# 4.2: Self-Calibrating Tiled Displays

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## Abstract
*This paper presents seamless tiled displays via completely distributed network of projector-camera systems that calibrates itself without any user intervention. This makes projection-based tiled displays very easy to deploy and maintain. The decentralized calibration methodology presented to achieve this also enables advanced capabilities like scalability, reconfigurability and fault-tolerance.*

## 1. Objective and Background
Large area displays that can provide life-size images at a very high resolution are critical for many applications like scientific and medical visualization, training and simulation, and entertainment. Displays made by tiling multiple projectors in a 2D array are the only way to build high-resolution displays that are completely seamless.

Displays made of multiple projectors suffer from two problems (Figure 1). (a) The image is not *geometrically* matched across the projector boundaries (causing the repetition and ghosting of the red umbrella and the chairs and tables across the projector boundaries). (b) The *color* and *brightness* of the image is non-uniform primarily due to two reasons. First, due to their casual alignment, adjacent projectors overlap in their projection area on the screen, thus those regions are much brighter. Second, commodity projectors lack sophisticated optics, resulting in the 'hot-spot' effect, that is, 30-40% brightness fall-off from center to fringe. A process that removes geometric misalignments and color variations is called *calibration* [5].

At the inception of tiled displays a couple of decades ago, exorbitant costs of projectors ($75,000) and monolithic rendering engines ($1,000,000) restricted the number of projectors in the display to a few (two to four). Thus, manual calibration was feasible during initial set-up or periodic recalibration. However, several man-hours and dollars were spent on calibration using custom made mounts and optical elements. For example, mounts with six degrees of freedom were manually adjusted in order to achieve geometric calibration. High precision optical elements like filters and Fresnel lenses were used to achieve color uniformity. This quarantined such displays to only high-tech environments.

Current, projectors (in the $1000 range) and rendering PCs (in the $2000 range) are both commodity products. Thus building a reasonably large multi-projector display (10-20 projectors) is quite affordable today. However, manual calibration is no longer feasible, and of course not scalable. So, the past decade has seen a plethora of *camera-based* calibration techniques for calibrating these displays *automatically*, *repeatably*, and *inexpensively*. A camera is used to provide visual feedback about the geometry and color mismatches, which are then compensated by digitally changing the images going to the projector [4].

However, all calibration techniques devised till now use a centralized architecture (Figure 2) [2] where a centralized server dispatches imagery to a number of clients, each displaying the image on its display unit. To calibrate the display, the server follows the following four steps: (a) instructs the projector to project patterns; (b) instructs the camera to capture the patterns; (c) generates correction parameters; (d) corrects the image and sends appropriate parts of it to the clients to achieve a seamless display. Thus, this is a centralized synchronize push architecture where the server bears the overhead of *managing the imagery* while the clients are dumb display stations.

However, the biggest limitation of the centralized approach is that setup demands an educated user. There are several common venues like schools, museums, malls where such multi-projector displays are highly desired. Imagine the huge difference in the experience for students in a classroom or viewers in museum if they can use a 4-projector display for visualizing scientific data or for a historic site exploration. The centralized approach being complex does not foster confidence in a layman to set-up and use such displays regularly. Further, it is not easy to *scale* the display by adding/removing projectors. A complete recalibration needs to be triggered by the user. The same is true when one wants to *reconfigure* the display, for example if the user wants to change the aspect ratio from TV mode to a widescreen movie mode. Finally, *fault tolerance* is important. For example, a museum is New York is now trying to put up a billion pixel display, which would essentially mean about a 1000 projectors. Now, if bulbs on a few of these projectors go out, the display would be incapacitated until bulbs are replaced and another recalibration is triggered by a user, even though most of the projectors still work and can operate to create a display of lower resolution.

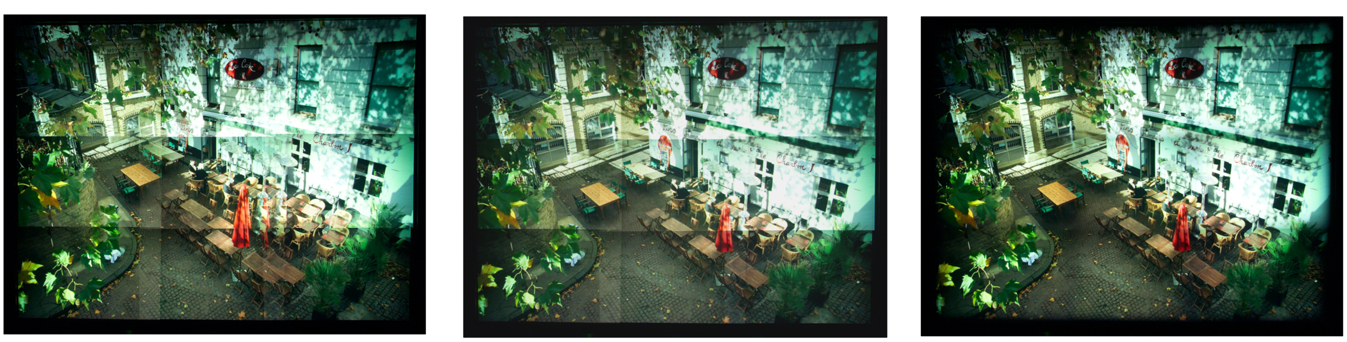

**Figure 1. Left to right: Image seen (a) from front of a multi-projector display made of 9 rear-projectors arranged in a 3x3 array, (b) after a camera is used to correct geometry mismatches, (c) after geometric and photometric mismatches are corrected.**

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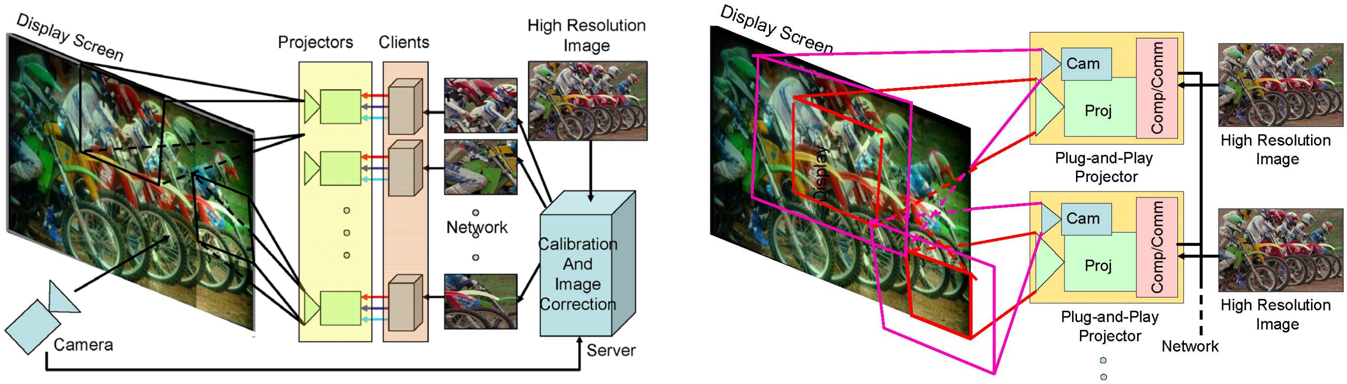


**Figure 2. A centralized architecture for multi-projector displays (left) and a decentralized architecture using plug-and-play projectors (right).**

So, though affordable, multi-projector displays still have not made their way to regular venues like school, museums, public places or even as TVs in our homes.

## 2. Results

In this paper we introduce a tiled multi-projector display that would be able to calibrate itself, with no input from the user. It can detect additions, removals, and faults, and recalibrate in response to these events. So, all the user needs to do is arrange projectors physically and the rest is taken care of by the system. Thus, the projector becomes almost like a flashlight, letting you move the light around wherever you want it. And a cluster of these projectors calibrates itself to create a giant high-resolution display without the user worrying about manual set-up or maintenance.

***A Decentralized Approach:*** To achieve such self-calibrating tiled displays, we propose a completely decentralized approach. First, we propose a *projector-sensor display unit* that becomes the building block for such self-calibrating displays. Next, we present a *decentralized architecture*, which is essentially a distributed network of such projector-sensor units. Finally we present an *asynchronous decentralized calibration* process that helps each of these display units calibrate with the other units in a decentralized manner without any synchronization.

### 2.1 Projector-Sensor Unit

We propose an augmented display unit consisting of a projector, a camera, and embedded computation and communication hardware. Each display unit thus forms a self-sufficient unit with the capacity to sense environmental changes (using the camera), adapt or react to those changes (using the computation unit) and communicate those changes to other display units (using the communication unit). For our prototype, we use a laptop to simulate the computation and communication unit (Figure 3).

### 2.2 Decentralized Architecture

Our multi-projector display is a distributed network of projector-sensor units and has no centralized server. Each display unit pulls the data directly from a standard data server which can in turn be distributed. The data server can be completely oblivious to the fact that the data is being requested by display units. So, each display unit behaves just like any other independent data client and is entirely responsible for managing its own pixels.

***Camera-Based Communication:*** The camera on each display unit sees only a part of the display, and hence we only need a low-resolution camera. However, the camera field-of-view needs to be a little larger than that of the projector, so that it can observe parts of its neighbors' projections, and react accordingly. This ability of each unit to sense changes in its neighbor via its own camera enables us to use an alternate modality of sensor-based communication, in addition to the traditional communication channel. Patterns observed by a neighboring projector are analyzed to find the relative orientation between the neighboring projectors, and locations in the display array. Thus, the overlapping field of view of sensors in adjacent display units provides an underlying mesh interconnection network at no additional cost.

### 2.3 Decentralized Calibration

We present an asynchronous decentralized calibration that takes advantage of the decentralized architecture. This is a SPMD (single program multiple data) algorithm that runs on each PPP to achieve calibration with no user intervention. Initially, every unit believes it is alone is the environment and has the sole responsibility of displaying the data (Figure 4). Then each PPP runs the identical SPMD algorithm consisting of two steps. First, it identifies its immediate neighbors, the display configuration and its own coordinates in the display. Finally, it projects an image that is geometrically and photometrically matched with its neighbors to achieve a seamless display.

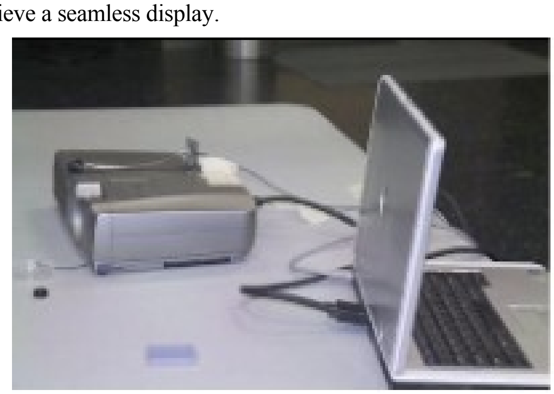

**Figure 3. The Projector-Sensor Unit**

**Figure 4. Left to right: (a) Initially, every display unit thinks that it is only display unit present, and is therefore solely responsible for displaying the whole image. (b) After configuration identification each display unit knows the display configuration – total number of projectors, and total display dimensions – and their own coordinates in the array. Thus they know which parts of the display they are responsible for, but still do not know the relative orientations of their neighbors. So, the image is not seamless. (c) After alignment each display unit matches geometrically and photometrically with its neighbors to create a seamless display.**

***Identifying own position and neighbors in the 2D array:*** use asynchronous sensor-based and wireless communication to find

own (row, column) in the 2D array, and left, right, top, and bottom neighbors, whenever they exist. For an $m \times n$ array, the algorithm takes $O(m + n)$ parallel steps.

***Geometric and Color Correction with no global coordinates:*** We use a decentralized method to perform geometric and photometric correction without considering a global coordinate system, in $O(m + n)$ steps [1,3]. One projector is *dynamically* chosen to be the *leader* against whom everyone else will calibrate. To avoid a change of coordinate in every frame (can lead to visual flicker), the leader does not change unless it crashes.

***Addition/Removal/Faults:*** Since the camera and projector is in a feedback loop in every display unit, addition or removal (can be due to a fault) of a unit is easily detected by neighboring units. This initiates the recalculation of display configuration and individual positions of units in the display, followed by the reshaping of the imagery to fit into the largest rectangle contained within the projected area of all the active display units.

## 3. Impact

### 3.1 Next-Generation Visualization Systems

Large visualization systems today are built primarily using very large arrays of LCD panels. However, the bezels around the panels results in seams that can be distracting and even detrimental in executing certain tasks due to mangling of text and patterns. But people still tend to stick to LCD panels due to the relative ease in setting them up on a single substrate in a rigid fashion, even though this initial set-up demands huge financial, engineering and personnel resources. People do not consider a seamless projection based tiled display since installing and maintaining them is too hard. And of course, the necessity of advanced capabilities like scalability and reconfigurability is not even evaluated. Our proposed plug-and-play projector will enable next generation super high-resolution entirely seamless visualization, training and simulation systems where the number of pixels can be scaled easily to even billions. Thus, this will enable displays that can match the size and resolution of the exponentially growing size of the data. Common data today like seismic charts, GIS data, genome data, and CAD drawings can easily be 10000x10000 in scale.

### 3.2 Pack-and-Go Displays

Projectors today are portable and lightweight, so much so, that they can even fit in the palm of one's hand (Figure 5). Thus, it is easy to carry a bunch of projectors in one car's trunk enabling portable seamless high-resolution displays via tiling of these projectors. But, setting these up need an educated user with technical expertise on cameras used for display calibration, calibration methods, and even operating systems and user interfaces. This does not foster confidence in a `layman' user, such as a doctor in a hospital or a historian in a museum, to install a multi-projector display in their workplace.

**Figure 5. The MERL pocket projector weighs about 14 ounces, can fit in the palm of your hand, and costs just $700.**

The proposed projector-camera display unit along with the decentralized architecture and calibration would enable *pack-and-go displays* where individuals can carry their own high-resolution displays with them and set them up easily wherever needed in any scale and configuration. Such pack-and-go displays can have broad applications in many areas such as archeology, education, medicine, and entertainment. In particular, it can enable mobile science laboratories and mobile command and control units (in war grounds or emergency-incident-site). They can be set-up easily, dismantled and moved to a different location when required. Finally, Pack-and-go displays could spark and foster novel paradigms of collaboration where each person carries his own projector and when more than one person meet for collaboration, their respective displays are put together to create a seamless high resolution display. This display can easily scale as the number of collaborators. More interestingly, such a shared display space that has access to data from multiple machines might foster new directions of research in user interfaces for data sharing.

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