Abstract

A handheld camera pointed at the display can receive not only the display image, but also an underlying message. Differencing the camera-captured alternate frames leaves the small intensity pattern, but results in errors due to photometric effects that depend on camera pose. The online radiometric calibration algorithms described in this paper significantly reduces message recovery errors, especially for low-intensity messages and oblique camera angles.

Introduction

We present a novel method for communicating between a moving camera and an electronic display by embedding and recovering hidden, dynamic information within an image. A small intensity pattern is added to alternate frames of a time-varying display. A handheld camera pointed at the display can receive not only the display image, but also an underlying message. Differencing the camera-captured alternate frames leaves the small intensity pattern, but results in errors due to photometric effects that depend on camera pose. Robustly decoding the message requires careful photometric modeling for message recovery. We model the photometry of the system as a camera-display transfer function (CDTF).

Radiometric Calibration

The emittance function has three components, i.e. $e = (e_r, e_g, e_b)$. Therefore the emitted light $I$ as a function of wavelength $\lambda$ for a given pixel $(x,y)$ on the electronic display is given by

$$I(x,y,\lambda) = \rho \cdot e(\lambda,\theta).$$  \hspace{1cm} (1)

Now consider the intensity of the light received by one pixel element at the camera sensor.

$$I_s = \int \left[ \rho \cdot e(\lambda,\theta) \right] s(\lambda)d\lambda.$$  \hspace{1cm} (2)

where $s = (s_r, s_g, s_b)$.

When accounting for the nonlinearity in the camera and display, we rewrite Equation 2 to include the radiometric response function $f$.

$$I_r = f^{-1} \left( \int \left[ \rho \cdot e(\lambda,\theta) \right] s(\lambda)d\lambda \right).$$  \hspace{1cm} (3)

The captured image $I_c$ from the camera viewing the electronic display image $I_d$ can be modeled using the image formation pipeline in Figure 2.

Results

Table 1: Accuracy of embedded message recovery and labeling with additive intensity \( k = +3 \) on [0,255] and captured with 45° oblique view. Low \( k \) values are desirable (because they are less noticeable) but lead to larger errors, especially at oblique views. Our calibration methods can greatly increase accuracy (from 47-50% to over 90%) in some cases.

Key Results

Online radiometric calibration significantly reduces messaging errors, especially for desirable low intensity messages and camera-captured at oblique angles.

Camera-Display Transfer Pipeline

The captured image $I_c$ from the camera viewing the electronic display image $I_d$ can be modeled using the image formation pipeline in Figure 2.

Figure 2: Image Formation Pipeline: The image $I_d$ is displayed by an electronic display with an emittance function $e$. The display is observed by a camera with sensitivity $s$ and radiometric response function $f$.

Conclusion

The results indicate a marked improvement in message recovery over naive thresholding for camera-display messaging with our methods. We demonstrate experimental results for nine different camera-display combinations at frontal and oblique viewing directions. We show that naive thresholding, while intuitively simple, is a poor choice because the variation of display intensity with camera pose is ignored. These methods lead to lower message recovery rates, especially for oblique views (45°) and small intensity messages. Prior methods of digital watermarking do not take into account the photometric effects of the camera-display transfer function and the resulting dependence on camera pose. Therefore these prior methods are likewise prone to error. Our experimental results show that hidden, dynamic messages can be embedded in a display image and recovered robustly.

References


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