Customizing Time of Flight Modulation Codes to Resolve Mixed Pixels

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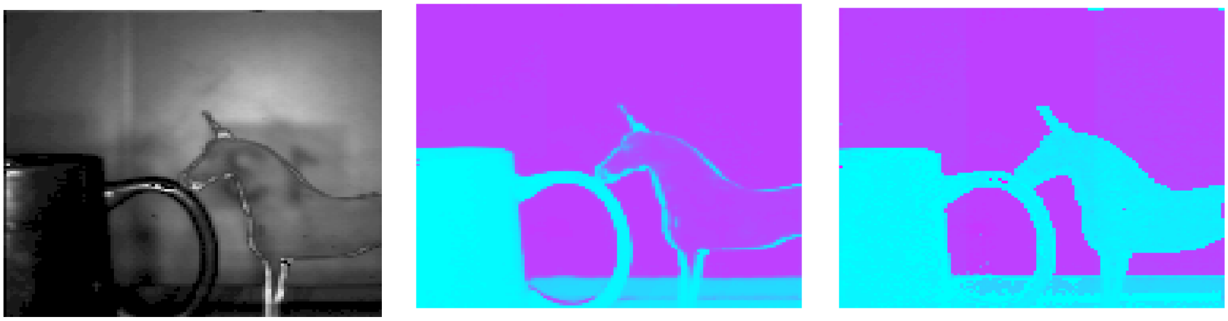

(a) *Amplitude Image of the Scene* **(b)** *Phase Image* **(c)** *Depth Recovery of Transparency*

Figure 1: *Depth imaging of transparent objects. One modulation frequency, ZERO post-image processing. (a) The amplitude image of a scene as measured by our customized time of flight camera. In this scene a near-transparent acrylic unicorn is placed at approximately the same depth as an opaque coffee mug. Specularities can be seen on the edges of the unicorn. (b) The measured phase image. The body of the unicorn is a mix between the background and foreground. The edges are resolved due to the specularities, but the rest of the unicorn is at an incorrect depth. (c) By resolving the mixed pixel problem we are able to obtain the correct depth of the near-transparent unicorn.*

Abstract

We couple custom binary sequences with sparsity based approaches to address the multi-path problem in time of flight imaging. In particular, we utilize maximum length m-sequences that allow us to produce non band-limited correlation functions. Coupled with a tailored sparse deconvolution approach, we are able to resolve the constituent phases and amplitudes of a mixed pixel measurement. Finally, we demonstrate application scenarios, including depth imaging of near-transparent objects.

1 Introduction

Current time of flight cameras cannot resolve the mixed pixel problem. The mixed pixel problem occurs when light from two or more different depths combine at a single pixel. Even a perfect, planar, opaque object is susceptible to mixing—the edge pixels are often a mixture of foreground and background. More troublesome, however, are transparent and reflecting objects. In a transparent object, light from the background and foreground mix to yield a depth that is neither the foreground or background (see Figure 1b). Most realistic scenes captured with a time of flight camera contain mixed pixels, such as from a corner, which acts as a reflector.

In recent years, many algorithms have been proposed to resolve the mixed pixel problem. Success with many current approaches is limited due to scene-dependent assumptions. For instance, [Fuchs 2010] proposed an interesting forward model that serves as the basis for unmixing. However, their forward model is scene-dependent and has not been experimentally validated on other scenes. In a more general framework, [Godbaz et al. 2012] have proposed using multiple frequencies of modulation to unmix pixels, though this approach is ill-conditioned, which limits the practical implications.

2 Our Approach

In this paper, we provide two key insights:

- By sending custom codes, coupled with sparse deconvolution, we are able to resolve the multi-path problem on real, experimental data.
- We consider each component of multipath to be important. In particular, for the case of a transparent object, we can obtain both the depth of the foreground object, as well as the background wall.

In order to send custom codes, we have built our own time of flight camera, with operation details provided in supplementary material. In brief, the camera is able to send custom binary sequences to both the reference and illumination. We formulate the problem such that the codes form a convolution with the environment. In matrix form this can be expressed simply as a linear system: $\mathbf{y} = \mathbf{H}\mathbf{x}$. The smearing matrix $\mathbf{H}$ is a Toeplitz matrix determined by the particular codes that are selected for use with the camera, $\mathbf{y}$ is the measured cross-correlation at a mixed pixel and $\mathbf{x}$ is the recovered environment variable to create the output. By optimizing the codes, and accounting for sparsity, we can reconstruct accurate component depths: see Figure 1c for one particular case.

References

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