# HIGH-RESOLUTION LIGHTING OF 3D RELIEFS USING A NETWORK OF PROJECTORS AND CAMERAS

Behzad Sajadi, Mahdi Abbaspour Tehrani, Mehdi Rahimzadeh, Aditi Majumder

Department of Computer Science, University of California, Irvine

## ABSTRACT

Vibrant lighting of relief maps via high-resolution dynamic projected imagery can be a powerful tool for simulation, augmented reality, and visualization, enabling several scientific, educational and entertainment applications. This is usually achieved via multiple projectors lighting the relief map, which are then sensed by multiple cameras for geometric and color calibration. However, cumbersome semi-automatic calibration techniques have limited the applicability of such systems.

In this paper we present the first fully-automatic lighting system that registers high-resolution images on arbitrarily-shaped relief maps using a network of projectors and cameras. The devices are uncalibrated and casually aligned with the only constraint that every surface point of the relief is seen by at least two of the cameras. Our method achieves precise geometric registration followed by seamless edge blending. Quick recalibration allows changes in the position and number of the devices, as well as the surface geometry. Thus, our work can enable easy deployment of spatially augmented reality environments in various scales playing a fundamental role in increasing their popularity in several applications like geospatial analysis, architectural lighting, cultural heritage restoration, theatrical lighting and visualization. It can also be applied to any immersive VR environments on non-planar surfaces like domes or cylinders.

*Index Terms* — immersive visualization, auto-registration, multiprojector display, camera-based calibration, self-calibration

## **1. INTRODUCTION**

Lighting real 3D objects to create a compelling spatially augmented reality (SAR) experience is becoming popular for several applications like cultural heritage restoration, architectural relighting, geospatial analysis, scientific visualization, and theatrical lighting. The key to providing a compelling experience in such applications depends on augmenting a 3D surface with high-resolution, vibrant dynamic imagery. This demands projecting light on the object from multiple projectors to create image quality that would successfully match a real experience. To register multiple such projectors accurately on the surface demands multiple sensors. However, a scalable automatic calibration that can address multiple such devices on a real surfaces has only been explored in a limited manner before [1, 2, 3]. Hence, such SAR systems have focussed on small objects (outside-looking-in environments) using one or a few projectors being sensed by a single camera that observes all the projectors and hence, provides the common centralized reference with respect to which the registration is performed.

In this paper, our goal is to provide a compelling SAR on large 3D white relief maps (inside-looking-out environments) that are instrumented with multiple projectors to create high resolution imagery that matches the limits of the human visual system. This demands multiple cameras sensing the projected images on the relief. To enable sub-pixel accuracy in registering these projectors that is critical to create a vibrant experience. Finally, we desire a completely scalable and automatic solution where users can easily add/change the number of projectors or cameras and their positions (to increase realism) or the relief sections (to increase span, structure and details) on demand.

Towards this end, we adopt a distributed method inspired by [4, 5]. We present a system where a large 3D relief map is lighted by a network of n projectors and m cameras connected to p computers. Our architecture is completely flexible with casually placed uncalibrated devices that follow the only constraint that every surface point is visible to at least two cameras and that the surface is completely lighted by the projectors. Such a set up can be achieved relatively easily since the camera field-of-view (FOV) is usually much larger than the projector FOV. Therefore, in most common scenarios m < n, though our method works for  $m \ge n$  as well where usually each surface point is visible to more than two cameras. Note that large multi-projector systems are usually run by cluster of machines which is ann inexpensive way to provide multiple i/o ports for the large number of devices such systems usually have. Hence, the assumption of having a large number of machines (p > 1) to create a more efficient system does not entail any additional cost.

Our method achieves completely registered imagery from n projectors on the 3D relief, and consists of geometric registration and edge blending. The geometric registration technique entails a distributed method to recover the salient device parameters enabling recovery of the 3D surface geometry and registration of images on the surface. The photometric registration is achieved by a distributed edge blending technique. Our loosely constraint method renders an hitherto unseen scalability to allow the addition of devices and expansion or change in structure of the relief sections.

Main Contribution: Our work provides the first general solution for any multi-projector display auto-calibration on insidelooking-out systems for larger 3D surfaces (e.g. immersive environments, large reliefs) and is complementary to (a) small scale outside-looking-in systems where a single projector-camera is used for depth reconstruction via imperceptible structured light [6] or to correct image distortion with small head movements without recovering the 3D depth [7]; and (b) large scale multi-projector displays on planar surfaces [8, 9, 10, 11, 12, 13, 14, 15, 16]. Though distributed techniques exist to register multiple projectorcamera units on planar displays [4, 5] leading to a network of equal numbered projectors and cameras (special case of m = n), the proposed system is the first one that can handle completely uncalibrated devices and unknown non-planar surface geometry, as opposed to systems where either device parameters or the surface geometry needs to be known or the devices are tightly coupled with each other (e.g. 1 or 2 cameras per projector) [17, 18, 19]. Several color registration techniques [20, 21], including a smooth gamut morphing [22], has been proposed earlier. These can be applied only on 2D parametric surfaces (e.g. planes and cylinders) where the projectors are arranged in a 2D grid. Our edge blending method is relatively simpler and can achieve adequately acceptable smooth blending for non-rectangular overlap regions. However, it is our desire to extend more sophisticated color calibration methods to this more general setup [22].

The generality of our system can be demonstrated by deploying systems in many different configurations (Section 4). For example, if n = 1 and m = 2 (1 projector with 2 cameras) we can use our method to recreate the interactive sandbox ecosystem that uses one projector and a kinnect for 3D reconstruction [23]. In fact, we can increase the quality of display and sensing many fold by using n > 1 and m > 2 with no additional algorithmic cost. It can also be used for large non-planar display surfaces like domes or cylinders in immersive visualization environments. Instead of using custom solutions for each kind of surface [24, 25, 26, 27, 28], our general solution can be used to deploy multiple uncalibrated devices registering images seamlessly across all such display shapes.

Our method allows a hitherto unseen ease in deployment of such systems, several of which are illustrated in Section 4. Since our solution is designed to scale well for large values of m and n, when driven by multiple computers (p > 1) our method can distribute the work load across multiple machines much more conducively creating a more efficient system.

#### 2. OUR METHOD

We consider a system of n projectors lighting a 3D display surface D, being sensed by m cameras such that any point on the surface is seen by at least two cameras. These devices are connected to p computers in a loosely coupled distributed architecture, where the n projectors and m cameras are connected to the p machines via two static independent interconnection network respectively that do not change during calibration.

We assume uncalibrated projectors and cameras devoid of any lens distortion. We denote a camera by  $C_i$ ,  $1 \le i \le m$ , a projector by  $P_j$ ,  $1 \le j \le n$  and a computer by  $S_k$ ,  $1 \le k \le p$ . Further, we assume all the cameras have the same focal length, f, practically enforced via same zoom settings. For projectors, we do not need complete projector calibration to achieve our goal and hence no other assumption is required.

Our method has two components: an *offline calibration* algorithm and an *online image correction* algorithm. The goal is to reconstruct the display surface and recover geometric and color parameters of each  $P_j$  required to achieve a registered image. The recovered parameters are then used in the online image correction phase (Section 3) to warp the geometry and attenuate the color of the images projected by each  $P_j$  in real-time. The result is seamlessly registered relief map that can be wallpapered for multiuser applications or can be registered from any arbitrary viewpoint of a moving user for single-user applications.

The calibration has three steps: *configuration identification* (Section 2.1), *geometric registration*(Section 2.2) and *edge blending* (Section 2.3).

## 2.1. Configuration Identification

Configuration identification entails recovering the connectivity of the projectors and cameras in the context of overlaps in their display space or sensing space. In contrast to most prior distributed calibration techniques [4, 5], we do not assume the projectors or cameras form a regular grid (often not possible in practice) and hence the configuration can be much more complex.

To recover configuration, each projector  $P_j$  displays white while all the other projectors display black. Further, all cameras  $C_i$  capture a picture. We iterate this procedure over all pro-



Figure 1. This figure shows the pipline of our method.

jectors. Thus deciphering the projector-projector and projectorcamera overlaps. This information is utilized to expedite the geometric registration process by projecting patterns in parallel from the non-overlapping projectors.

### 2.2. Geometric Registration

Geometric registration consists of three steps. First, each camera calibrates itself with respect to its neighboring cameras. Next, they calibrate themselves with respect to a reference camera. The recovered camera parameters are then used to reconstruct the 3D geometry of the relief.

*Relative Camera Calibration:* The goal of this step is to recover the parameters (intrinsic and extrinsic) of each camera  $C_i$ with respect to all its adjacent cameras i.e. the cameras whose FOV overlaps with that of  $C_i$ . For each overlapping pair of cameras, we first recover the set of correspondences between the cameras which are then used to recover the relative camera calibration parameters.

To recover the correspondences between two overlapping cameras, we use binary structured light patterns (SLP) from projectors  $P_j$ 's, such that these are seen by both  $C_i$  and  $C_j$ . This allows the recovery of the correspondences between  $C_i$  and  $C_j$ . The configuration information from previous step allows non-overlapping projectors to put up their SLP for capture simultaneously making the process time-efficient.

Once  $C_i$  has recovered its correspondences with its neighbor, it uses an iteratively weighted least squire method by Weng et al. [29] to find the fundamental matrix between  $C_i$  and  $C_j$ , denoted by  $F_{ij}$ . Next, using the assumption of same focal length, the computer that hosts  $C_i$  then performs self-calibration routine akin to [30] to recover its camera focal length and hence its common intrinsic matrix K. Now, with known  $F_{ij}$ s and K, for each  $C_i$  its essential matrix with respect to adjacent camera  $C_j$  is computed, using  $K^T F_{ij} K$ . Next, we use the corresponding points between  $C_i$  and  $C_j$  and the essential matrix to recover the relative rotation  $R_{ij}$  and translation  $T_{ij}$  of the camera pairs, up to a scale factor, using the method presented by Longuet and Higgins [31]. We denote the recovered relative pose of  $C_i$  with respect to  $C_j$  by  $[R_{ij}|T_{ij}]$ .

Complete Camera Calibration: In this step, each camera  $C_i$ finds its position and orientation with respect to a global coordinate system. We denote this with a  $3 \times 4$  matrix,  $E_i = [R_i|T_i]$ . Our goal in this step is to recover  $E_i$  for all the *n* cameras, leading to 12n unknowns. We can express this  $E_i$  in terms of the already recovered relative calibration parameter with neighbor  $C_j$  as

$$E_i = \left(\begin{array}{cc} R_{ji} \mid s_{ji}T_{ji} \end{array}\right) \left(\begin{array}{cc} R_j \mid T_j \\ 0 & 0 & 0 \end{array} \right| \begin{array}{c} T_j \\ 1 \end{array}\right) = \left[R_{ji}R_j \mid s_{ji}T_{ji} + R_{ji}T_j\right]$$
(1)

where  $s_{ji}$  is an unknown scale factor. All cameras consider camera 1 as the reference by assuming  $E_1 = I$ .

To achieve this in our system, all computers broadcast their recovered camera parameters  $R_{ij}$  and  $T_{ij}$ . Using these for each camera we run a linear least squares to find its  $E_i$ .

Surface Reconstruction: At this point, each camera  $C_i$  is calibrated with respect to the global coordinate system, as given by  $E_i$ . Using structured light patterns we know the set of cameras that see each part of the surface. We use  $E_i$  of those cameras to recover the surface geometry utilizing structure from motion method [29].

## 2.3. Edge Blending

In this step, first each computer connected to its projector applies a white balancing to achieve a target white point W across all the  $P_j$ s, by altering the maximum value for each channel in each projector. For brightness smoothing, we achieve a  $C^1$  continuous brightness across the display in an iterative manner, by applying a brightness attenuating profile  $B_j$  for each projector  $P_j$ . The attenuation value for those pixels  $B_{j(u,v)}$  of  $P_j$  that are not in the overlap region is set to 1, while for those pixels in overlap region is inversely squared proportional to  $\alpha_{j(u,v)}$ . Where  $\alpha_{j(u,v)}$  is the proportion of the nearest distance from that pixel to the edge of  $P_j$  to the nearest distance from that pixel to the edge of  $P_j$  to the nearest distance from that pixel to the edge of the has overlap with  $P_j$ . In each iteration, one projector register itself with the overlapped sub-regions to form its  $B_j$ . Hence, at the end of this step, we achieve a smooth blending of color from one pixel to another across the entire display.

### **3. IMAGE CORRECTION**

The last step of our algorithm is the online image correction on the 3D relief such that overlapping pixels from different projectors display the same content in a seamless manner. To generate the image  $I_j$  to be projected by  $P_j$ , we can perform the geometric registration in two different ways: view-dependent geometric registration for single-user applications; and view-independent geometric registration for multiuser applications. Following this,  $I_j$  is attenuated using the attenuation map from previous step to achieve the edge blending. All these can be run in real-time by implementing these using the GPU fragment shaders as in [22, 16, 24].

*View-Independent Geometric Registration:* In multiuser applications we need to wallpaper the image on the surface. In such applications, for every location on the surface, color is usually determined based on the specific characteristics of that location. A simple example is indicating the height of the points in a relief map using different colors. In this case the color is decided solely based on the *Y* coordinate of the pixels. Another example is pasting different map layers over the surface, e.g. satellite imagery, road map, or traffic map. These examples are demonstrated in Figure 2. Due to the nature of such applications, we do not need to change the image based on the location of the user. Therefore, the scene can be viewed correctly by multiple users simultaneously.

View-Dependent Geometric Registration: To achieve a viewdependent registration for single user applications, we first define the virtual camera (or viewpoint) with projection matrix V. Note that this can be different from the viewpoint of any of the calibrating cameras. Next we use the standard two-pass rendering approach in [8]. First, we render the 3D scene from this virtual camera using V. To generate the image  $I_j$  for each projector, at any pixel we find the corresponding 3D coordinates of the surface



Figure 4. This figure shows a VR dome display calibrated by our algorithm in simulation. Left: This shows a image registered on this dome from the viewpoint of the camera used to capture the scene. Right: The image corrected for a viewpoint on the left side of the viewpoint of the capturing camera.

geometry. Then we project this 3D point using V to find the corresponding pixel from the image rendered in the first pass. We use the color at this pixel to generate the image  $I_j$ .

## 4. IMPLEMENTATION AND RESULTS

We have implemented our algorithm successfully to set up multiple different systems using different configurations (varied values of m, n and p). This demonstrates both the generalizability and flexibility of our proposed framework.

First, we have lighted a real 3D geographical relief map using six projectors and six cameras (m = n = 6) as illustrated in Figure 2. We have used Epson Powerlite LCD projectors. A logitech VGA webcam is mounted on each projector. Finally each projector is driven by a desktop machine equipped with a commodity GPU, i.e. p = 6. Our offline calibration takes around 4 minutes on Dell T-5400 workstations and the image correction runs in realtime at 30 fps. We use our method to light the relief map to simulate a river flow. We then simulate different levels of flooding on the relief by changing the 3D surface dynamically. For example, we add an extra geometric element to simulate a dam. The system quickly recalibrates to update the surface geometry which is then used to simulate the effect of dam on the flooding scenario (Figure 2). Note that in these applications we use a view-independent registration suitable for multiple users.

To show the power of our framework, we have used it on a relief made of sand using four projectors and six cameras driven by two machines (m = 4, n = 6, p = 2) as in Figure 3. For this purpose, we used 100 lbs of kinetic no-mess play-sand usually used by kids. We have modeled the sand quickly to create multiple architectural facades (e.g. pyramids) and relight them to create the effect of architectural lighting. We also demonstrate the same system by deploying many more cameras such that m > n as in [18] (Figure 3).

We also show our method at work for registering 3 projectors on an immersive VR environment of a dome(Figure 4). Here we show a view-dependent registration for a gaming application. Note that distortions appear as the capturing camera's view deviates from the location of the viewer.

#### 5. CONCLUSION

In conclusion, we have presented a fully-automatic distributed technique for lighting relief maps using multiple projectors and cameras. Our method allows distributed registration of multiprojector relief maps, for the first time, with unknown geometry and uncalibrated devices. We believe that our method will enable easy deployment, very rich SAR systems in the future, especially when considering very large relief artifacts. Our technique has the key capabilities of using uncalibrated devices, unknown geometry and distributed methodologies (avoiding mammoth centralized systems that need regular manual upkeep) that make its deployment in such systems easy, robust, and flexible to changes and extensions.



Figure 2. Example of visualization of flooding scenario using lighting of relief maps. Left: Our setup with 6 projectors and 6 cameras. Middle: Flooding in normal situation. Right: Flooding when a dam is simulated using a physical barrier. The system quickly recalibrates itself to capture the new surface geometry.



Figure 3. This is the example of our framework relighting temporary structures made by kinetic no-mess play sand using 4 projectors, 3 cameras driven by 4 machines. Note that we can relight pyramids to give them special effects (left) or showing the depth field (middle). The same system is demonstrated with m = 6 and n = 4 to create a configuration akin to [18](right).

## References

- R. Raskar, G. Welch, M. Cutts, A. Lake, L. Stesin, and H. Fuchs, "The office of the future: A unified approach to image based modeling and spatially immersive display," in *Proceedings of ACM Siggraph*, 1998, pp. 168–176.
- [2] R. Raskar, G. Welch, K-L. Low, and D. Bandyopadhyay, "Shader lamps: Animating real objects with image based illumination," *EG Workshop on Rendering*, pp. 89–102, 2001.
- [3] Laura Tateosian, Helena Mitasova, Brendan Harmon, Brent Fogleman, Katherine Weaver, and Russel Harmon, "Tangeoms: A tangible geospatial modeling system," *IEEE TVCG*, vol. 16, no. 6, pp. 1605–1612, nov-dec 2010.
- [4] E. Bhasker, P. Sinha, and A. Majumder, "Asynchronous distributed calibration for scalable reconfigurable multi-projector displays," *IEEE TVCG*, 2006.
- [5] P. Roman, M. Lazarov, and A. Majumder, "A scalable distributed paradigm for multi-user interaction with tiled rear projection display walls," *IEEE TVCG*, vol. 16, no. 6, pp. 1623–1632, nov.-dec. 2010.
- [6] D. Cotting, M. Naes, M. Gross, and H. Fuchs, "Embedding imperceptible patterns into projected images for simultaneous acquisition and display," *ISMAR*, 2004.
- [7] Stefanie Zollmann, Tobias Langlotz, and Oliver Bimber, "Passive-active geometric calibration for view-dependent projections onto arbitrary surfaces," *Journal of Virtual Reality and Broadcasting*, vol. 4, no. 6, Oct. 2007.
- [8] Ramesh Raskar, "Immersive planar displays using roughly aligned projectors," in *IEEE VR*, 2000.
- Han Chen, Rahul Sukthankar, Grant Wallace, and Kai Li, "Scalable alignment of large-format multi-projector displays using camera homography trees," *IEEE Vis*, 2002.
- [10] Ramesh Raskar, Jeroen van Baar, Paul Beardsley, Thomas Willwacher, Srinivas Rao, and Clifton Forlines, "ilamps: Geometrically aware and self-configuring projectors," ACM Transaction on Graphics (SIGGRAPH), 2003.
- [11] Andrew Raij and Marc Polleyfeys, "Auto-calibration of multi-projector display walls," *ICPR*, 2004.
- [12] Ruigang Yang, David Gotz, Justin Hensley, Herman Towles, and Michael S. Brown, "Pixelflex: A reconfigurable multi-projector display system," *IEEE Vis*, 2001.
- [13] Ruigang Yang, Aditi Majumder, and Michael Brown, "Camera based calibration techniques for seamless multi-projector displays," *IEEE TVCG*, 2005.
- [14] Andrew Raij, Ginnette Gill, Aditi Majumder, Herman Towles, and Henry Fuchs, "Pixelflex 2: A comprehensive automatic casually aligned multiprojector display," *IEEE PROCAMS*, 2003.
- [15] Mark Ashdown, Matthew Flagg, Rahul Sukthankar, and James M. Rehg, "A flexible projector-camera system for multi-planar displays," *IEEE CVPR*, 2004.

- [16] Ezekiel Bhasker, Ray Juang, and Aditi Majumder, "Registration techniques for using imperfect and partially calibrated devices in planar multi-projector displays," *IEEE TVCG*, 2007.
- [17] Jin Zhou, Liang Wang, Amir Akbarzadeh, and Ruigang Yang, "Multi-projector display with continuous self-calibration," in *IEEE PROCAMS*, 2008.
- [18] D. Cotting, R. Ziegler, M. Gross, and H. Fuchs, "Adaptive instant displays: Continuously calibrated projections using per-pixel light control," *Eurographics*, pp. 705–714, 2005.
- [19] T. Johnson, G. Welch, H. Fuchs, E. La Force, and H. Towles, "A distributed cooperative framework for continuous multi-projector pose estimation," *IEEE Virtual Reality*, 2009.
- [20] Aditi Majumder and Rick Stevens, "Color nonuniformity in projection-based displays: Analysis and solutions," *IEEE TVCG*, vol. 10, no. 2, 2003.
- [21] Aditi Majumder and Rick Stevens, "Perceptual photometric seamlessness in tiled projection-based displays," ACM TOG, 2005.
- [22] Behzad Sajadi, Maxim Lazarov, Aditi Majumder, and M. Gopi, "Color seamlessness in multi-projector displays using constrained gamut morphing," *IEEE TVCG*, 2009.
- [23] Reed S., Kreylos O., Hsi S., Kellogg L., Schladow G., Yikilmaz M.B., Segale H., Silverman J., Yalowitz S., and Sato E., "Shaping watersheds exhibit: An interactive, augmented reality sandbox for advancing earth science education," *American Geophysical Union (AGU) Fall Meeting*, 2014.
- [24] Behzad Sajadi and Aditi Majumder, "Markerless view-independent registration of multiple distorted projectors on vertically extruded surface using a single uncalibrated camera," *IEEE TVCG*, 2009.
- [25] Behzad Sajadi and Aditi Majumder, "Auto-calibration of cylindrical multiprojector systems," *IEEE Virtual Reality*, 2010.
- [26] Behzad Sajadi and Aditi Majumder, "Scalable multi-view registration for multi-projector displays on vertically extruded surfaces," *EuroVis*, 2010.
- [27] Behzad Sajadi and Aditi Majumder, "Auto-calibrating projectors for tiled displays on piecewise smooth vertically extruded surfaces," *IEEE TVCG*, 2011.
- [28] Behzad Sajadi and Aditi Majumder, "Automatic registration of multi-projector domes using a single uncalibrated camera," *IEEE EUROVIS*, 2011.
- [29] J. Weng, T.S. Huang, and N. Ahuja, "Motion and structure from two perspective views: algorithms, error analysis, and error estimation," *IEEE PAMI*, vol. 11, no. 5, pp. 451–476, may 1989.
- [30] Peter F. Sturm, Z. L. Cheng, Peter C. Y. Chen, and A. N. Poo, "Focal length calibration from two views: method and analysis of singular cases," *Computer Vision and Image Understanding*, pp. 58–95, 2005.
- [31] H. C. Longuet-Higgins, "Readings in computer vision: issues, problems, principles, and paradigms," chapter A computer algorithm for reconstructing a scene from two projections, pp. 61–62. Morgan Kaufmann Publishers Inc., 1987.