Carnegie Mellon University
Electrical & Computer Engineering

Ph.D. Thesis Defense

Advancing Mobile Photography using Under-Display Cameras and Sensor Design

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Zoom Meeting

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ABSTRACT

The ubiquity of mobile devices has made mobile photography an indispensable part of our daily life. Unlike standalone cameras, mobile device cameras have to adhere to unique design constraints imposed by the compact form factors and multi-functionality of these devices. In this thesis, we investigate two distinct challenges arising from current mobile device design trend and propose novel camera and sensor designs to address them.

First, the conflict between screen size and camera placement has never been more severe than it is now, driven by the demand for full-screen devices. The prevalence of organic light-emitting diode (OLED) displays, with their partial transparency, offers an exciting opportunity to place a conventional camera beneath the screen, allowing the simultaneous operation of both components.

We study under-display cameras (UDCs), an emerging type of camera that captures a scene through the micron-scale openings of an OLED display panel. Their image quality is hindered by poor signal-to-noise ratio and severe diffractive blur due to the presence of the display. Can we redesign the hardware to improve the overall image quality of UDCs? Based on Fourier optics, we find that the diffractive blur of a UDC is fundamentally determined by the shape of the display opening. Therefore, we propose a suite of modifications to the display layout, including using a random pixel tiling and optimizing the opening shape of each pixel. The proposed method significantly advances image quality by improving the invertibility of the diffractive blur. However, this requires nontrivial display redesign. As a complementary solution, we propose to optically modify the display opening shape by adding two phase masks, one in front of and one behind the display. The first phase mask concentrates light onto the display openings, and the other phase mask restores the original wavefront, effectively rendering the display invisible to the camera under certain assumptions. This approach improves UDCs light throughput and the conditioning of the blur, and maintains display quality.

Second, the continuous shrinking of image sensor pixels, with the potential to increase image resolution under a constrained sensor die size, presents challenges. Since small pixels collect less light, they are more susceptible to noise degradation in low-light conditions. Can we design novel computational techniques to combat noise and expand dynamic range of these sensors?

We propose two spatially varying readout techniques that adapt to local scene brightness. The first technique involves spatially varying gain. The key insight is that a larger gain or ISO setting can overcome read noise by amplifying the signal level. Conventional sensors apply a constant gain across the entire frame, limiting the use of a large gain when the scene has a wide dynamic range. In contrast, our approach adjusts gain at small regions of interest or even individual pixels, allowing a much larger gain for dark regions while avoiding saturation in bright regions, thus effectively expanding the sensor's dynamic range. The second technique is spatially-varying binning. We investigate the optimal pixel size in terms of noise and resolution, and show that the optimal size is tightly coupled with the scene light level. We develop a simple theory that maps scene brightness to optimal pixel size, and implement this varying pixel size through binning. We demonstrate the proposed spatially varying techniques in various applications, including high dynamic range imaging, vignetting, and lens blur, and show consistently improved noise performance and effective resolution.

This thesis takes a leap forward by innovating optics and sensors to address the unique challenges in mobile photography. Interestingly, many of these challenges are fundamentally linked to classic problems in computer vision, such as mitigating blur and noise, and enhancing resolution and dynamic range. We hope that the techniques presented in this work will not only open new avenues for mobile photography but also inspire broader innovation in the field of computational imaging.

PUBLIC DEFENSE

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