What's Next in ToF Imaging: Passive Operation, One-bit Quantization, and Spatiotemporal Superresolution

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Abstract: Time-of-Flight (ToF) imaging is an active 3D imaging technique that leverages the fact that time of arrivals of photons can be used to encode the 3D geometry of a scene. Decoding distances from photon arrivals requires time-resolved pixels, known as ToF pixels. ToF imaging is nowadays a mature technology and a number of design choices have become standard, be due to legacy from initial designs, coherence with conventional imaging, or simplicity. In this talk we draw attention to three typically unspoken design tradeoffs and unveil their potential to refine the performance of future ToF imaging systems. These are: 1) passive operation, 2) bit depth, and 3) demodulation schemes.

Keywords: Time-of-Flight, one-bit quantization, passive ToF, compressive sensing, superresolution

1. Introduction

Time-of-Flight (ToF) imaging is an active 3D imaging technique that leverages the fact that photons can be used to encode the 3D geometry of the scene in their arrival times, thanks to the constancy of the speed of light in a given medium. The scene is flood-illuminated with modulated light and the reflected light is projected onto an array of demodulating pixels by means of a lens. These pixels, known as ToF pixels, are necessarily endowed with time-resolving capabilities. In other words, the measured value depends on when the photon arrivals occur, by virtue of a time-domain control signal. ToF imaging is nowadays a mature technology and a number of design choices have become standard, be due to legacy from initial designs, coherence with conventional imaging, or simplicity. In this talk we focus on three often-neglected design tradeoffs and unveil their potential to further improve the performance of state-of-the-art ToF imaging systems [1].

2. Collaboration instead of competition

A key opportunity that has remained largely ignored to date is the exploitation of existing sources of modulated light. With the increasing presence of LEDs and VCSELs as light sources in illumination systems, novel devices often exploit the modulation bandwidth of these emitters to provide simultaneous lighting and communications. We will show how such opportunity illuminators can be leveraged to obtain "passive" ToF imaging. Recent works have shown the feasibility of this idea, demonstrating depth estimation without photon emission, leveraging existing VLC and LiFi modules [2].

3. One-bit ToF imaging

A second design parameter that is often overseen is the bit depth of the measurements. Typically, uniform quantization at constant bit depth is assumed. The number of bits is then chosen to obtain the resolution dictated by the best-case noise floor of the measurements. This is suboptimal, in general. In modern systems acquiring multiple frames of raw data for generating each depth image, correlations between consecutive measurements can be exploited to implement low-bit quantization schemes. The band-limited nature of real cross-correlation functions allows for one-bit ToF imaging. This idea was first introduced in [3], where multi-path ToF imaging was demonstrated using one-bit ToF raw data obtained using well-understood noise-shaping techniques.

4. Demodulation schemes for spatiotemporal superresolution

The third often-neglected design possibility is the engineering of optimal demodulation functions, so that the maximum amount of information from the scene response function (SRF) is captured with the minimal number of measurements. This allows for minimizing the number of measurements (thus, maximizing the frame rate) required to obtain a desired depth resolution or, complementarily, aiming for temporal superresolution exploiting compressive sensing (CS) techniques [4]. From the CS perspective, the challenge is to obtain a sensing matrix with the lowest possible inter-column coherence. In combination with custom ToF array designs that allow single-shot acquisition of raw data, spatiotemporal superresolution becomes feasible by leveraging both temporal sparsity of the SRF, and local spatial correlations [5].

5. Conclusion

Despite current ToF imaging techniques are the result of a process of continuous improvement over the last two decades, exciting research avenues remain largely unexplored and hold promise for further improvements in terms of power consumption, depth resolution, and data flow.

References

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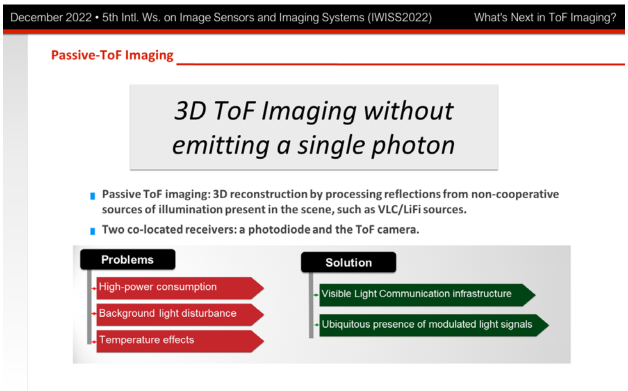
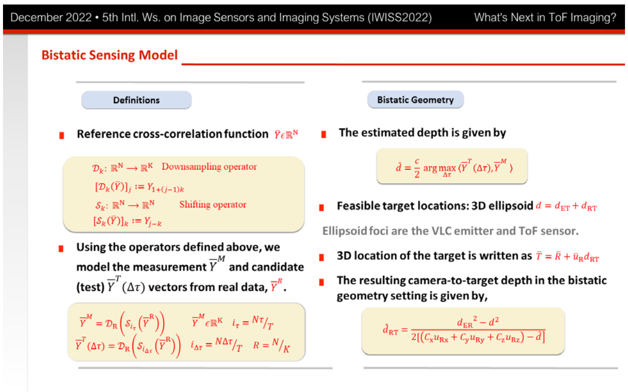
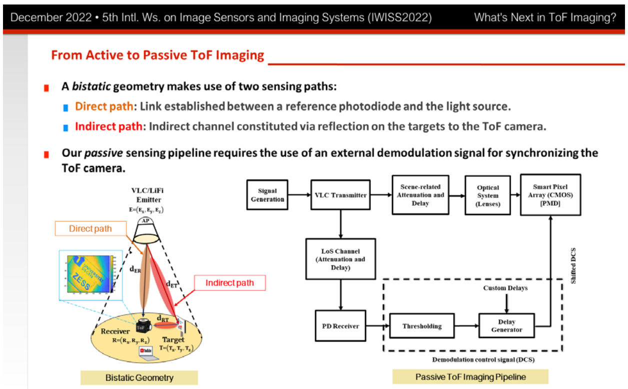
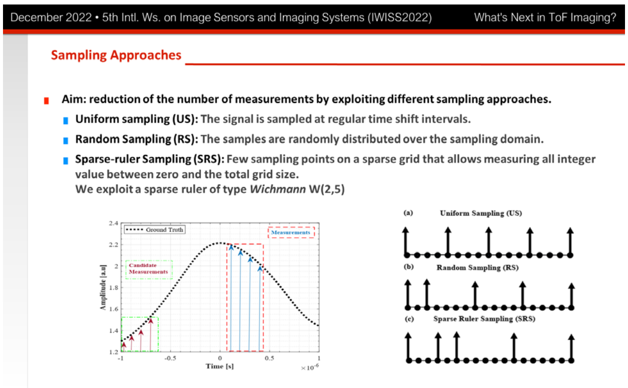
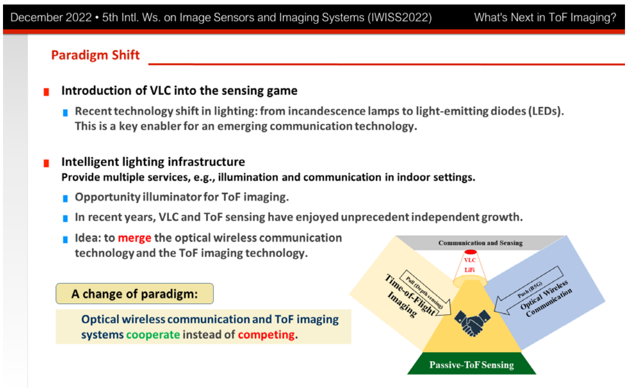
Annex 1: Slides on Passive ToF Imaging

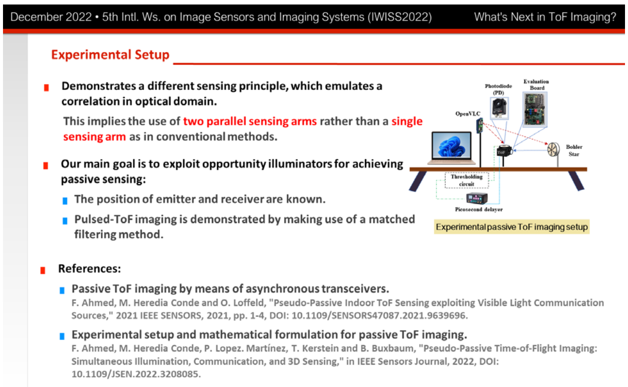


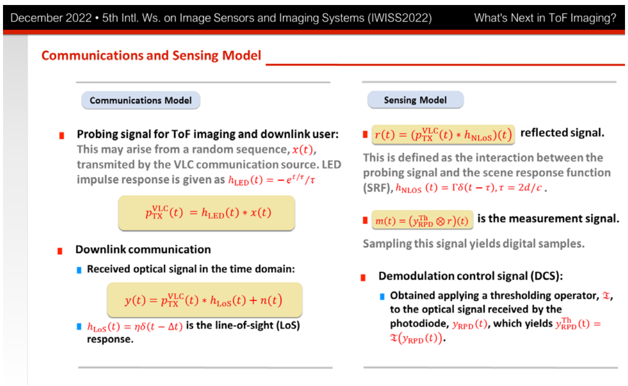


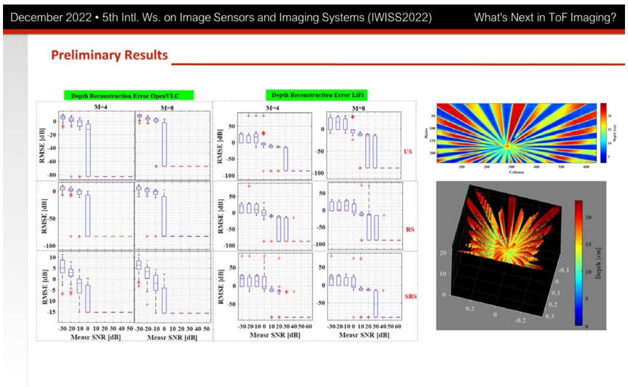




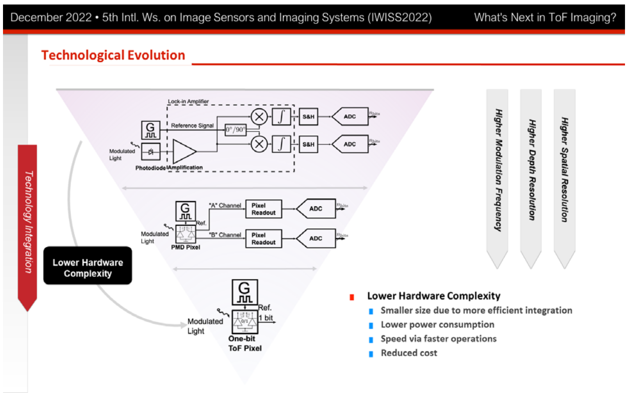


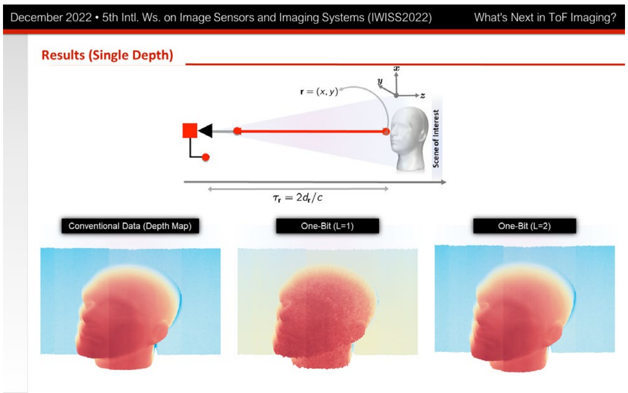


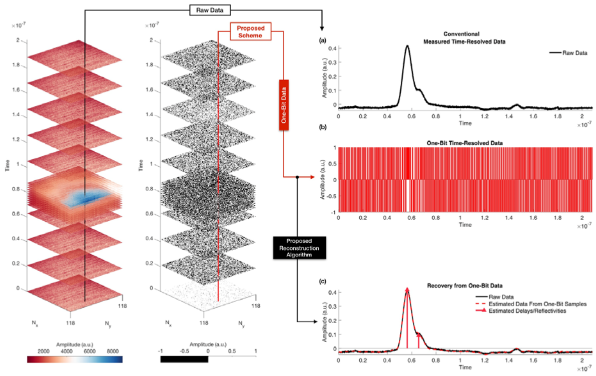


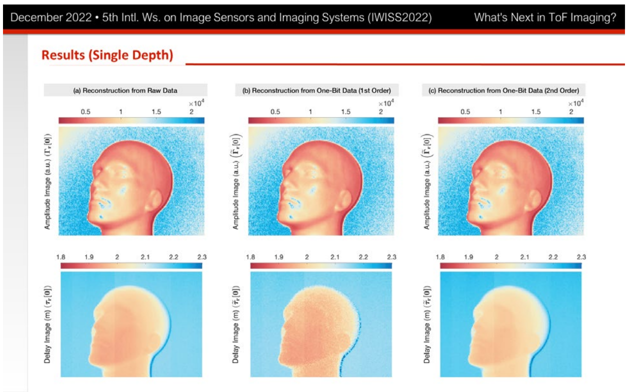


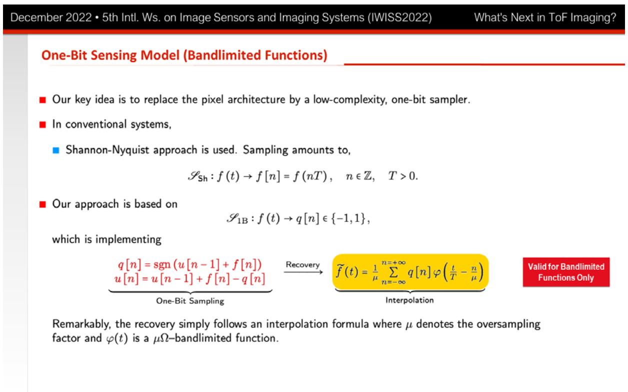
Annex 2: Slides on One-bit ToF Imaging

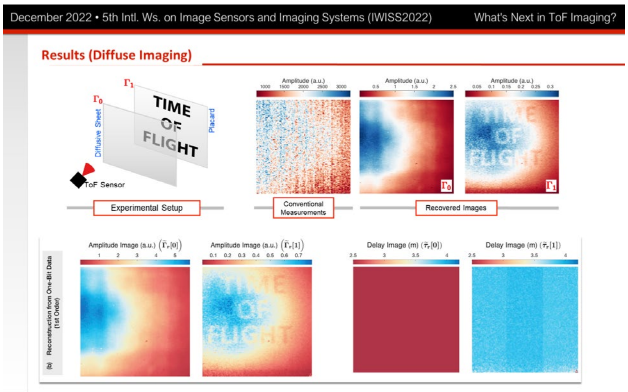


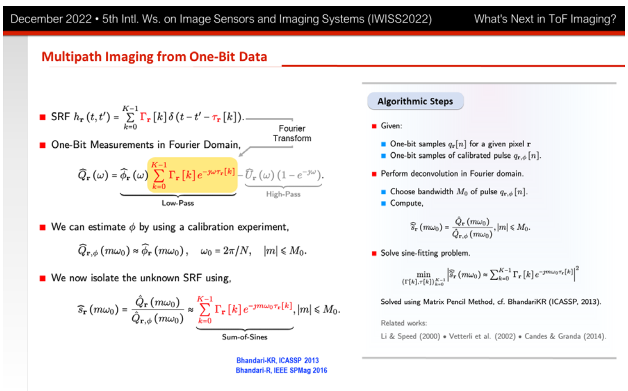


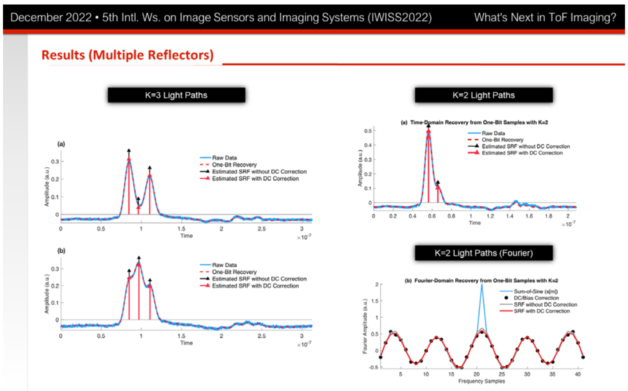












Annex 3: Slides on Spatiotemporal Superresolution