic method for the geometric calibration of a video projector. The approach is based on the Heikkila's camera calibration algorithm. It combines Gray coded structured light patterns projection and a RGBD camera. Any projection surface can be used. Intrinsic and extrinsic parameters are computed without a scale factor uncertainty and any prior knowledge about the projector and the projection surface. While the structured light provides pixel to pixel correspondences between the projector and the camera, the depth map provides the 3D coordinates of the projected points. Couples of pixel coordinates and their corresponding 3D coordinates are established and used as input for the Heikkila's algorithm. The projector calibration is used as a basis to augment the scene with information from the RGBD camera in real-time.

## 1 INTRODUCTION

For a long time, video projectors have been reduced to a very classical use: projection on a planar screen with the projector located in front. The homography applied on the projected image has enabled to change the projector but the screen is still a planar surface. With structured light scanning, projection on complex surfaces can be performed (Tardif et al., 2003) but the correction is perfect from only one point of vue: the camera. Furthermore, if any object moves, the process has to be restarted again.

With the rise of intelligent TV and social gaming, most of the applications need to provide a visual feedback to the user. Microsoft's Kinect sensor allows to track people easily and to develop intuitive human to computer interactions (Harrison et al., 2011). Tracking moving objects or people is easier (Bradski and Kaehler, 2008; OpenNI, 2010; Kalal et al., 2010) but to project on them, a full geometric calibration of the projector is required. The need for an easy-to-use projector calibration is growing.

Multiple methods for projector calibration have already been proposed. Audet and Okutomi (Audet and Okutomi, 2009) method provides a good way to calibrate the intrinsic parameters of the projector but it does not solve the problem of the extrinsic calibration. The method uses a planar board to calibrate a camera and a projector at the same time . If the projector is not close to the camera, it is difficult to project on the board and in the same time, put the board in a good position for the camera detection. A solution is to increase the size of the board but the method become less user-friendly.

In (Ashdown and Sato, 2005; Audet and Cooperstock, 2007; Griesser and Van Gool, 2006), the projector calibration is done in two step. The camera is calibrated first and the projector afterwards. Moreover, the process is not fully automatic as the user has to move a board to get different views. Finally, the extrinsic calibration between the camera and the projector requires a planar surface.

Raij and Pollefeys (Raij and Pollefeys, 2004) proposed an auto-calibration method for projector-camera system but it requires planar surfaces. Drareni et al.(Drareni et al., 2009) developed an automatic method for the geometric calibration of multiple projectors using an uncalibrated camera. However, the proposed method needs a planar projection surface to realise the calibration.

In (Li et al., 2008), the authors proposed a method using structured light (Salvi et al., 2004). This method needs a planar board with known points for the system calibration. Furthermore, multiple views of the board in different positions are needed and the structured light has to be performed for each view. In (Yamazaki et al., 2011), Yamazaki et al. presented a method for the geometric calibration of a video projector using

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an uncalibrated camera and structured light. Nevertheless, the method performs the calibration up to a scalar factor. Moreover, a prior knoweledge of the principal point is needed.

In this paper, we propose a fully automatic method for the geometric calibration of a projector. The process is based on the Heikkila's algorithm (Heikkila, 2000) but it is extended to projector calibration with the use of the structured light and a RGB-Depth (RGBD) camera. Unlike the previous methods, the projection surface itself is used to perform the intrinsic and extrinsic calibration. Neither a chess board, nor a planar projection surface nor any prior knoweledge are required. The only constraint is that the calibration surface has to be non-planar. It can be composed by multiple planes (at least two) or any complex 3D surface.

The rest of the paper is organised as follows. Section 2 describes the projector model. Section 3 introduces the principle of the proposed projector calibration method. Section 4 gives details about our implementation, explains the different setup used for the experiment and gives the results. Section 5 shows how the real-time visual feedback is implemented. Finally, Section 6 concludes the work and gives some perspectives to improve the method.

## 2 PROJECTOR MODEL

The mathematical model of the projector used in this paper is the pinhole model (Hartley and Zisserman, 2004). Indeed, a projector is the same as a camera, the only diffrence being the light ray direction (Kimura et al., 2007). This model is represented mathematically by equation 1.

$$x \sim P\, X_{world} = K[R|t]X_{world} \tag{1}$$

In this equation, $x(u,v,1)$ is the pixel position in the projected image and $X_{world}(X,Y,Z,1)$ is a 3D position where the pixel $x$ light up. The matrix $K$ is called the projector calibration matrix. It is defined by:

$$K = \begin{bmatrix} f_u & 0 & u_0 \\ 0 & f_v & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where $f_u$,$f_v$ are the focal length in the u and v direction respectively and $(u_0, v_0)$, the principal point coordinates. $[R|t]$ is the pose of the projector and represents the change of coordinate frame from the world to projector coordinate. The pinhole model can be extended in order to take into account the lens distortion. The reader can find more details in (Hartley and Zisserman, 2004; Forsyth and Ponce, 2002).

## 3 OUR APPROACH

The projector calibration needs multiple couples of 3D coordinates and pixel coordinates. Using the Zhang algorithm (Zhang, 2000), the constraint of a planar surface is imposed and multiple views have to be acquired to achieve a good calibration. To get rid of the constraint of the planar surface, we propose to use the Heikkila's algorithm (Heikkila, 2000). The algorithm is based on the image acquisition of a known 3D patterns (e.g. a white cube with black circular points).

In our case, we need to calibrate a projector and the calibration surface is unknown. To solve those issues, we proposed to use the structured light and a RGBD camera. While the structured light gives pixel to pixel correspondences between the projector and the camera, the depth map provides the 3D coordinates of the projected points. Therefore, couples of 3D and pixels coordinates are retrieved. The proposed method is represented in figure 1.

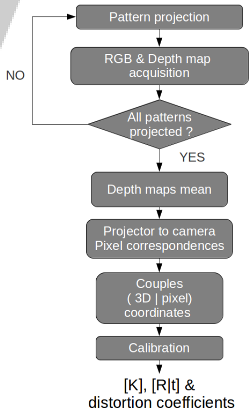


Figure 1: Calibration process.

The process is decomposed in different steps:

1. Project the Gray-coded binary patterns
2. Acquire a RGB and a depth map for each projected pattern
3. Compute the correspondences between the pixel of the projector and the RGBD camera
4. Average the depth maps
5. Compute the couple of pixel coordinates and 3D coordinates
6. Apply the Heikkila's algotrithm

The major advantages of the method are:

**Non Planar Surfaces.** The combination of the structured light and the RGBD camera removes the planar surface constraint.

**Simplicity.** The RGBD camera gives the 3d coordinates and allows to use classical calibration methods.

**Fully Automated.** No user intervention is needed.

**No Prior Knowledge Required.**

To perform the projector calibration, couples of pixel coordinates and world coordinates are needed. This is achieved by using a 3D camera and a structured light system.

## 3.1 Structured Light

The structured light is a method for retrieving the pixel correspondence between a projector and a camera. Our method is based on the Gray coded patterns. Each pixel of the projector is coded in unique binary code that is different from the neighbour pixel by one bit. Each bit of the binary code is processed individually and a binary image is created per bit, pixels value being equal to 255 if the bit is equal to 1 and to 0 if the bit is equal to 0. An example of a set of Gray coded patterns is shown in figure 2. Figure 3 shows the results of the structured light from the camera point of view. Figure 3.c is the image of the decoded columns and figure 3.d, the image of the decoded rows.

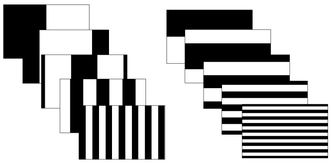


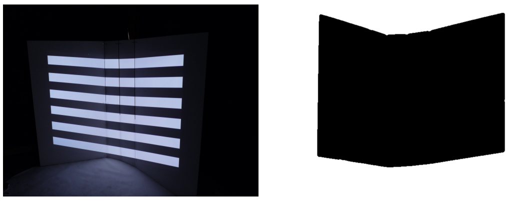
Figure 2: Gray-coded binary patterns.

## 3.2 Depth Camera

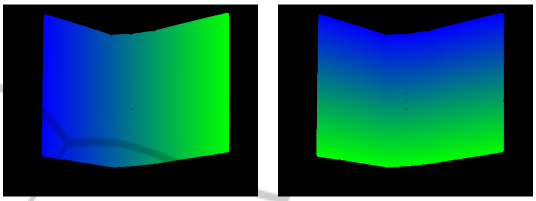
The depth camera is a RGBD camera. The RGB part of the camera allows to acquire images of the projected patterns while the depth camera is used to get a 3D model of the calibration surface. As both cameras are calibrated together, a pixel can be associated with a 3D coordinate. To reduce the inherent error of the 3D measure, a depth map of the projection surface is acquired each time a pattern is projected. At the end, all the depth maps are averaged to reduce error.

# 4 EXPERIMENTS

The structured light is implemented in C++, based on (Lanman and Taubin, 2009). The Camera calibration toolbox for Matlab from Heikkila (Heikkila, 2000) and from Bouguet (Bouguet, 2010) provides an implementation of the algorithm.



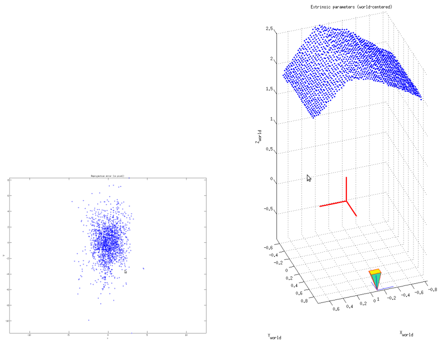
(a) Projector field of view and projection surface (b) Projection area in the camera image



(c) Decoded pixel columns position in the camera view (d) Decoded pixel rows position in the camera view

Figure 3: Results of the structured light. Pixel correspondences from projector to camera.

In our experiments, we used an OPTOMA EX762 projector with a resolution of 1024x768 and a Microsoft Kinect camera. We performed multiple calibration for different camera positions and for different zoom of the projector. Example of results are shown on the figure 4. The average reprojection error is presented in the table 1.



(a) Reprojection error (b) Side view

Figure 4: Results of the calibration.

Compared to state of the art methods (Yamazaki et al., 2011; Audet and Okutomi, 2009), the method provides a higher reprojection error. Those high values are explained by:

- the error introduced during the structured light correspondences estimation,
- the error introduced by the RGBD camera,

Table 1: Average reprojection error RMSE.

| Average reprojection error | |
|---|---|
| u | v |
| 2.5368 | 2.3558 |

- the Heikkila's algorithm which is less accurate.

Indeed, figure 5 shows that projecting on multiple planes, the pixel of the projector does not appear on a straight line. Therefore, the pixel coordinates used for the calibration are biased by the error introduced by the structured light method. As the projector has a higher resolution than the camera and the projected image occupies a small part of the camera image, an interpolation is done to get subpixel resolution in the camera coordinates and this process introduces error. Moreover, the 3D coordinate measured by the RGBD camera are also affected by an error. Finally, as (Sun and Cooperstock, 2006), Heikkila's calibration method is less robust to measurement error than classical method.

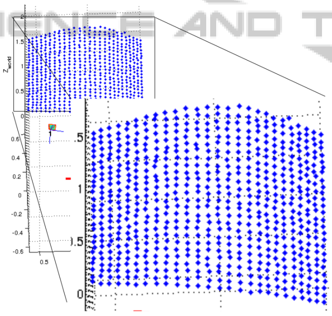


Figure 5: Error introduced by the structured light.

## 5 REAL-TIME VISUAL FEEDBACK

To perform the real-time rendering, the projector is modelled in the virtual world by a perspective projection called frustum. A frustum describes a pyramid in which every objects present is rendered (see Figure 6). It is created using glFrustum() function from OpenGL. It takes six parameters: near, far, left, right, top, bottom. The left (right) is the position of the left (right) plane of the pyramid along the x axis. The top (bottom) is the position of the top (bottom) plane of the pyramid along the y axis. Those values are obtained from the K matrix ($f_u$,$f_v$, $u_0$, $v_0$, width and height). The position and the orientation of the camera are set with gluLookAt().

To take into account the lens distortion, the rendering result is set in a texture. The position of each pixel is modified according to the distortion equation (Bradski and Kaehler, 2008).

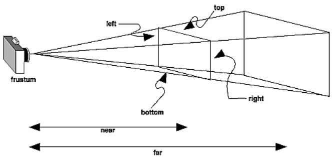
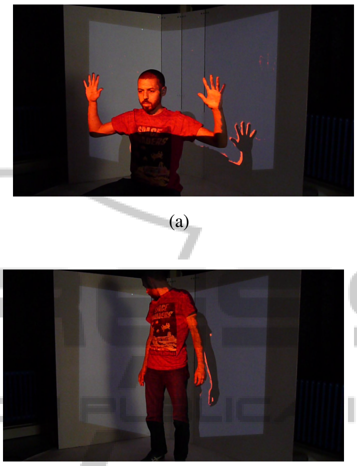


Figure 6: Perspective projection defined with glFrustum() (Opengl et al., 2007).



(a)

(b)

Figure 7: Results of the structured light. Pixel correspondences from projector to camera.

indent Figure 7 shows the reprojection of a 3D tracking information from OpenNI. On this figure, we can see that the red blob projection follows the user in real-time regardless the user position.

## 6 CONCLUSIONS AND FUTURE WORKS

We have described an original method for the geometric calibration of a projector and applied this new method to real-time rendering. The proposed method has multiple advantages.

First, the planar surface constraint introduced by most of the state of the art techniques is removed by the combination of the Heikkila's algorithm (Heikkila, 2000), the structured light and the RGBD camera. The RGBD camera simplifies the calibration process, thanks to the depth map. In the same time, the RGB captor allows to acquire images of the projected Gray coded patterns and then, to calculate the projector to camera pixel correspondences. With this combination, the calibration can be performed on any complex surface. Second, the method is fully automated and does not require any user intervention. Third, no prior knowledge about the projection surface and the projector are needed to achieve the calibration.

Nevertheless, our implementation requires some improvements. The current projector to camera correspondences computation introduces errors. A better interpolation method has to be implemented.

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