Bringing VLC into ToF imaging: Pseudo-Passive Indoor ToF Imaging

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Abstract. *High power consumption is a fundamental problem in active Time-of-Flight (ToF) modalities in contrast with passive imaging modalities, particularly when the ToF camera is incorporated into low-power devices, i.e., smartphones. This work introduces a novel concept that provides ToF-based measurements of a scene by empowering the light-based communication infrastructure in bistatic configuration. This provides a potential platform due to the pervasive presence of modulated light sources in indoor infrastructure. In this context, we are attempting to use VLC infrastructure, which synergistically supports lighting and communication, as an opportunity illuminator to attain ToF sensing for free. Such capabilities are demonstrated by performing simulations based on continuous-wave (CW) ToF and pulse-based (PB) ToF sensing in a passive approach. The passive modality not only makes the need for illumination units futile in ToF cameras, but also, consequently, will reduce the power consumption and cost of the system.*

Keywords. Passive sensing, visible light communication, OpenVLC, Time-of-Flight, bistatic, adaptive thresholding

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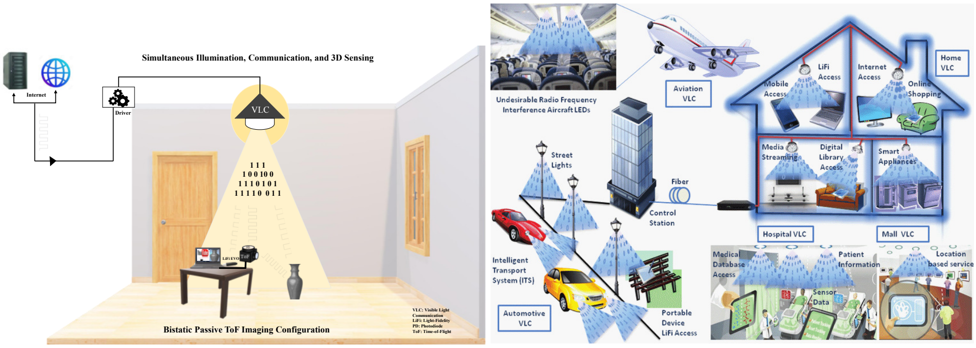
1 Introduction

Over the past few years, 3D Time-of-Flight (ToF) imaging has evolved significantly and attracted the attention of both industry and academia researchers due to its wide range of applications, such as mobile robotics, indoor sensing, autonomous driving, surface mapping, and human-machine interaction, previously driven by LIDARs, and 3D imaging systems [1], [2]. A ToF camera exploits the underlying principle of ToF to compute the radial distance between the ToF sensor and each scene point. An optical signal propagates through free-space at the speed of light, $c \approx [3 \times 10^8]\text{m/s}$, the distance d covered by an optical signal over the time τ is $d = c\tau$. The optical signal is reflected by the scene and then returns to the ToF sensor. Provided that the distance covered by the light signal is $2d$ at time τ, and distance can be computed as $d = \frac{c\tau}{2}$.

ToF technology can be classified into *pulsed* ToF and *continuous-wave* (CW) ToF systems, considering the time or phase shift of the reflected signal with respect to the emitted signal, thereby yielding depth, respectively. In 1997, phased ToF cameras based on *charged coupled devices* (CCD) were pioneered by Prof. R. Schwarte, from the University of Siegen, Germany [3]. Since then, ToF imaging technology has been widely used in 3D imaging applications. The prominent core technology for CW-ToF cameras is known as *Photonic Mixer Device*(PMD). Despite of the many theoretical and engineering advances in ToF imaging in the last few years, the need for a dedicated illumination unit is one of the drawbacks of cutting-edge ToF cameras and results into high power consumption. However, this problem has received unfortunately little attention. Therefore, this has pushed the research community to look at alternative ways of illumination in indoor settings. In recent years, rapid advances in solid-state technology have profoundly transformed the lighting infrastructure from conventional lamps (e.g., incandescent and halogen) to light-emitting diodes (LEDs). LEDs are increasingly popular for displays and light sources due to their long lifetime, small size, low cost, energy efficiency, and very low $\mathcal{O}(\mu\text{sec})$ switching transient [4]. Recently, new pathways have been opened by introducing modulated light sources, such as LEDs, which exhibit high modulation bandwidth. This motivated the migration from radio to optical spectrum to enable high-speed optical wireless communication. This has given a birth to an emerging communication technology known as Visible Light Communication (VLC). We have exploited the OpenVLC1.3 module as an illumination and communication source [5] that supports [1]MHz bandwidth. Existing VLC infrastructure (see Fig. 1b) illuminates the scene [6], and an asynchronous ToF camera captures the scene to retrieve depth. Our previous work [7] exploited a standard method for CW-ToF depth estimation, such as the four-phases algorithm, which results in an unknown depth offset. This unknown depth offset is due to the absence of synchronization between the source and the ToF camera. Furthermore, this passive modality still needs to be ameliorated to achieve accurate depth.

The bistatic configuration addresses the synchronization problem by providing two parallel channels, one of which establishes a direct link between the VLC source and a reference photodiode to obtain an external reference signal for the PMD camera. The second one is the sensing channel that captures scene reflections. The measurements profiles are obtained by performing a cross-correlation between the reference and the sensed signals. Besides, the reference photodiode signals are not digital. So, we developed an appropriate signal conditioning to transform the analog signals into the digital signals that operate the PMD pixels. A custom PMD camera module with built-in external reference signal capability allows us to implement the bistatic operation in the passive ToF concept. This passive operation mode collides with the classical operation mode of ToF cameras based on PMD. The bistatic setup demonstration and a schematic of the proposed VLC-enabled passive 3D ToF system are shown in Fig. 1a and Fig. 2 respectively. Consequently, the sensing pipeline has to be revised according to the bistatic configuration [8]. Simulations are carried out in PB-ToF for varying measurement signal-to-noise ratio (SNR). The improvement of depth accuracy via passive modality is still a new area of research and will be explored further.



(a) Passive ToF Setup **(b)** VLC infrastructure

Figure 1. Bistatic VLC-enabled passive ToF Imaging configuration and readily available VLC infrastructure opportunities adopted from [9].

2 Opportunities and Limitations

The bistatic configuration translates drawbacks into opportunities. The background light is transformed into a useful optical signal for ToF sensing, while it was previously a challenge for ToF cameras. This also eliminates the need for an infrared filter and allows ToF cameras to become receiver-based systems, due to the proposed passive operation mode. The sensing accuracy depends on the light intensity, which may be low owing to indirect scattering of light, and the bandwidth of VLC sources, which may be less than that of a dedicated ToF illumination unit. Additionally, the need for adaptive thresholding may further reduced accuracy due to the existence of jitter.

3 Discussion and Conclusion

A novel passive ToF imager concept without an illumination unit for indoor sensing has been presented in this work. We leveraged commercially available components to develop the 'proof-of-concept' illustrated in Fig. 2. Based on our simulation results, we believe the PB-based ToF is superior to the CW-ToF approach for passive ToF. The root-mean-square error (RMSE) was evaluated in a preliminary noise analysis. An evaluation of the related

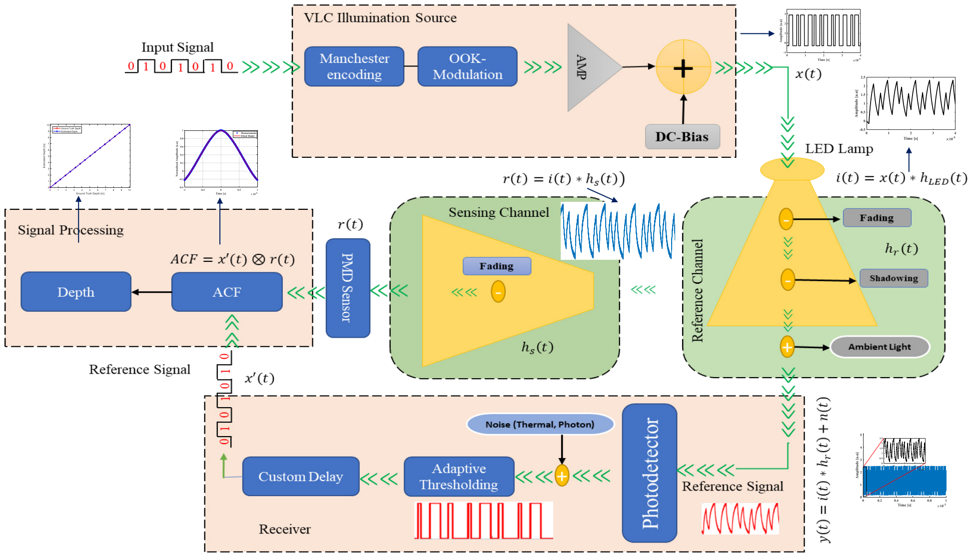
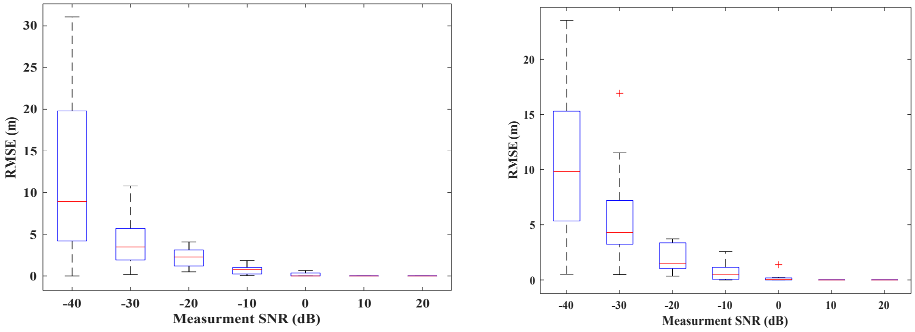


Figure 2. VLC-enabled Bistatic Passive ToF framework [8]. The illumination signal is represented by $i(t)$, the received photodiode signal is denoted by $y(t)$, and the autocorrelation function (ACF) is performed between thresholded signal $x'(t)$ and the reflected signal $r(t)$.



(a) RMSE vs. SNR for [10]m range **(b)** RMSE vs. SNR for [50]m range

Figure 3. Simulation results showing depth reconstruction error in RMSE vs. SNR for different target locations.

depth-RMSE for different ranges ([10]m and [50]m) are shown in Fig. 3. It can be seen that the RMSE decreases by increasing the measurement SNR, as expected until negligible values are attained. Furthermore, we demonstrated the possibility of simultaneously performing illumination, communication, and 3D ToF sensing. VLC is an integral part of the lighting infrastructure, allowing us to use ubiquitous modulated light signals to provide a novel kind of passive ToF sensing in indoor spaces. Simulations validate the proposed concept, and good fitting models of the cross-correlation function were found both for [10]m and [50]m (range). The overarching idea of this work is to dovetail both worlds—that of

VLC communication and that of ToF imaging—in the best possible way. This will reduce the cost and power consumption of the proposed system. This allows the entry into new application fields, such as smart homes, office premises, industries, and vehicles, where the VLC infrastructure (Fig.1b) and ToF cameras are valuable assets. Future research will focus on the evaluation of the experimental implementation.

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