Supplemental Material for Free-form Scanning of Non-planar Appearance with Neural Trace Photography

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1 PROTOTYPE SCANNER DETAILS

The LED panel is made up of 32×16 standard 3535 RGB SMD LED modules. The main circuits on the panel implement a FIFO that acts like a back buffer. Each bit of the FIFO corresponds to the on/off state of one of half of all LEDs on the panel. To drive the entire panel of LEDs, the following process is performed at a high speed: 1) push half of a binary lighting pattern to the FIFO; 2) set the on/off states of half of the LEDs according to the FIFO, and turn off the remaining LEDs; 3) return to the first step and work on driving the other half of the lighting pattern.

The key component of our scanner is a custom-designed main board with an Intel Cyclone 10 FPGA (10CL015YU256C8). Our board independently controls the intensity of each LED, which is stored in an SDRAM, quantized with 8 bits per channel and implemented via PWM. We achieve a speed of 48,000 frames per second for projecting binary RGB lighting patterns. The main board is also in charge of high-precision, circuit-level synchronization between the LEDs and the camera, so that the camera begins its exposure right before the lighting pattern projection, and ends the exposure immediately after the pattern projection finishes.

2 CALIBRATIONS

2.1 Color

Our color calibration method is similar to the one described in [LeGendre et al. 2016]. We denote the unknown spectral distribution curves of an RGB LED as $S^L_{c_1}(\lambda)$, where λ is the wavelength and c_1 is one of the RGB channels. Then the spectral distribution $L(\lambda)$ of an LED with intensities $\{I_R, I_G, I_B\}$ can be expressed as:

$$L(\lambda) = I_R S^L_R(\lambda) + I_G S^L_G(\lambda) + I_B S^L_B(\lambda). \tag{1}$$

We also assume that the spectral distribution curve of any reflectance $\rho(\lambda)$ can be expressed as a linear combination of three unknown basis ones $S^\rho_{c_2}(\lambda)$:

$$\rho(\lambda) = \rho_R S^\rho_R(\lambda) + \rho_G S^\rho_G(\lambda) + \rho_B S^\rho_B(\lambda), \tag{2}$$

where $\rho_{R/G/B}$ are the corresponding coefficients, and c_2 indicates one of the RGB channels. Similarly, the unknown spectral response curve of the camera is denoted as $S^C_{c_3}(\lambda)$. With Eq. 1 and Eq. 2, the camera measurement of the reflectance $\{\rho_R, \rho_G, \rho_B\}$ under an LED with intensities $\{I_R, I_G, I_B\}$ at a particular channel c_3 can be modeled as follows:

$$\begin{aligned}
&\int L(\lambda)\rho(\lambda)S^C_{c_3}(\lambda)d\lambda \\
=& \int [I_R S^L_R(\lambda) + I_G S^L_G(\lambda) + I_B S^L_B(\lambda)] \\
&[\rho_R S^\rho_R(\lambda) + \rho_G S^\rho_G(\lambda) + \rho_B S^\rho_B(\lambda)] S^C_{c_3}(\lambda)d\lambda \\
=& \sum_{c_1, c_2} I_{c_1}\rho_{c_2} \int S^L_{c_1}(\lambda)S^\rho_{c_2}(\lambda)S^C_{c_3}(\lambda)d\lambda \\
=& \sum_{c_1, c_2} I_{c_1}\rho_{c_2}\delta(c_1, c_2, c_3),
\end{aligned} \tag{3}$$

where

$$\delta(c_1, c_2, c_3) = \int S^L_{c_1}(\lambda)S^\rho_{c_2}(\lambda)S^C_{c_3}(\lambda)d\lambda. \tag{4}$$

Eq. 3 describes the **relationships** among the RGB light intensities, the RGB reflectance values and the RGB camera measurements.

While directly measuring S^L, S^ρ or S^C would be cumbersome, it is sufficient to obtain the tensor $\delta(c_1, c_2, c_3)$ for the evaluation of Eq. 3. As in our case $c_1/c_2/c_3$ has three choices, there are 3×3×3 = 27 combinations in total. To calibrate δ, we take photographs of color checkers under three lighting conditions: $\{I_R, I_G, I_B\}$ = {1, 0, 0}/{0, 1, 0}/{0, 0, 1}. In conjunction with the known, reference RGB albedo $\{\rho_R, \rho_G, \rho_B\}$ of each color checker, we set up a system of linear equations, according to Eq. 3. Its solution is the final color calibration result $\delta(c_1, c_2, c_3)$.

Accordingly, the rendering equation (Eq. 1 in the main paper) can be extended to RGB channels as follows:

$$\begin{aligned}
&B(I, \mathbf{x_p}, \mathbf{n_p}, \mathbf{t_p}; c_3) \\
=& \sum_{l, c_1, c_2} I(l; c_1) \int \frac{1}{||\mathbf{x_l} - \mathbf{x_p}||^2} \Psi(\mathbf{x_l}, -\omega_\mathbf{i}) V(\mathbf{x_l}, \mathbf{x_p}) \\
& f(\omega_\mathbf{i}'; \omega_\mathbf{o}', \mathbf{p}, c_2)(\omega_\mathbf{i} \cdot \mathbf{n_p})^+ (-\omega_\mathbf{i} \cdot \mathbf{n_l})^+ \delta(c_1, c_2, c_3) d\mathbf{x_l}.
\end{aligned} \tag{5}$$

2.2 Angular Emission Distribution

The angular emission distribution of LEDs (i.e., Ψ) is measured as follows. We set each LED to its maximum intensity, and measure

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its HDR emission using bracketing, with a machine vision camera mounted on a tripod that is fixed for a particular view direction. With known spacing between LEDs, the camera can be easily localized with respect to the panel. The camera and the tripod are then adjusted for taking measurements from different view directions.

In experiments, we observe that the angular emission distribution is almost constant within a subtending angle of 115.8°, which is determined by our predefined valid volume. This is not unexpected, because the LED module is designed to exhibit a relatively uniform emission profile at a broader range of over 160°. Therefore, a constant Ψ is used in all our experiments. We expect that the measurement of angular emission distribution can be skipped, for other high-quality LEDs that are carefully engineered to produce a uniform emission profile.

3 CHALLENGES IN EXTENDING TO A TABLET

While it is tempting to extend our framework to an off-the-shelf tablet such as an iPad, there are two main challenges that researchers should be aware of before pursuing future work.

The first challenge is the lack of hardware-level synchronization between the screen (i.e., the light source) and the camera in current off-the-shelf tablets. At the initial stage of our project, we planned to conduct experiments on an iPad. Unfortunately, we were not able to find any function in the SDK that would allow us to perform high-precision light-camera synchronization. Unsynchronized acquisition may considerably complicate appearance computation and lead to lower-quality results. One possible solution is to place a reference sample next to the object of interest during acquisition, to compensate for the issue in post-processing.

Next, the power of the screen in contemporary tablets is limited, resulting in longer exposure time during acquisition / lower SNR measurements. From our experiments, the measured light emission of our prototype scanner is 6.4 times that of an 11-inch iPad Pro (2nd generation), despite their similar form factors. That being said, it will be interesting future work to study if our framework can produce reasonable results by training on synthetic low SNR measurements.

We hope that the manufacturers could take into the above challenges into consideration when designing future tablets, which will help push high-quality appearance acquisition to a broader audience.

REFERENCES

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