Camera Based Calibration Techniques for Seamless Flexible Multi-Projector Displays

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Abstract. Multi-projector large-scale displays are commonly used in scientific visualization, VR, and other visually intensive applications. In recent years, several camera-based computer vision techniques have been developed that help reduce the effort needed to construct tiled projection-based display such that they are *seamless* both in terms of *geometry* and *color*. These automated techniques have replaced the traditional labor intensive manual deployment by using cameras to "calibrate" display geometry and photometry, computing per-projector corrective warps and intensity correction to create seamless imagery across projector mosaics. These techniques have made projector-based displays cost-effective, low-maintenance, and flexible. In this paper, we present a summary of the different camera-based geometric and color registration techniques. Several techniques have been proposed and demonstrated, each addressing particular display configurations and modes of operation. We overview each of these approaches and discuss their advantages and disadvantages.

1 Introduction

Expensive monolithic rendering engines and specialized light projectors have traditionally made projector-based displays an expensive “luxury” for large-scale visualization. However, with advances in PC graphics hardware and light projection technology, it is now possible to build such displays with significantly cheaper components. Several systems [12, 10, 9] have demonstrated the feasibility of cost-effective large-format displays composed of commodity light projectors and driven by a cluster of PCs.

The mosiaced image created by multi-projector displays must be seamless, i.e., appear is if it is being projected from a single display device. This involves correcting geometric misalignments and color variations within and across the different projection devices thus creating an image that is both geometrically and photometrically seamless. This process is commonly referred to as “calibration”. Calibration involves two aspects: *geometric registration* and *color correction*. Geometric registration deals with geometric continuity of the entire display, e.g., a straight line across multiple projector images should remain straight in the final image. Color correction deals with the color continuity of the display, e.g., the brightness should not vary visibly within the display.

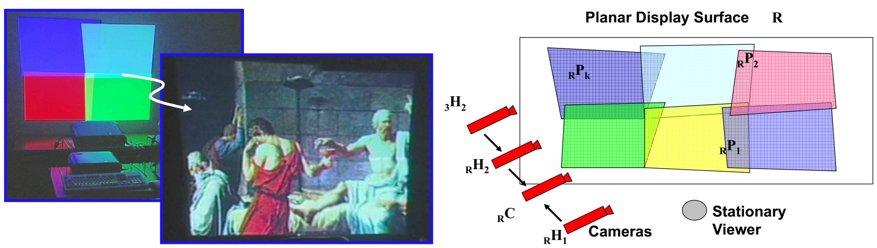

Fig. 1. Left: Camera-based geometric registration is used to calculate image-based corrections that can generate a seamless image from several (unaligned) overlapping projectors. Right: 3×3 linear homographies are compute which relate the projectors to the display reference frame R. A camera (or cameras) is used to observe projected imagery. Projector-to-camera homographies concatenated with camera-to-reference frame homographies are used to compute the necessary projector-to-reference frame mapping.

Recently, techniques have been developed that use one or more cameras to observe a given display setup *as it is*. Camera-based feedback is used to monitor the contribution from the different projectors and then compute the necessary adjustments needed to register the imagery, both in terms of geometry and color [26, 23, 5, 30, 4, 11, 2, 24, 18, 17, 20]. These adjustments can then be applied automatically in software to create a large seamless imagery as shown in Figure 1(left).This greatly reduces the time and effort needed to setup a display. For example, the configuration in Figure 1(left) can be quickly deployed even by a novice user. Accurate manual geometric alignment and color compensation of a similar display, a common approach adopted by many research and commercial systems [6, 12, 8, 21], can take several hours even with the help of precise mounting hardware and manual manipulation of the projector settings. Hence, camera-based calibration techniques have not only simplified the deployment of projector-based large-format displays, but have also allowed for flexible and cost-effective projector arrangements.

In this paper we present a brief overview of various camera-based calibration techniques. Our goal is to provide potential developers of large format displays a useful summary of available techniques, and a basic understanding of their benefits and limitations. We start with geometric registration techniques in Section 2. We discuss techniques for display on planar surfaces and arbitrary surfaces with stationary and moving viewers. In section 3, we focus on photometric registration techniques that address the color variation across such displays for surfaces of both Lambertian and non-Lambertian nature. Next, in Section 4, we list several representative systems that use camera-based calibration and discuss their pros and cons. Due to space limitation, we only briefly outline the basic algorithms with references to the original papers. A longer more in-depth technical report is available for interested readers [31].

2 Geometric Registration

When building a multiple-projector display, two types of geometric distortions must be addressed. First, there are *intra-projector* distortions, i.e., distortions due to off-axis projection and/or non-planar display surfaces. Secondly, there are *inter-projector* distortions, i.e., edges at adjacent projector boundaries do not match. Geometric registration techniques are designed to detect both types of distortions and correct them.

Such camera-based registration techniques can be divided into two categories based on the type of display surfaces addressed, either *planar* surfaces or *non-planar* surfaces. We first discuss techniques for planar display surface. These are used to construct large-scale video walls. Later, we extend the discussion to arbitrary display surfaces, for example, multiple planar walls or semi-spherical screens. These scenarios are particularly suited for immersive displays.

2.1 Planar Display Surfaces

Consider a planar display composed of several projectors. Each projector P_k's image can be related to a reference frame, R, on the display surface via a 2D planar homography . This projector-to-reference frame homography is denoted as ${}_R\mathbf{P}_k$ where k is the index of the projector (notation adopted from [4]). Projected imagery can then be aligned to the display surface by pre-warping displayed imagery of projector P_k using the homography ${}_R\mathbf{P}_k^{-1}$. This pre-warp can be performed directly in the rendering pipe-line [30] or using a post-rendering warp [26].

To determine the correct ${}_R\boldsymbol{P}_k$ for each projector P_k, we need to establish point-correspondences between each projector and the display's reference frame R. This is accomplished by using a camera (or cameras) to observe the projected imagery, as shown in figure 1(right). To compute a homography, it is necessary to establish four point correspondences between coordinate frames. Using more than four point correspondences allows a least-square fit solution which is often desirable in the face of errors and small non-linearities (see [5, 23] for more details about computing homographies).

Using Single Camera We first consider the case where only one camera is used. A camera-to-reference frame homography, ${}_R\boldsymbol{C}$, between the camera and display reference frame, R, is computed. This is typically done by manually selecting point correspondences between the camera image and known 2D points on the display surface. After this, projected imagery from each P_k is observed by the camera. A projector-to-camera homography from each projector k to the camera, denoted as ${}_R\boldsymbol{C}_k$, is calculated. Afterwards, ${}_R\boldsymbol{P}_k$ can be indirectly computed using the projector-to-camera homography and then the camera-to-reference frame homography as: ${}_R\boldsymbol{P}_k = {}_R\boldsymbol{C} \times {}_R\boldsymbol{C}_k$ where the operator $\times$ represents a matrix multiplication. This simple technique has been used in many research systems [30, 25, 11]. Sub-pixel registration accuracy between adjacent projectors has been reported.

Using Multiple Cameras While the above single camera approach is simple, fast, and accurate, it does not scale well for large displays because of the limited resolution and field of view of a single camera. Extending this approach to multiple cameras (or a single moving camera) can overcome this limited field of view problem. Such approaches require registering each camera's reference frame to the world reference frame. Registering the multiple cameras can be cast as a global optimization problem. For example, Y. Chen et al [5] used simulated annealing to find a global registration from images collected by a pan-tilt camera. More recently, H. Chen et al [4] further improved both the accuracy and speed for this global registration by building a minimum-spanning "homography tree" that minimizes registration errors among camera-to-camera reference frames. These approaches proved effective in building displays composed of up to 24 projectors.

2.2 Arbitrary Display Surfaces

Geometric registration via homographies work only if the display surface is planar. Immersive environments, such as video domes, often use non-planar display surfaces. The following approaches address such non-planar display surfaces in two modes of operation. One for a stationary viewer and another for a moving head-tracked viewer. These techniques can of course be also applied to planar display surfaces.

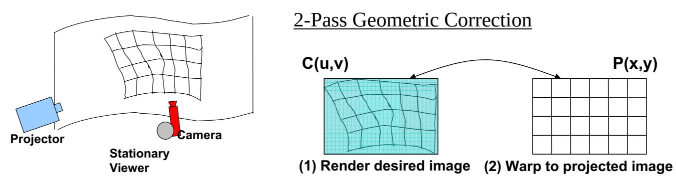

Fig. 2. Projectors display features which are observed by a camera placed near the desired viewing location. The desired image is (1) rendered and then (2) warped to the projected imagery based on its mapping to the camera.

Stationary Viewer Raskar [27] and Surati [28] propose a registration algorithm that uses a two-pass rendering technique to create seamless imagery on arbitrary display surfaces. Their approach uses a single camera placed at the location from where the viewer will observe the displayed imagery. Projected features from each projector, P_k, are displayed and registered in the camera image plane. This establishes a mapping, $C(u, v) \Rightarrow P_k(x, y)$, from the projectors features $P_k(x, y)$ to their positions in the camera's image plane $C(u, v)$. The projected features $P_k(x, y)$ are typically used to form a tessellated grid in the projector space as well as the camera image space (see Figure 2).

To correct the displayed imagery, a two-pass rendering algorithm is used. In the first pass, the desired image to be seen by the viewer is rendered. This rendered image is assumed to be aligned with camera reference frame. In the second pass, this image is warped to the projected image using the $C(u, v) \Rightarrow P_k(x, y)$ mapping. For clarity, Figure 2 shows this procedure using only one projector. This technique will produce a seamless image when multiple overlapping projectors are observed by the camera (see [2] for details). The warp specified from the $C(u, v) \Rightarrow P_k(x, y)$ mapping generates a geometrically correct view from where the camera is positioned. As the viewer moves away from this position, the imagery will begin to appear distorted. Several systems such as the PixelFlex by Yang et al [30] and the one by Brown et al [2] have incorporated this fixed mapping technique for registration. Sub-pixel registration accuracy between projectors has been reported.

Moving (Head-Tracked) Viewer For a moving viewer in an arbitrary display environment, a necessary warping function between each projector and the desired image must be dynamically computed as the view position changes. Raskar et al. [26] presented a two-pass rendering algorithm to address this situation. Figure 3(a) shows a diagram of this rendering approach. The desired image is rendered in the first-pass. This image is then used as a projective texture and projected from the viewer's point of view onto a 3D model of the display surface. This textured 3D model is then rendered from the view point of the projector (second-pass). When displayed, this second rendered image will appear as the correct desired image to the viewer.

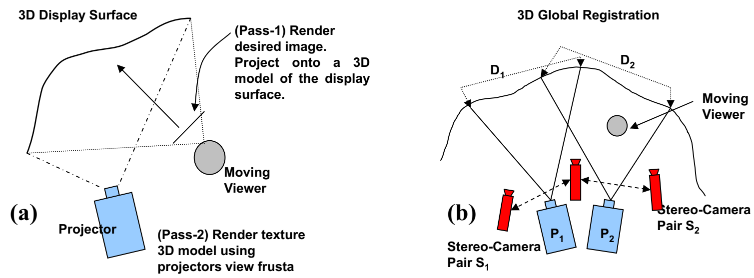

Fig. 3. a) two-pass rendering algorithm for a moving-viewing and an arbitrary display surface. The first-pass renders the desired image to be observed by the user. This is used as a projective texture and projected from the viewer's point of view onto the display surface. The textured display surface is then rendered from the projector's point of view. When projected, 2-pass image will look correct to the viewer. (b) stereo-camera pairs are used to determine the 3-D display surface D_1 and D_2 and projector locations P_1 and P_2. These are then registered into a common coordinate system along with the head tracker.

To realize this algorithm three components must be known: (1) a 3D model of the display surface, (2) the projectors' view frustum with respect to the display surface and (3) the viewer's location with respect to the display surface. All three items need to be in the same coordinate frame system for the algorithm to work. Computer vision techniques can be used to extract the information automatically. For example, Raskar et al [23] proposed a system that used multiple stereo cameras to reconstruct the 3D display surface as well as calculate the projectors' positions (as shown in Figure 3(b)). Reconstructed display surfaces together with a head-tracker are all registered into a global coordinate frame. A third pass warp was introduced to help eliminate errors arising in the overall 3D reconstruction and registration process. In practice, this system approach is non-trival to implement. Recently, Raskar et al [24] introduced a simplified parameterized transfer equation for warping on quadric surfaces.

3 Photometric Correction

Color is a three dimensional quantity defined by one dimensional luminance (defining brightness) and two dimensional chrominance (defining hue and saturation). The entire range of colors that can be reproduced by a display is represented by a 3D volume is called the *color gamut* of the display. Majumder et al [19, 14] showed that most current tiled displays made of projectors of the *same model* show large spatial variation in luminance while chrominance is almost constant spatially. Thus, the subproblem of *photometric (luminance) variation* is the most significant contributor to the color variation problem. The color variation in multi-projector displays has been classified in three different categories. The detailed description of these and their causes are available at [19]. In brief, these categories are: *Intra-Projector Variation*, *Inter-Projector Variation*, and *Overlap Variation* (i.e., variations in overlap regions).

Traditionally, intra and inter projector variations are compensated by manual manipulation of projector brightness, contrast or white balance. For known overlap regions (which is a by-product from geometric registration), blending or feathering techniques are used to smooth color transitions across these regions. Blending can be achieved in either software [26, 30] or hardware [13, 3] (see Figure 4). Some works use expensive light measuring instruments such as a spectroradiometer to address various photometric issues such as gamut [29] and luminance uniformity [16].

Fig. 4. Left: Attenuation masks computed for each projector. Applied in software this pixel-wise attenuation helps produce smooth (feathered) seams in the overlapped region. Right:Optical Blending by mounting metal masks on the optical path of the projector that attenuates the light physically.

We describe here recent approaches that address intra, inter and overlap photometric (luminance) variation using an inexpensive digital camera and compute the necessary corrections. We should note, however, that a commodity camera cannot be used to estimate the chrominance variation accurately because of its limited color gamut. Its primary use is to *estimate* and *correct* the luminance variation of a display since it can capture a high range of luminance using different exposures. Such a method devised in [18, 19] aims at achieving *photometric uniformity*, that is, *identical* photometric response at every display pixel. This method comprises of an offline camera based *calibration* and an online *image correction*.

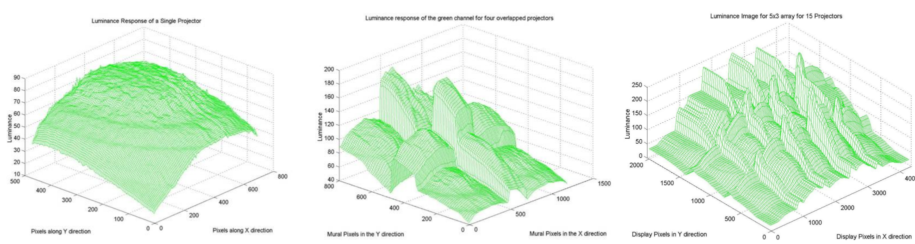

Fig. 5. Left: The luminance surface for one projector. Middle and Right: Display luminance surface for a 2×2 array of four projector and 3×5 array of fifteen projectors respectively. (All for the green channel)

To begin, geometric registration method is first performed to find the correspondences between the camera and the projector pixels. The camera is then used from the same position to capture three images for each projector P_j, one for each channel when they are projecting the maximum luminance input. From these images and the geometric registration information, the projector luminance function, L_{P_j}, for each projector is generated. These projector luminance functions are then added up spatially using the geometric calibration information to generate the display luminance function L_D. The luminance surfaces thus generated for a projector and the whole display is shown in Figure 5. Next a common achievable response that can be achieved by every pixel of the display is identified. Since the dimmer pixels cannot match the brighter pixel, this is given by $L_{min} = \min_{\forall(x_d,y_d)} L_D$. Finally, a per pixel map is generated which provides the attenuation factor for each pixel to achieve the common achievable response at that pixel. This display *luminance attenuation map (LAM)*, A_d is given by

$$A_D(x_d, y_d) = \frac{L_{min}}{L_D(x_d, y_d)}$$

¿From the display LAM, a LAM for each projector, A_{P_j} is cut out using geometric calibration information.

This calibration process assumes linear response for the projectors. To compensate for their non-linearity, the intensity transfer function (ITF) for each channel of each projector needs to be estimated. Since this fuction is spatially invariant [14], a photometer can be used to estimate this at one location for each projector. Or, to avoid such cost prohibitive sensors, [22] presents a method where the high dynamic range (HDR) images [7] is used to measure the ITF of the projector.

In the image correction step, the image from a projector is multiplied by the projector LAM. Then the inverse ITF is applied to the image to compensate for the projector's non-linearity. This two steps can be applied to any image projected from the display. The results of this method is presented in Figure 6.

Fig. 6. The top row shows the image before correction, and the bottom row shows the image after luminance matching. Left and middle: Digital photograph of 2×2 array of four projectors. Right: Digital photograph of 5×3 array of fifteen projectors. In this case, the image after correction was taken at a higher exposure.

This method achieves reasonable seamlessness. But it matches the photometric response of every pixel is to the 'worst' pixel on the display ignoring all the 'good' pixels that are very much in majority. Hence, this results in compressed dynamic range. Ongoing research [15] is directed towards achieving a perceptual uniformity rather than a strict phorometric uniformity.

All of the methods mentioned so far assume white display screen. Some recent work addresses the issue of using such displays to project on displays of any surface reflectance like a brick wall or a poster-board [20] which can be of use for specific defense and emergency applications.

4 Discussion and Conclusion

All of the approaches discussed in the previous sections have been used and tested in various projector-based display systems. In this section, we summarize several representative systems in chronological order (Table 1) and discuss the pros and cons of various approaches.

System	Display surfaces	number of projectors	number of cameras	Resolution (mega pixels)	Geometric registration	Photometric correction	Rendering passes
Surati [28]	arbitrary♡	4	one	1.9	fixed warping	color attenuation	two
Raskar et al [23]	arbitrary◇	5	multiple	3.8	full 3D model	software blending	three
Y. Chen et al [5]	planar	8	one on PTU	5.7	Simulated annealing	optical blending	one
PixelFlex [30]	arbitrary♡	8	one	6.3	fixed warping	software blending	two
H. Chen et al [4]	planar	24	multiple	18	homography tree	optical blending	one
Metaverse [11]	multiple walls◇	14	one	11	homography	software blending	one
iLamp [24]	quadric surfaces	4	one/projector	3.1	full 3D model	software blending	two

◇ head-tracked moving viewer. ♡ static viewer (image is correct for a single viewing position).

Table 1. Characteristics of representative large-format displays using camera-based calibration

Compared to traditional systems relying on precise setup, large format displays constructed using camera-based calibration provide the following advantages:
More flexility: These can be deployed in a wide variety of environments, such as existing rooms with non-planar walls which traditional systems may find difficult to work with.
Easy setup and maintenance: Set-up procedures can be completely automated. This is especially attractive for temporary setups in trade-shows or a field environment. In addition, professional maintenance of precise alignment and color balance is not required to keep the display functional.
Reduced costs:.Expensive projectors with high quality optics to reduce radial distortion and color non-uniformity can be replaced with inexpensive commodity projectors. Also, projectors can be causally placed using commodity support structures (or even as simple as laying the projectors on a shelf).

On the other hand, camera-based calibration techniques require cameras and support hardware to digitalize video signals. This, however, can be amortized by the savings from the long-term maintenance cost. Also, there are some rendering overheads to correct various distortions which can be reduced or eliminated by recent hardware. For example, 3D-Perception CompactView X10 projectors is one of the first companies to offer a projector which can perform real-time corrective warp to the incoming video stream [1].

On the geometric front, restricting the display surface to be planar has many benefits. First, there are more scalable techniques to register very large arrays with sub-pixel accuracy, such as the homography tree approach [4], that cannot be applied to surround immersive environments. The parameterized transfer equation extends planar surface algorithms to quadric surfaces [24]. While some screens can be modeled as quadric surfaces, it is difficult to manufacture them precisely. However, homography-based approaches assumes all of the distortions are linear. It cannot, for instance, correct the non-linear radial distortion introduced by projector's optical system. Non-linear approaches like [9] can be used to correct these non-linearities, but are difficult to scale.

For arbitrary display surfaces, the direct mapping from camera space to projector space is the most efficient way to generate seamless images from one fixed view location. The resulting two-pass rendering algorithm compensates for display surface distortion as well as projector lens distortion. For small arrays (4-5 projectors), this approach is very flexible and can allow quick deployment of projector-based displays in a wide range of environments. However, since it requires the camera to see the entire display, it is not scalable. The technique for a moving user and arbitrary display surfaces involves a full 3D modeling of the display environment including projector poses and display surface geometry. While it is the most general solution to large scale display deployment, it is non-trivial to implement a robust and practical system. Due to its complexity, the best registration error reported so far is about 1-2 pixels.

Almost all geometric correction can be achieved using texture mapping in real time on commodity graphics hardware. The non-linear corrections required to achieve photometric uniformity are encoded efficiently as per-pixel linear operations and 1D color look-up-table (LUT), that can be applied in real time on commodity graphics hardware using pixel-shaders and dependent texture look up respectively. (Details in [17]).

Determining which technique is most suitable for a given application depends on the display configuration and requirements of the application. However, all the techniques presented are sufficiently robust for their intended configurations.

In conclusion, camera-based calibration techniques allow the deployment of a much wider range of configuration for projector-based displays. The capability to automatically align and blend multiple projected images eases setup and maintenance efforts and greatly reduces their cost. Coupled with advances in distributed rendering software and graphics hardware, creating inexpensive and versatile large format displays using off-the-shelf components is now a reality. It is our hope that the information summarized in this paper will provide projector-based display users a starting point for understanding the various available techniques and their associated advantages and disadvantages.

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