# Cascaded Displays: Spatiotemporal Superresolution using Offset Pixel Layers

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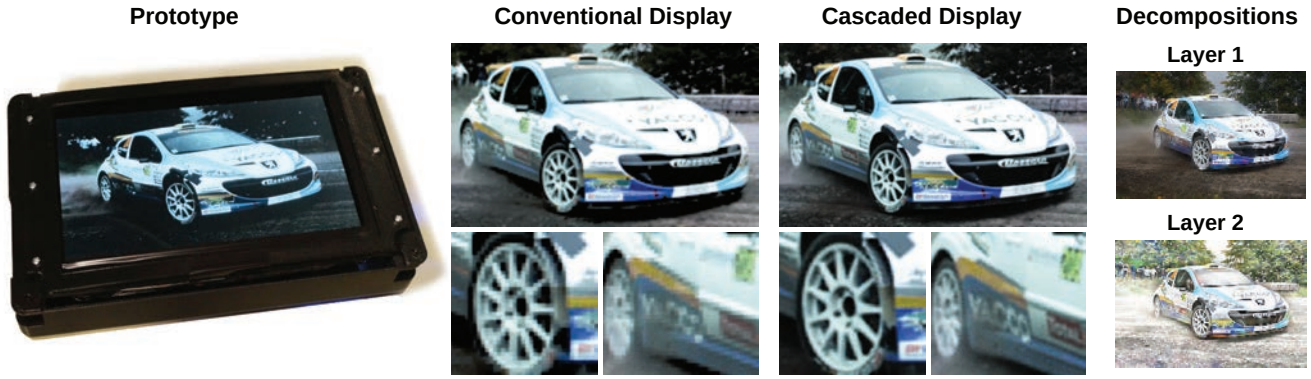


**Figure 1:** *A pair of off-the-shelf LCDs were modified to create a* cascaded display*: placed in direct contact with a fixed lateral offset. In comparison to any single LCD used in their construction, cascaded displays can quadruple spatial resolution by presenting attenuation layer patterns that are optimized, in real time, using non-negative matrix factorization. (Motorsport image courtesy Aurélien Vialatte.)*

## Abstract

We demonstrate that layered spatial light modulators (SLMs), subject to fixed lateral displacements and refreshed at staggered intervals, can synthesize images with greater spatiotemporal resolution than that afforded by any single SLM used in their construction. Dubbed *cascaded displays*, such architectures enable superresolution flat panel displays (e.g., using stacks of liquid crystal displays (LCDs)) and digital projectors (e.g., relaying the image of one SLM onto another). We introduce a comprehensive optimization framework, leveraging non-negative matrix and tensor factorization, that decomposes target images and videos into multi-layered, time-multiplexed attenuation patterns—offering a trade-off between image brightness, spatial resolution, and refresh rate. We develop a real-time dual-layer factorization method that quadruples spatial resolution and doubles refresh rate. Compared to prior superresolution displays, cascaded displays place fewer restrictions on the hardware, offering thin designs without moving parts or the need for temporal multiplexing. We validate these concepts using three prototypes: printed multi-layer films, a dual-modulation liquid crystal on silicon (LCoS) projector, and a dual-layer LCD, with the latter emphasizing head-mounted display (HMD) applications.

## 1 Overview

The development of higher-resolution displays is of central importance to the consumer electronics industry. Mobile displays already exceed the resolution of the human eye when viewed at the distance of a phone or tablet. Similarly, "4K ultra-high definition (UHD)" displays are being aggressively marketed. Beyond these trends, several emerging technologies necessitate even greater resolutions, including wide-field-of-view HMDs, such as the Oculus Rift, and light field displays. We propose *cascaded displays* as a means to achieve high-resolution displays using current-generation light-attenuating SLM technology: stacking two or more SLMs on top of one another, subject to a lateral offset of half a pixel or less along each axis. Lateral offsets are necessary so that each pixel on one layer modulates multiple pixels on another. In this manner, the intensity of each *subpixel fragment*—defined by the geometric intersection of a pixel on one display layer with one on another layer—can be controlled, thereby increasing the effective display resolution (see Figure 1). In this manner, cascaded displays may operate as "compressive displays": utilizing fewer independently-addressable pixels than apparent in the displayed image. We further demonstrate temporal resolution may be similarly enhanced, using stacks of two or more SLMs refreshed in staggered intervals.

## 2 Related Work

The majority of prior superresolution displays exploit **additive superposition** of shifted low-resolution images. Allen and Ulichney [2005] introduce "wobulation" to double the resolution of front-projection displays, using a piezoelectrically-actuated mirror to displace the projection by half a pixel. Time multiplexing can be eliminated by using projector arrays. In contrast, cascaded displays create a **multiplicative superposition**: synthesizing higher spatial frequencies by the (simultaneous) interference of shifted light-attenuating displays, achieving spatiotemporal superresolution using thin architectures without moving parts.

## 3 Implementation

We constructed three prototypes: a dual-layer LCD, a digital projector containing a pair of LCoS microdisplays, and a multi-layer stack of printed films. Our dual-layer LCD contains a pair of 7-inch HannStar HSD070PWW1-B00 LCD panels (see Figure 1). A custom enclosure was fabricated using a Dimension 1200es 3D printer. We emphasize that this construction converts to a head-mounted display by attaching a binocular lens assembly, showcasing the application of cascaded displays to wide-field-of-view HMDs.

## References

ALLEN, W., AND ULICHNEY, R. 2005. Wobulation: Doubling the addressed resolution of projection displays. *SID Digest 36*, 1.


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