AUTOMATIC MULTI-PROJECTOR CALIBRATION
A Review of Systems for Non-experienced Users

Stefan Klose, Jérémie Gerhardt
Fraunhofer FIRST, Kekuléstr. 7, 12489 Berlin, Germany

Timo Engelke, Arjan Kuijper
Fraunhofer IGD, Fraunhoferstr. 5, 64283 Darmstadt, Germany

Keywords: Multi-Projector Systems, Three-Dimensional Graphics and Realism, Virtual Reality, Camera Calibration.

Abstract: Multi-projector systems are widely used in many application areas. Such systems are for instance employed to increase the brightness or the resolution of projected images. Intrinsic to multi-projector systems are problems like geometric misalignment, especially when projecting onto complex arbitrarily formed projection surfaces, and photometric deviations. Therefore, several difficult calibration tasks (geometry, brightness, color) have to be performed. A high-quality and easy-to-use calibration process is the key to good usability for untrained or unexperienced users. Due to the fact that manual calibration is time-consuming and imprecise, automatic approaches were developed in recent years. This paper analyzes the most popular state-of-the-art algorithms and setups with respect to their advantages and disadvantages. We summarize the general working principles of calibration algorithms and provide an outlook into the fields in which the described algorithms are most useful.

1 INTRODUCTION

Projection systems are widely used in many application areas of industry, research and development, art and culture or teaching. Single-channel systems are not adequate for more complex use cases that aim to increase the brightness or resolution, display three-dimensional stereoscopic content, obtain redundancy, or guarantee a focused projection on a three-dimensional projection surface. Therefore, *multi-projector* systems are utilized. However, without adaptations the partial projections of such a system do not form a homogeneous projection. Visible *artifacts* due to pixel offsets, brightness differences, and deviations from the geometry of the projection surface may occur.

In order to eliminate those effects a multi-projector system has to be calibrated in pixel-perfect fashion. In most cases this calibration is a *non-trivial* task that has to be solved with manual, semiautomatic or *fully automatic algorithms*.

In general, the following problem has to be solved: An arbitrarily formed projection surface will be illuminated by a projector cluster. The projectors are only roughly aligned, yielding a view that clearly shows the different projectors; see for an example Figure 1. The goal of calibration algorithms is to achieve a homogeneous projection that looks like it was projected only from one device. Therefore, several calibration tasks have to be solved:

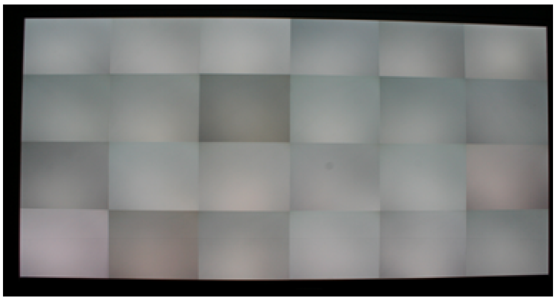
Figure 1: Uncalibrated projector setup.

1. *Geometry Correction:* Adjustment of the projectors with respect to each other and a camera or other reference systems, such as the projection surface itself.
2. *Vignetting and Brightness Correction:* Adjustment of the projectors' visible brightness fall-off and brightness deviations that occur in overlap-

Klose S., Gerhardt J., Engelke T. and Kuijper A..
AUTOMATIC MULTI-PROJECTOR CALIBRATION - A Review of Systems for Non-experienced Users.
DOI: 10.5220/0003356702860295
In *Proceedings of the International Conference on Computer Graphics Theory and Applications* (GRAPP-2011), pages 286-295
ISBN: 978-989-8425-45-4

ping regions or result from the projection angle or the projector type.

3. *Color correction:* Adjustment of deviations in the overall chromaticity due to aging lamps or different projector models.

These three tasks should be solved in such a way that a multi-projector system provides best visual quality with minimal setup costs. There should be no time consuming manual tasks but an automatic approach instead, using measurement devices like digital cameras.

The aim of this paper is to provide a comparison of such approaches with respect to *utilization for users without too much experience*. To our best knowledge there is currently no such paper available. It will help both experienced and inexperienced users to choose appropriate calibration methods or to improve their own algorithms. For some older more technique-focused in-depth surveys on multi-projector displays and (vision-based) calibration techniques we refer to, for example, (Majumder and Brown, 2007; Brown et al., 2005; Ni et al., 2006; Bimber et al., 2008; Bimber and Raskar, 2005; Li et al., 2004; Pollefeys et al., 1999).

In the remainder we present the essential components of a multi-projector system, followed by the more general principles of calibration. The most popular dedicated state of the art automatic algorithms are discussed in section 4. Subsequently, we list their advantages and disadvantages, again from the point of view of untrained users, and provide application examples in which the described techniques can be used. We complete this paper with a short conclusion.

2 SYSTEM SETUP

In multi-projector setups we usually deal with high resolution content that shall be displayed in real time. Bandwidth problems in transferring the image information to the projection unit usually appear. Thus a common approach is to cluster the system, running multiple render units connected to the projectors and creating the resulting image, see Figure 2.

One or multiple cameras capture the projection surface and work with the calibration application and the clustering master in order to create proper calibration data. These data will be used by designated applications, which are rendered through the cluster machines. In this section we describe the general options in configuring multi-projector setups.

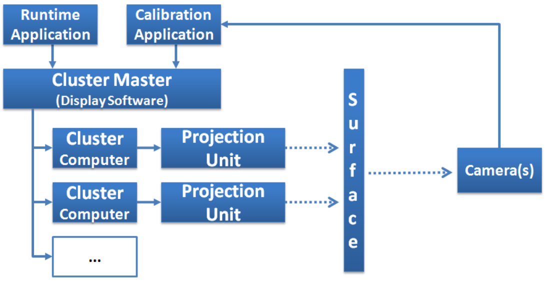

Figure 2: Generalized Setup Components.

2.1 Cluster Setup

A cluster usually consists of a distributed rendering system with at least one master. The master distributes the information to be displayed to the clients – the cluster machines. Mainly the clients are used for applying the rendering loop. The cardinality between projector and render machine can be chosen freely, but should be consistent throughout the entire configuration. In order to configure and setup viewing and calibration parameters, clients and master must be able to communicate with each other. Already existing frameworks are for example (Fellner et al., 2009; Isakovic et al., 2002).

Technologies like Remote Desktop Applications (RDP, VNC, etc.) are a way for transmission of content in such a cluster. These technologies deliver content but can be ineffecient or incapable on high densities of information, like multimedia or 3D-Content, since there is no hardware abstraction.

One possible solution for effiecient hardware abstraction is Chromium (aka. WireGL (Humphreys et al., 2001)), which simulates a network-bound graphics card and smartly distributes the OpenGL commands via network to the clients. The main advantage is the compatibility with older OpenGL software. The disadvantage comes with maintenance of the large and constantly changing OpenGL standard (Humphreys et al., 2008).

Scene graph distribution delivers the main advantage by being a complete abstraction of hardware standards and at the same time delivering parts of the scene graph description through the network at high performance. Additionally this method can be combined with image-based distribution, allowing load balancing within the cluster (Roth et al., 2006). Both 2D and 3D applications can be realized with such a system. A main disadvantage is the insufficient support of standard applications. This can be compensated by rendering X-Window drawing commands or RDP as textures. An abstract language definition allows the description of the main application (Behr et al., 2007).

A potential problem of display in a cluster is the synchronization of the vertical sync signal of all video outputs. On fast moving scenes it can prevent the partial simulcast display of two consecutive images. Professional graphic cards therefore support gen locking (NVidia, 2010). Another solution is using custom-built software/hardware (Allard et al., 2003).

2.2 Projector Devices

Different projection technologies can change the approach for calibration. Generally there is a need for stability in terms of light intensity, colors and resolution.

A good contrast and black value is important. Otherwise, especially when projecting dark scenes with projector clusters, the effect of a homogeneous projection vanishes. LCD (Liquid Christal Display) usually delivers a bad contrast, while newer technologies like LCoS (Liquid Crystal on Silicon) and SLP (Spatial Light Modulators aka DLP or DMD) gain much better contrast.

3D projections can have an impact on the calibration as well. Passive frequency shifting systems like Infitec (Infitec, 2010) need to be setup with stacked projectors, which leads to loss of pixels. Additionally the color space in such systems is reduced. Newer systems, like RealD (RealD, 2010) or active approaches like presented in (Havemann et al., 2007) are using only one projector. Therefore, the latter systems have a huge impact in hardware for synchronizing each eye in multi-projector setups.

2.3 Projection Setups

Depending on the field of application, several projection setups or a combination of them are utilized:

- Stacked Projection: At least two projectors illuminate the same area of the projection surface to increase the overall brightness, for redundancy reasons, to facilitate 3D-stereoscopic projections, or to increase the usable color space.
- Mosaicked or tiled projection: At least two projectors are aligned side by side or one upon the other to increase the overall resolution. The combination of vertically and horizontally adjusted components is also possible. The uncalibrated and overlapping projections can form a relatively regular or an irregular grid. Depending on the size of the overlapping regions soft-edge or hard-edge blending will be deployed.

  Hard-edge blending does not allow the physical overlap of adjacent projections. It demands a huge effort in hardware and manual calibration while coping with projectors having a bad black value. Soft-edge blending compensates the addition of light in the overlapping regions by modifying the input images accordingly.
- Windowed Projection: Several independent projection surfaces or a plurality of monitors are used. This is similar to a mosaicked projection but without any overlapping regions at all. Due to those gaps the overall projection appears like a window to a virtual world. When using at least two projectors the overall resolution is increased, as well.

In the first two cases the spatial, geometric, and colorimetric synchronicity is crucial to create the illusion of a homogeneous projection. The projections must be aligned in pixel-perfect and synchronous fashion to prevent fuzzy or even doubled images, which can lead to headaches (Pastoor, 1995). In the latter case, the projections should also be aligned with respect to their window.

2.4 Measurement Devices

Measurement is typically used in some kind of control system, where the input of the visible image is fed back into the control system and changes the appearance of the displayed content. Typical setups are using one (Bimber et al., 2005; Klose, 2009), multiple static (Raskar et al., 2006; Dingeldey et al., 2010) or movable cameras. These are usually used for either sampling of calibration patterns or photometric measurement. For correct chromatic measurements calibrated colorimeter (Pagani and Stricker, 2007) or colorimeter cameras (SphereOptics, 2010) are used. Thus mostly a combination of colorimeter and digital cameras are used. High Dynamic Range (HDR) cameras also offer a promising approach for delivering higher photometric resolution.

In order to achieve good calibration results, the images taken must be focused and well-exposed. The capturing must also be reproducible.

3 GENERAL PRINCIPLES OF CALIBRATION

For the automatic calibration of projectors it is important that geometric, brightness and color correction are processed consecutively as these steps depend on each other. The result of all processes can be combined in GPU-based shaders and applied within the render pipeline. Another approach would be to apply the results within a graphic card driver or the projector engine itself.

3.1 Geometry Correction

As defined previously in this paper, the geometry correction retrieves the parameters to adjust the projectors with respect to each other, the projection surface and the observers.

The calibration starts by projecting reference patterns on the surface. The patterns can for example be fiduciary markers, coded light stripes or binary patterns. Captured images of those projected patterns are then analyzed by filtering, black image subtraction, thresholding, or gradient-based contour detection. This allows registering the projectors with respect to the projection surface in the space of the measuring device.

Two calibration approaches can be compared for a matter of complexity (calibration with respect to a camera or to a projection surface). The calibration with respect to a camera (or observer calibration) is relatively easy because of its direct mapping from projector space to camera space:

$$(\mathbf{u},\mathbf{v}) : \mathbf{T_{p \to c}}(\mathbf{x},\mathbf{y}) \tag{1}$$

where $(\mathbf{u},\mathbf{v})$ are the coordinates of projector space in camera space $(\mathbf{x},\mathbf{y})$. The border of the overall projection will be set with respect to the camera's field of view (i.e. largest inscribing rectangle of the multi-projection). Because the calibrated image is aligned with respect to a camera and not to the shape of the projection surface, this approach is not observer-independent.

The calibration with respect to a projection surface is more complex because the actual projection screen has to be reconstructed or detected:

$$(\mathbf{u},\mathbf{v}) : \mathbf{T_{c \to s}}(\mathbf{T_{p \to c}}(\mathbf{x},\mathbf{y})). \tag{2}$$

This is done by (physical) marker detection, user interaction, model matching, or 3D reconstruction. Because the calibrated image will be wallpapered across the projection surface, this approach is observer-independent.

Once the calibration method is chosen, the warping parameters $(\mathbf{u},\mathbf{v})$ can be derived. They can be calculated using global or local approaches. Global warping applies a homography matrix. This method assumes a perfect projection surface and can lead to errors. Local per-pixel warping is more accurate. The latter can also correct distortions introduced by slopes and dales of the projection surface.

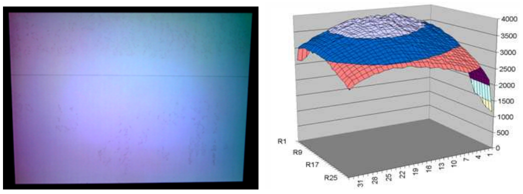

Figure 3: Brightness and luminance profile of one tile.

3.2 Vignetting and Brightness Correction

Figure 1 already showed an example of an uncalibrated hard-edge multi-projector setup. In Figure 3 one sees the result of one projector (tile) with the measured brightness values as well. The general aim of this correction is gaining uniformity in luminance. Based on the measured brightness values over all the partial projections of a multi-projector system, the algorithm has to select the point with the lowest brightness. In order to guarantee uniformity in luminance, all the projectors in the installation have to be adjusted to that brightness. The main disadvantage of this approach is the fact that the dynamic of the brightness gets lost.

Majumder and Stevens propose a photometric calibration with simple monochromatic cameras that need fixable exposure and shutter (Majumder and Stevens, 2004). A more precise measurement can be done using Colorimeter cameras which directly results in absolute CIE coordinates and luminance values. If a regular camera allows taking high resolution pictures (and then accurate spatial information) the direct use of its RGB values should be avoided, especially if the camera sensors remain unknown (Vora and Trussell, 1993). One possible approach is taking a high dynamic range (HDR) image (Debevec and Malik, 1997) of each ramp level (Pagani and Stricker, 2007) from which only the luminance values are used.

A very universal approach for applying the calibration is the use of a 3D look-up table (LUT) per primary color channel represented in two dimensions for the pixel location and for the pixel level adjustment. This is common sense as it can easily be implemented in GPU shaders or is supported by a variety of professional projector engines. In order to compute a LUT for each projector, the following operation needs to be repeated: project and measure ramps of pure red (R), green (G) and blue (B). With this information the response curves of a projector can be measured (global and per color channel) and its gamma value can be determined. A typical response curve is a gamma shape: x^{γ}, where x is between 0 and 1 and γ approximately between 2 and 3.

In a tiled display installation with overlapping projections, soft-edge blending has to be performed additionally. The geometrical calibration provides the information on overlapping regions which can be used for the blending. Soft-edge blending reduces the brightness in the overlapping regions such that it is as bright as the rest of the global projection. This is done by cross-fading the light intensity between the projectors with a proper blending function. A sigmoid blending function offers a more subtle transition between blended and unblended areas compared to linear blending. The following example applies to two overlapping projectors:

$$\begin{aligned} f(x) &= \sin\left(x\pi - \frac{\pi}{2}\right)0.5+0.5 \\ g(x) &= \sin\left(-x\pi + \frac{\pi}{2}\right)0.5+0.5 \qquad (3) \end{aligned}$$

where the results have to be gamma-corrected by the projectors' known exponential factors $1/\gamma$ or by their inverse response curve function.

3.3 Color Correction

This operation requires estimating the common gamut of the installation, i.e. defining what the common displayable colors of the projectors are (Pagani and Stricker, 2007; Bern and Eppstein, 2003; Wallace et al., 2003). The CIE XYZ primary values of each projector are computed from the measured corresponding spectral reflectances.

Once the common gamut is defined, the gamut mapping operation is performed by a matrix operation. For each projector the new RGB values will be computed that map to the same (global) XYZ values. The great advantage of a gamut mapping operation is that it ensures that color differences are not visible to the human eye. But it can also drastically reduce the color dynamics. The following equation demonstrates how the RGB values are modified before projection:

$$c' = g_p^{-1}(\mathbf{M_p}\mathbf{M_c}c_\gamma) \qquad (4)$$

where $\mathbf{M_p}$ is the matrix of one projector, $\mathbf{M_c}$ is the matrix characterizing the common gamut, c_γ the corresponding RGB values for the installation response curve (which is defined by the user) and $g_p^{-1}(c)$ the inverse response curve function of projector p.

4 CALIBRATION ALGORITHMS

We have described the general working principles of automatic calibration algorithms. Now we present selected state-of-the-art algorithms utilizing these principles. Again, we focus on automatic approaches only. We provide a short description and evaluate the algorithms regarding unique characteristics and advantages, accuracy, simplicity and drawbacks.

4.1 iLamps/Display Grids (iL/DG)

Short Description: Raskar et al. have developed several automatic multi-projector calibration algorithms. Notable approaches are iLamps (Raskar et al., 2006) and Display Grids (Raskar et al., 2004).

The system consists of several autonomous projectors that build ad-hoc clusters. Projectors can be registered and non-registered dynamically. The used projectors are modified and enhanced with a camera, a tilt sensor, a wireless communication module, and a computer. With the help of those additional modules, the topology of the projectors and their geometric neighborhood will be detected. This information leads to an automatic geometric correction including blending.

Using the integrated camera, the 3D depth of the projection surface at certain manually-aligned calibration markers is triangulated using structured patterns. Not only the projector that contains the camera but the adjacent projectors are taken into account. Under the assumption that the projection surface is a vertical plane or a vertical quadric, the deviation from the world horizontal and vertical can be determined using the integrated tilt sensor. The triangulation data and the tilt values are used to calculate homography matrices for each projector. Applying those matrices corrects the projector distortions with respect to their neighborhood and the desired parallelism to the world horizontal and vertical. A similar method was described in (Webb and Jaynes, 2007).

Unique Characteristics and Advantages: Self-configuring ad-hoc clusters using projectors with integrated cameras are an excellent way to create seamless tiled projections with very large aspect ratios.

Accuracy: For the triangulation the projector-camera system has to be perfectly calibrated. An imprecise system calibration leads to significant 3D reconstruction errors. The use of global homography matrices implies projection errors because those methods assume perfect planes or quadrics. This assumption is often insufficient in reality and is also described in (Okatani and Deguchi, 2006).

Simplicity: The system extensibility is very good due to the automatic registration and non-registration. The use for the modified projectors leads to a very simple setup process. The simplicity is unfortunately decreased by using manually aligned physical markers.

Drawbacks: Modified projectors are still no off-theshelf product. Therefore, the modified projectors have to be assembled and calibrated very carefully. Otherwise the projection would suffer from substantial errors. Due to the used homography matrices, the method is only applicable to perfect surfaces or a second per-pixel post warp is needed. The partial projections and their corresponding camera images, respectively, have to overlap to detect neighboring projections. Therefore, the previously described windowing setup is limited or impossible.

4.2 Embedded Light Sensors (ELS)

Short Description: An automatic calibration method that adjusts the projection with respect to a reference projection surface was developed by Lee at al. (Lee et al., 2004).

In contrast to most other automatic approaches it uses no digital camera, but light sensors that are embedded at the corners or other feature points of the projection surface. Due to the low amount of used sensors a per-pixel calibration is not possible. To determine the geometrical relation between projector and projection surface, a homography transformation matrix is calculated. For this, several pixel-to-sensor relations have to be measured. A relation implies that a certain projected pixel illuminates a certain sensor. To measure these relations an iteratively refining binary pattern is projected. Once the relations between sensors and projected pixels are known, the homography matrix can be determined. Applying this matrix in real-time on the projected image leads to the projection fitting in the projection surface. Embedded sensors are also used by 3D Perception (3DPerception, 2010).

Unique Characteristics and Advantages: No digital camera is needed because the projection surface itself measures the distortions via embedded light sensors. The projection is observer-independent because it is aligned with respect to a rectangular reference plane.

Accuracy: When using perfect planes this method implies a high quality.

Simplicity: When abstracting from modifying the projection surface with the sensors, it is a very easy-to-use method. The calibration can be triggered by simply holding the projection surface into the projector's frustrum.

Drawbacks: A crucial drawback of this algorithm is the applied global homography transformation. If the projection surface contains slopes and dales or is bent a homography is not sufficient anymore due to the errors that result from the difference between global transformation and local deviations. This particularly applies to multi-projector systems. Therefore, a perfect projection surface is needed. Also a modified projection surface is needed.

4.3 Smart Projectors (SP)

Short Description: The Smart Projector technology was developed by Bimber et al. (Bimber et al., 2005). Meanwhile it is distributed by the company Vioso under the name *Vioso Presenter*. Vioso particularly specialized in extreme case projections like structured walls, colored wallpapers, curtains, or rocks.

The system is capable of correcting geometric and photometric distortions. Therefore, structured light is projected and captured with a digital camera. Due to the placement of the projectors or the structure of the projection surface, the calibration patterns are distorted. Those distortions are also visible in the camera's image plane. Because the method assumes that camera and observer position are identical, it corrects the distortion with respect to the image plane. Due to the projected structured light the position of each pixel on the projection surface is known and is stored in a look-up-table. Furthermore, the desired undistorted projection with respect to the image plane is also known. It is a rectangular projection, that shares the content's aspect ratio, that is parallel to the image frame, and is also within the distorted projection. Hence for every projected pixel, an distortion correction vector and a photometric correction value can be calculated and stored within a look-up -table. The correction of the projected content is done in real-time using pixel shaders. Similar algorithms were described in (Klose, 2003) and (Majumder and Brown, 2007).

Unique Characteristics and Advantages: The algorithm offers a fast and precise correction of geometric and photometric distortions on markerless, arbitrarily formed projection surfaces.

Accuracy: Due to the dense sampling with structured light the calibration is very accurate.

Simplicity: Uncalibrated projectors are used for this method. Due to the assumption that camera and observer position are identical, there is no need for a system calibration that determines the relationship between camera and projectors. No further markers or knowledge about the projection surface is needed.

Drawbacks: As mentioned before the method assumes that camera and observer position are identical. Therefore, the camera has to be placed very carefully. When projecting onto highly distorted surfaces such as corners, the corrected image will always appear to be wrong, because it is aligned with respect to the flat image plane and not with respect to the three-dimensional structure of the projection surface.

4.4 Markerless View-independent Registration of Multiple Distorted Projectors on Extruded Surfaces (MVIRoMDPoES)

Short Description: Sajadi and Majumder developed an algorithm for markerless, view-independent, camera-based registration of multiple distorted projections on extruded projection surfaces (Sajadi and Majumder, 2009).

Their method works for projection displays defined by a 2D curve (profile curve) that is vertically extruded and limited by two virtual horizontal planes. The aspect ratio of the rectangle that is shaped by the four corners of the projection surface is also known.

In the first step of the algorithm, the intrinsic and extrinsic parameters of the camera are determined. A first guess, using the known focal length of the camera, is optimized using the four corners, and is stored in a camera matrix. Secondly, with the help of this matrix display parameters are recovered. Samples on the upper and lower border of the projection surface (in the image plane) are reprojected and intersected with the two virtual horizontal planes. This leads to two curves in 3D space that will be averaged. A parametric representation of those curves is found using polynomial curve fitting. In the last step, a mapping from projector coordinates to display coordinates via camera coordinates is found. The correspondence between projector and camera coordinates is defined using rational Bezier patches. For this, blobs are projected, whose positions in the projector space are known and that map to uv-coordinates in the camera space. Then rays are cast through those coordinates and intersected with the 3D model. This leads to 2D correspondences with the display coordinates, that are used to correct the distorted projection. In (Sajadi and Majumder, 2010) the method was extended for displays containing discontinuities, such as corners.

Unique Characteristics and Advantages: The method is one of the first algorithms for markerless calibration of 3D surfaces. Due to the calibration with respect to the actual shape of the projection surface it is observer-independent.

Accuracy: Due to the sparse sampling per-pixel calibration will only be achieved if the actual display does not contain local deviations from the expected shape.

Simplicity: Because of the markerless approach a complex and time-consuming setup is not necessary. The camera can be placed relatively freely. There is no extra system calibration because the calculation of those parameters is part of the algorithm itself.

Drawbacks: Currently the method requires user feedback. The blobs are partly registered by hand. The algorithm also assumes a linear camera. Using camera lenses with radial distortions leads to small errors. For geometric registration the projection has to be entirely inside the projection surface. Therefore, a rimless projection is not possible. Due to the sparse sampling local errors cannot be corrected.

4.5 Constraint-based 3D-Reconstruction with Automatic Calibration (AutoCalib3D)

Short Description: An automatic, camera-based, markerless calibration method was developed by Klose. It calibrates the projection with respect to a three-dimensional extruded projection surface (Klose, 2009) (Klose, 2010).

The projection surface can be described by either vertical or horizontal, equivalent vectors that stand orthogonal on a virtual plane (e.g. a cylinder segment or a room's corner). The projection surface itself serves as the reference system. Therefore, uncalibrated components can be used. For scanning the projection surface vertical and horizontal calibration patterns are projected. The corners and the borders of the display are detected by projecting white with all the projectors. Therefore, the entire projection has to be larger than the projection surface.

Due to the knowledge about the projection surface it is possible to reconstruct its 3D surface from a single filtered image of the corners and borders. In a first step, corresponding points on two opposite borders are determined by applying a homography transformation to the captured projection surface. After the homography transformation, the corresponding points share the same x- or y-value. Those points are marked within the untransformed image. Then rays are cast from a virtual camera to the marked points. The 3D model is calculated by optimizing vectors that connect the corresponding upper and lower rays until the conditions are satisfied (equivalent, orthogonal on a plane). Finally, rays are cast from the virtual camera to the intersection points of the calibration patterns in the image plane. To guarantee a rimless projection, several intersection points outside the projection surface are non-linearly extrapolated. The rays also intersect the 3D model and yield uv coordinates. Subsequently, each intersection point's position in the projector space and display space is known. Using those parameters, geometric correction and blending can be performed in real time.

Table 1: Decision support matrix; +: good, o: average, -:bad.

Algorithm	Calibration with respect to	Warping type	Accuracy	Simplicity
iL/DG (sec. 4.1)	plane, quadric	homography	-	o
ELS (sec. 4.2)	plane	homography	-	+
SP (sec. 4.3)	camera (arbitrarily formed surface)	per-pixel	+	-
MVIRoMDPoES (sec. 4.4)	extruded 3D surface	Bezier patches	o	o
AutoCalib3D (sec. 4.5)	extruded 3D surface	per-pixel	+	o

Unique Characteristics and Advantages: This algorithm is also one of the first approaches for markerless calibration of 3D surfaces. It yields a rimless projection. Even borders of the projection surface are used for calibrating the camera (ad-hoc lens distortion correction). The method was derived from perceptual psychological aspects. It is therefore also observer-independent.

Accuracy: Due to the dense sampling with calibration patterns, sub-pixel accuracy is achieved. The projection surface does not have to be perfect. Deviations on it will be also corrected.

Simplicity: The markerless approach and the use of uncalibrated components simplifies the setup process immensely. No time-consuming measurement of camera-projector-systems or camera-projectionsurface-system are neccessary.

Drawbacks: In order to achieve a rimless calibrated projection, the uncalibrated projection has to be larger than the projected surface. Hence, pixels are lost. If the optimization is aborted prematurely (i.e. the global optimum is not found), the 3D model and the calibration parameters are erroneous. To achieve good optimization results, the projection surface should also have a certain Δ in 3D depth (If a plane is defined by connecting left and right border of the projection surface, Δ is the longest line that is orthogonal to this plane and also connects the projection surface and the plane.).

5 COMPARISON OF THE APPROACHES - DECISION SUPPORT

In this section we will compare the most important properties of the described algorithms (see also Table 1). It also serves as a decision support for potential users, both experienced and non-experienced ones.

The first column of Table 1 contains the abbreviations of the described algorithms. The actual calibration will be performed with respect to a reference system which is stated in column 2. The next column contains the warping type that is used by the different algorithms. Column 4 and 5 indicate the accuracy and the simplicity of the described algorithms.

To decide which of the algorithms is suitable for a planned installation, the user must first know the type of the projection surface. *Warping type* and *accuracy* are related, because the latter depends on the first one, but also on the quality of the projection surface. Under the assumption that the projection surface is not perfect and contains slopes and dales, a dense sampling of the projection surface leads to a higher accuracy. Therefore, per-pixel warping is more accurate than Bezier patch warping, which is again more accurate than a homography warping. *Simplicity* depends on the setup process. Manual user interaction leads to a decrease in the simplicity score (iL/DG: manually aligned markers, SP: proper adjustment of the camera). iL/DG can increase its score by utilizing ad-hoc clustering. The waiver of the camera and the intuitive calibration with respect to the projection surface leads to the best simplicity score for ELS. Algorithms 4 and 5 gain a medium score because of the more complex system setup (compared to ad-hoc clusters). At the other hand the camera does not have to be placed accurately, because again, the projection surface serves as the reference system.

5.1 Applications

A variety of interesting setups can be realized with the described calibration methods, some of which are mentioned in the following.

Obvious applications are based on the previously mentioned advantages of multi-projector systems (e.g. higher resolution, brightness, redundancy). A high resolution and crisp image is for instance needed in car design. Outdoor events rely on bright projections, while redundant projections are essential for conferences. Stacked and mosaicked calibrated displays can be used for those applications. Stacked projections can also be used to display 3D-stereoscopic content, where two projectors project the left and right eye information. Another interesting application is the extension of color space by projecting low and high frequencies with two or more stacked and calibrated projectors (Boosmann, 2007).

Beyond that, interesting art or augmented reality projects are conceivable, like virtual art projections (Seales and Landon, 2005) or projections onto buildings (UrbanScreen, 2009). The latter can be utilized as a connection between past, present and future. A building can also be "x-rayed" or it can be illuminated for entertainment purposes or aesthetic reasons. Augmented projections can also be used in future shopping scenarios in which the projection has to be aligned with respect to the shelves.

Regarding the two methods presented last, eye catchers are not a nemesis for calibrators anymore. Such eye catchers can have interesting 3D shapes and are imaginable at fairs, in entrance halls but also in art exhibitions or for advertising reasons. More practical applications like immersive cylindrical displays or CAVEs are also realizable. The latter can be calibrated with a *divide and conquer* strategy with the described methods.

As one can see there are many exciting applications. It is also up to the reader to define new application areas beyond the ones described here.

6 CONCLUSIONS

In this paper we have presented general aspects, factors of influence, algorithms, and problems that have to be dealt with when setting up multi-projector installations. Often these problems are so multi fold that expert knowledge is required. In most cases this is lacking for non-experienced or untrained users. Within this context we therefore focused on automatic calibration. There is no general recipe for creating such an installation, requiring again a certain amount of insight for these non-experienced or untrained users. This paper contributes an abstraction of the main principles and delivers a guide for both experienced and inexperienced users willing to set up such a system or improve their methods. It can be applied in development of multi-projection systems for industry, research, art and culture, or teaching and should help making the best choice for a specific calibration problem.

REFERENCES

3DPerception (2010). Simulation. http://www.3d-perception.com/docs/SimulationLow.pdf.

Allard, J., Gouranton, V., Lamarque, G., Melin, E., and Raffin, B. (2003). Softgenlock: Active stereo and genlock for pc cluster. In *Proceedings of the Joint IPT/EGVE'03 Workshop*.

Behr, J., Dähne, P., Jung, Y., and Webel, S. (2007). Beyond the web browser - x3d and immersive vr.

Bern, M. and Eppstein, D. (2003). Optimized color gamuts for tiled displays. In *SCG '03: Proceedings of the nineteenth annual symposium on Computational geometry*, pages 274–281.

Bimber, O., Emmerling, A., and Klemmer, T. (2005). Embedded entertainment with smart projectors. *Computer*, 38(1):48–55.

Bimber, O., Iwai, D., Wetzstein, G., and Grundhfer, A. (2008). The visual computing of projector-camera systems. In *ACM SIGGRAPH 2008 classes, Los Angeles, California: ACM*, pages 1–25.

Bimber, O. and Raskar, R. (2005). *Spatial augmented reality: merging real and virtual worlds*. A. K. Peters, Ltd.

Boosmann, T. (2007). *PhD Thesis: Multispektrale Farbreproduktion: Projektionssystem und Algorithmen fr eine additive, multispektrale Farbsynthese*. Shaker Verlag, Aachen.

Brown, M., Majumder, A., and Yang, R. (2005). Camera-based calibration techniques for seamless multiprojector displays. *IEEE Transactions on Visualization and Computer Graphics*, (11):193–206.

Debevec, P. E. and Malik, J. (1997). Recovering high dynamic range radiance maps from photographs. In *SIGGRAPH '97: Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pages 369–378.

Dingeldey, F., Schiewe, M., Gerhardt, J., Ahlers, K.-I., and Haulsen, I. (2010). Interactive 3d stereoscopic dome with automatic calibration. In *Digital conference proceedings for Eurographics 2010, Areas Papers*, pages 9–16.

Fellner, D. W., Behr, J., and Bockholt, U. (2009). Instantreality – a framework for industrial augmented and virtual reality applications. In *Proc. Sino-German Workshop "Virtual Reality and Augmented Reality in Industry"*, volume 2, pages 78–83.

Havemann, S., Hopp, A., and Fellner, D. (2007). A single chip dlp projector for stereoscopic images of high color quality and resolution. In *Proc. 13th EG Symposium on Virtual Environments,10th Immersive Projection Technology*, pages 21–26.

Humphreys, G., Eldridge, M., Buck, I., Stoll, G., Everett, M., and Hanrahan, P. (2001). Wiregl: a scalable graphics system for clusters. In *SIGGRAPH '01: Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 129–140.

Humphreys, G., Houston, M., Ng, R., Frank, R., Ahern, S., Kirchner, P. D., and Klosowski, J. T. (2008). Chromium: a stream-processing framework for interactive rendering on clusters. In *ACM SIGGRAPH ASIA 2008 courses*, pages 43:1–43:10.

Infitec (2010). Infitec homepage. http://www.infitec.net/ infitec.html.

Isakovic, K., Dudziak, T., and Köchy, K. (2002). X-rooms. In *Proceedings of the seventh international conference on 3D Web technology*, Web3D '02, pages 173–177.

Klose, S. (2003). Auto-calibration of multi-projector systems. *Patent Number US 7,215,362 B2*.

Klose, S. (2009). Constraint-basierte 3d-rekonstruktion und automatische kalibrierung von multiprojektorsystemen. *3D-NordOst 2009, 12. Anwendungsbezogener Workshop zur Erfassung, Modellierung, Verarbeitung und Auswertung von 3D-Daten*, pages 61–70.

Klose, S. (2010). Autocalib3d: Constraint-basierte, automatische kalibrierung von multiprojektorsystemen bezüglich dreidimensional-verformter, markerloser projektionsflächen. *7. Workshop der GI-Fachgruppe VR/AR*, pages 33–45.

Lee, J. C., Dietz, P. H., Maynes-Aminzade, D., and Hudson, S. E. (2004). Automatic projector calibration with embedded light sensors. In *In Proceedings of UIST 2004*, pages 123–126.

Li, C., Lin, H., and Shi, J. (2004). A survey of multi-projector tiled display wall construction. In *Proceedings of the Third International Conference on Image and Graphics*, ICIG '04, pages 452–455, Washington, DC, USA. IEEE Computer Society.

Majumder, A. and Brown, M. S. (2007). *Practical Multi-projector Display Design*. A. K. Peters, Ltd.

Majumder, A. and Stevens, R. (2004). Color nonuniformity in projection-based displays: analysis and solutions. *IEEE Transactions on Visualization and Computer Graphics*, 10(2):177–188.

Ni, T., Schmidt, G. S., Staadt, O. G., Livingston, M. A., Ball, R., and May, R. (2006). A survey of large high-resolution display technologies, techniques, and applications. In *Proceedings of the IEEE conference on Virtual Reality*, VR '06, pages 223–236.

NVidia (2010). nvidia - genlock. http://www.nvidia.com/object/IO_10793.html.

Okatani, T. and Deguchi, K. (2006). Autocalibration of an ad hoc construction of multi-projector displays. In *Proceedings of the 2006 Conference on Computer Vision and Pattern Recognition Workshop*, CVPRW '06.

Pagani, A. and Stricker, D. (2007). Spatially uniform colors for projectors and tiled displays. *Journal of the Society for Information Display*, 15(9):679–689.

Pastoor, S. (1995). Human factors of 3-d imaging: results of recent research at heinrich-hertz-institut berlin. *Proc. 2nd Int. Display Workshop*.

Pollefeys, M., Koch, R., and Gool, L. V. (1999). Self-calibration and metric reconstruction in spite of varying and unknown internal camera parameters. *INTERNATIONAL JOURNAL OF COMPUTER VISION*, 32:7–25.

Raskar, R., van Baar, J., Beardsley, P., Willwacher, T., Rao, S., and Forlines, C. (2006). ilamps: geometrically aware and self-configuring projectors. In *ACM SIGGRAPH 2006 Courses*, SIGGRAPH '06.

Raskar, R., Vanbaar, J., and Beardsley, P. (2004). Display grid: Ad-hoc clusters of autonomous projectors.

RealD (2010). Reald homepage. http://www.reald.com.

Roth, M., Riess, P., and Reiners, D. (2006). Load balancing on cluster-based multi projector display systems. In *WSCG 2006*.

Sajadi, B. and Majumder, A. (2009). Markerless view-independent registration of multiple distorted projectors on extruded surfaces using an uncalibrated camera. *IEEE Trans. Vis. Comput. Graph.*, 15(6):1307–1316.

Sajadi, B. and Majumder, A. (2010). Auto-calibration of cylindrical multi-projector systems. *IEEE Virtual Reality*.

Seales, W. and Landon, G. (2005). The museum and the media divide: Building and using digital collections at the instituto de cultura puertorriquena. *D-Lib Magazine*, 11(3).

SphereOptics (2010). Pm 1200 - colorimeter. http://www.sphereoptics.de/Englisch/Products/10/PM-1200 Imaging Colorimeter 090904R.pdf.

UrbanScreen (2009). 555 kubik, how it would be if a house was dreaming. http://www.urbanscreen.com/usc/41.

Vora, P. L. and Trussell, H. J. (1993). Measure of goodness of a set of color-scanning filters. *Journal of the Optical Society of America. A, Optics and image science*, 10(7):1499–1508.

Wallace, G., Chen, H., and Li, K. (2003). Color gamut matching for tiled display walls. In *EGVE '03: Proceedings of the workshop on Virtual environments 2003*, pages 293–302.

Webb, S. and Jaynes, C. (2007). Image-based parametric projector calibration. *US Patent, Publication Number US 2007/0268306 A1*.