The Self-Equalizing De Bruijn Sequence for 3D Profilometry

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Three-dimensional non-invasive surface profilometry using structured light (SL) is a widely studied topic in the field of computer vision [2]. One of the most important issues of all SL systems is the design of a SL pattern: the pattern must enable reconstruction robust to the ambient light and to the characteristics of the observed object. SL patterns may be classified as *one-shot* patterns that enable reconstruction from a single image and as *multi-shot* patterns that require more than one image. Nowadays a well-designed pattern should enable both one and multi-shot reconstruction. Such SL patterns were proposed by Li Zhang et al. [3] for color light and Yueyi Zhang et al. [4] for monochromatic light.

We propose a novel De Bruijn sequence for color or multi-channel SL which we call the *self-equalizing* sequence. The proposed SL sequence enables a dense *multi-shot* reconstruction for static objects and a sparse *one-shot* reconstruction for moving objects. Additionally, the proposed sequence has several desirable properties: (1) it enables the extraction of ambient lighting, (2) it enables the cancellation of object albedo, and (3) it enables the equalization of channel gains. The proposed sequence thus effectively removes the need for a precise color calibration of the imaging system, which is a major advantage in real-world applications.

Current approaches to SL pattern construction based on a De Bruijn sequence either use a complete sequence or impose a constraint on neighboring colors only. We propose to impose the novel *self-equalizing* constraint on the entire De Bruijn window in such way to achieve the aforementioned desirable properties. The constraint essentially requires that in every De Bruijn window all channels span the full available dynamic range, which is the sufficient condition for the removal of ambient lighting, cancellation of object albedo, and equalization of channel gains thus enabling robust identification of the projected color. A De Bruijn sequence is associated with Eulerian cycle of a De Bruijn digraph which may be used to generate it. The proposed sequence is constructed as Eulerian cycle in the pruned De Bruijn digraph where edges belonging to the invalid windows that do not satisfy the proposed *self-equalizing* constraint are removed.

The proposed SL pattern is a cyclic sequence of images whose cycle is comprised of $L \cdot S$ frames (L is sequence length, $S \geq 3$ is the number of phase shifts per symbol), of which any one frame is sufficient for one-shot reconstruction, and of which any $n \cdot S$ ($n \ll L$) consecutive frames are sufficient for multi-shot reconstruction.

One model for RGB color-space widely accepted in the literature which relates recorded color I_c to projected color I_p under the influence of object albedo K and ambient lightning I_0 is proposed by Caspi et al. [1]:

$$\underbrace{\begin{bmatrix} R \\ G \\ B \end{bmatrix}}_{I_c} = \underbrace{\begin{bmatrix} a_{RR} & a_{RG} & a_{RB} \\ a_{GR} & a_{GG} & a_{GB} \\ a_{BR} & a_{BG} & a_{BB} \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} k_R & 0 & 0 \\ 0 & k_G & 0 \\ 0 & 0 & k_B \end{bmatrix}}_{K} f\left(\underbrace{\begin{bmatrix} r \\ g \\ b \end{bmatrix}}_{I_p}\right) + \underbrace{\begin{bmatrix} R_0 \\ G_0 \\ B_0 \end{bmatrix}}_{I_0}, \quad (1)$$

We propose a simplified model where ith channel is modeled as

$$I_c(i) = h(i)I_p(i) + I_0(i), \quad (2)$$

i.e. the channel cross-talk is disregarded making $A \cdot K$ a diagonal matrix. The cross-talk may be omitted if the color filters of the projector and the camera are well matched, which holds for standardized consumer electronics and which was also noted by Caspi et al. [1]. Combining the model (2) with the *self-equalizing* constraints imposed on the De Bruijn sequence allows the recovery of $I_p(i)$ from $I_c(i)$ independently for each channel.

We have performed three experiments: (1) the influence of channel gains, (2) the reconstruction of white and colored planar surfaces, and (3) qualitative reconstructions of several objects: fruits and vegetables, a
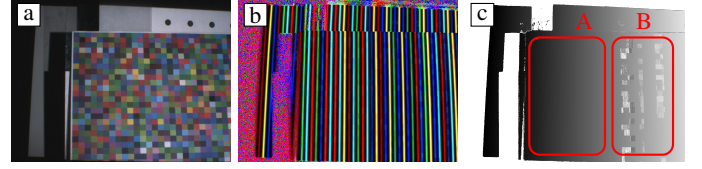

Figure 1: An extremely demanding colorful checkerboard: (a) scene seen by the camera; (b) equalized image; (c) unwrapped phase of the multi-shot method. Note the unwrapping succeeds for region A and fails for region B due to cross-talk which is disregarded in the current model.
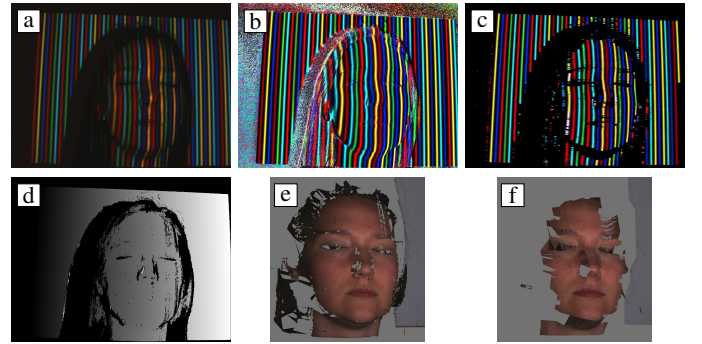

Figure 2: A female face: (a) the first of $n \cdot S$ input images; (b) temporally equalized input image (a); (c) spatially equalized input image (a); (d) the unwrapped phase; (e) textured 3D reconstruction using multi-shot method; (f) textured 3D reconstruction using one-shot method. Note that both the temporal and the spatial equalization successfully remove ambient lightning, object albedo, and varying channel gains.

human face, and a human hand. The first experiment demonstrates the insensitivity to artificially varying channel gains. The reconstruction of a colored planar surface of the second experiment demonstrates the insensitivity to object albedo, but only if there is no significant cross-talk between channels (see Fig. 1). The third experiment illustrates expected results in a real-world application; here we show results for a female face (Fig. 2).

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