Optimal Radiometric Calibration for Camera-Display Communication

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Abstract

- A handheld camera pointed at the display can receive both the display image, but also an underlying message.
- Differencing the camera-captured frames results in errors due to photometric effects, and distorts message recovery.
- Online radiometric calibration significantly reduces message recovery errors, especially for low intensity messages and oblique camera angles.

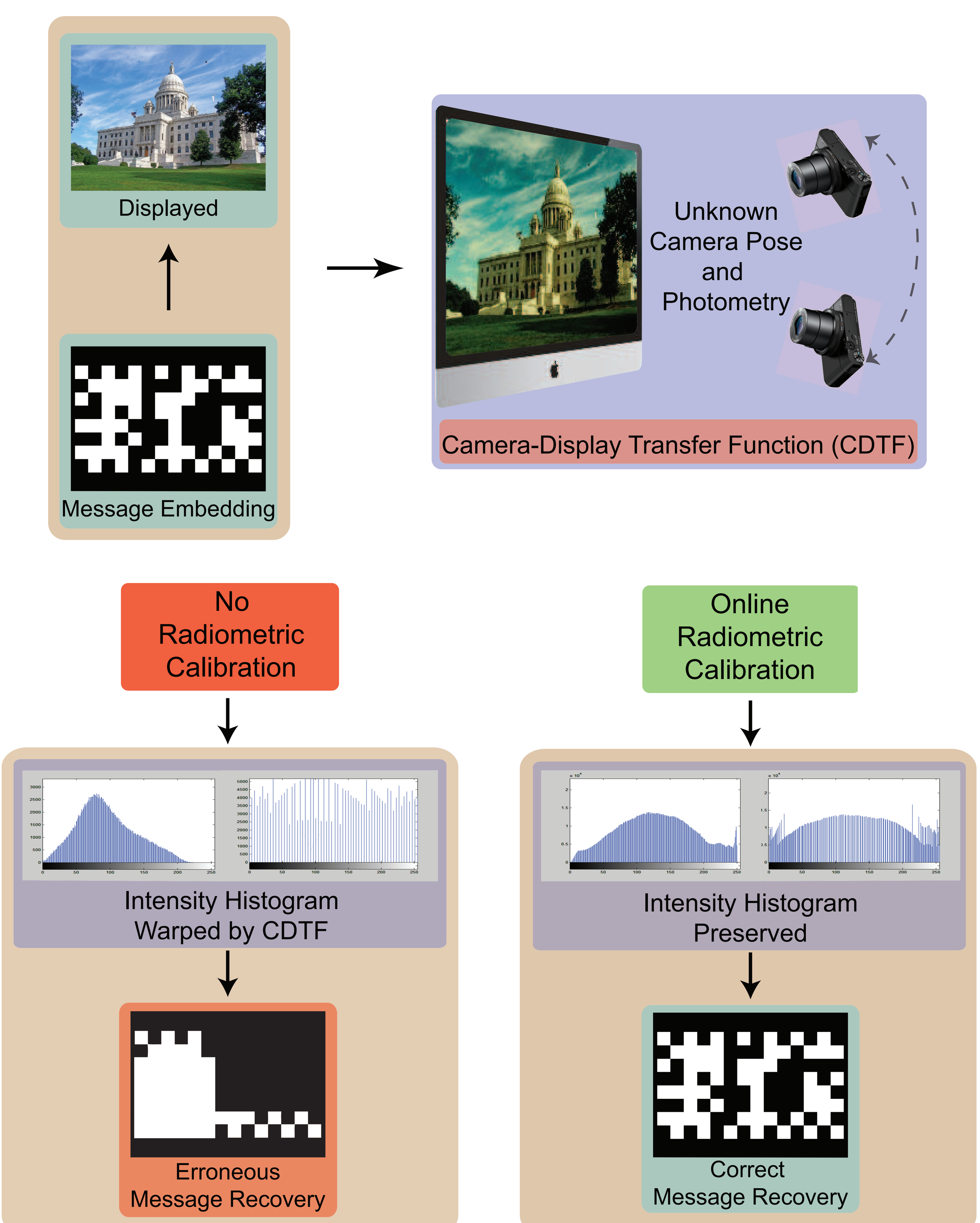

Figure 1: Online Radiometric Calibration mitigates the distorting effects of the CDTF and enables more accurate message recovery. From the display to the camera, the light signal is affected by display photometry, camera pose and camera radiometry. In each pair of intensity histograms shown above, the left represents an image histogram before passing through the CDTF, and the right represents the histogram after the CDTF.

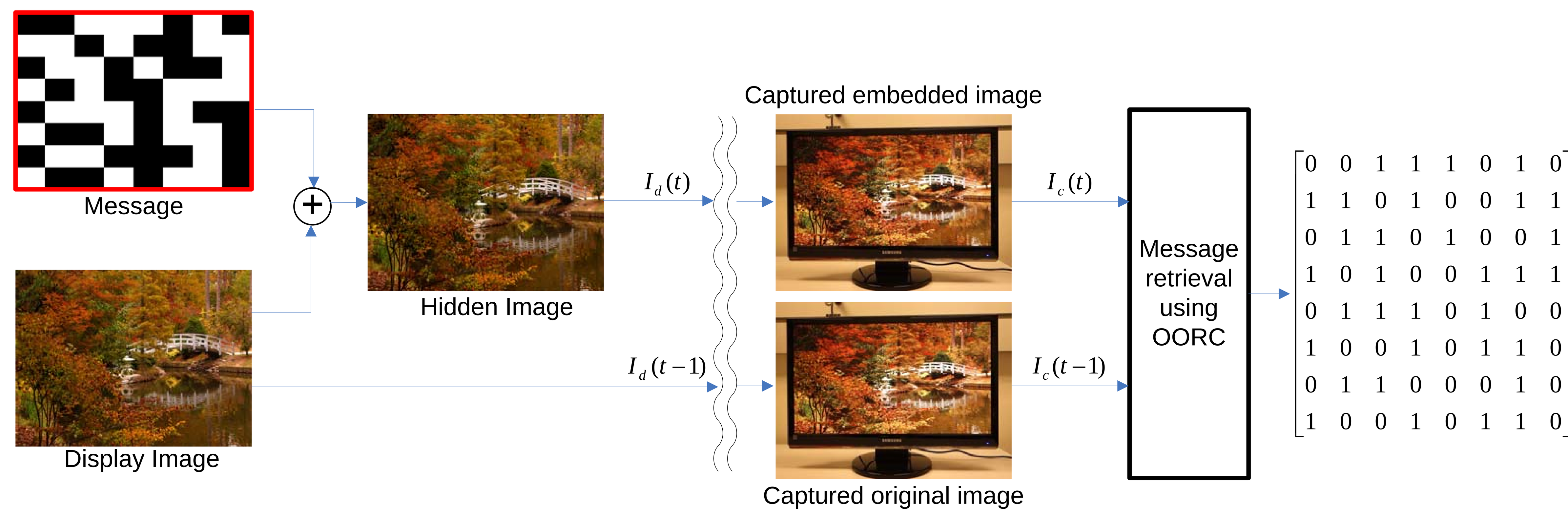

Figure 2: Message Embedding and Retrieval. Two sequential frames are sent, an original frame and a frame with an embedded message image. Simple differencing is not sufficient for message retrieval. Our method (OORC) is used to recover messages accurately.

Camera-Display Transfer Pipeline

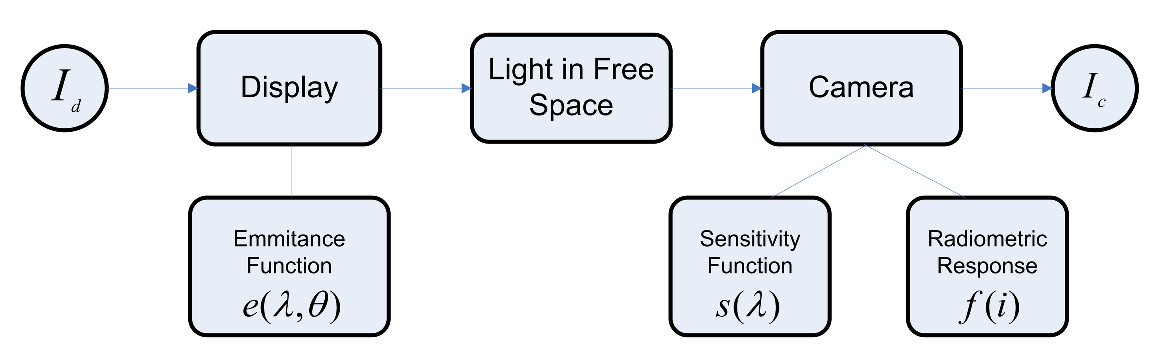

Figure 3: Image Formation Pipeline: The image $\mathbf{I_d}$ is displayed by an electronic display with an emittance function e. The display is observed by a camera with sensitivity s and radiometric response function f.

Radiometric Calibration

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

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

Accounting for nonlinearity of the camera and display, consider the radiometric response function f:

$$\mathbf{I_c} = f\left(\int_\lambda [\rho \cdot \mathbf{e}(\lambda, \theta)]\, \mathbf{s}(\lambda) d\lambda\right). \tag{2}$$

where $\mathbf{s} = (s_r, s_g, s_b)$. The camera-captured intensity is:

$$\mathbf{I_d} = f^{-1}(\mathbf{I_d}) = g(\mathbf{I_d}). \tag{3}$$

Let $g(i)$ be the inverse radiometric function f^{-1}, modeled with a fourth order polynomial:

$$g(i) = a_4 i^4 + a_3 i^3 + a_2 i^2 + a_1 i + a_0. \tag{4}$$

Key Result

Online Radiometric Calibration significantly improves robust messaging, especially for low-intensity messages and oblique camera angles

Results

Accuracy (%)	Naive Threshold	Two-step	OORC	Hidden Ratex
Canon-iMac	72.94	75.67	99.17	89.63
Canon-LG	58.94	84.94	98.44	95.74
Canon-Samsung	48.44	64.89	99.39	89.91
Nikon-iMac	60.17	75.50	95.17	90.00
Nikon-LG	49.72	73.39	99.33	94.81
Nikon-Samsung	47.22	72.89	95.00	89.54
Sony-iMac	64.44	76.00	99.06	71.11
Sony-LG	56.11	75.61	98.56	90.93
Sony-Samsung	47.50	79.11	98.89	87.80
Average	56.17	75.33	98.11	88.83

Table 1: Accuracy of embedded message recovery and labeling with additive intensity $\kappa = +3$ on [0,255] and captured with 45°oblique view. Low κ values are desirable (because they are less visible) but lead to larger errors, especially at oblique views.

Intensity vs Radiometric Pose

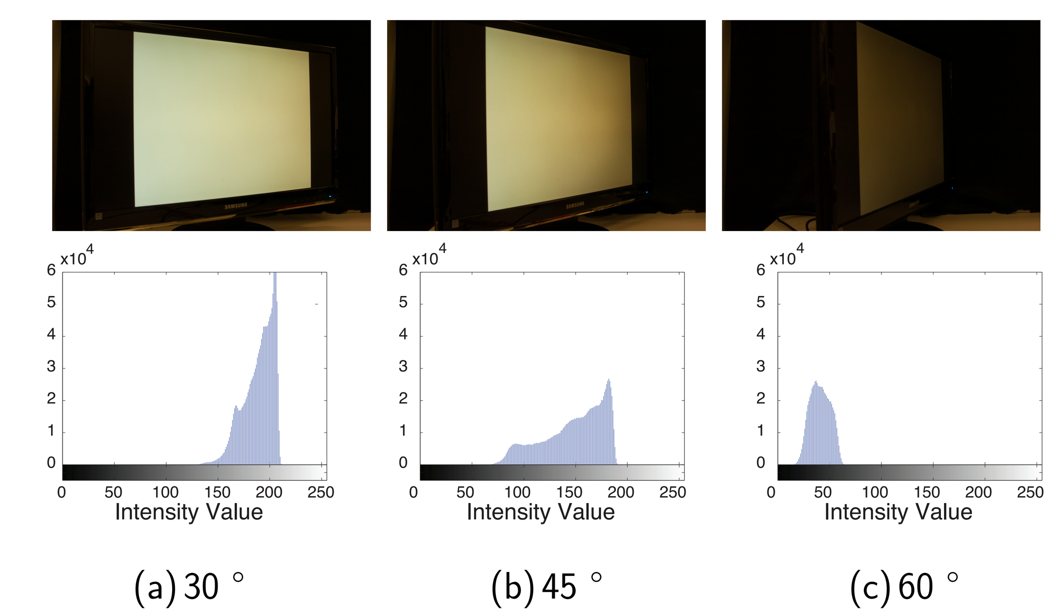

Figure 4: Notice as observation angle changes, so does the distribution of captured intensities illustrating the angular variation of the display emittance function.

Conclusion

- We demonstrate experimental results for **nine different camera-display combinations** at frontal and oblique viewing angles.
- Prior methods of digital watermarking ignore the photometric effects of the camera-display transfer function and the dependence on camera pose.
- Naive thresholding 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.
- Our experimental results show that hidden, dynamic messages can be embedded and recovered robustly.

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