Full-Field Time of Flight and Velocity Imaging with Multi-Heterodyne Interferometric Detection

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1 Motivation

Autonomous vehicles have the potential to find wide spread use in the near future. The successful deployment of these systems requires reliable imaging of their environments. Autonomous vehicles predominantly rely on Light Detection and Ranging (LIDAR) scanning units, which provide high resolution depth and velocity maps, but the current high cost of scanning LIDAR units makes them a costly option. On the other hand, the use of multiple cameras positioned around vehicles lack reliable depth information. Therefore, there is a need for reliable, cheap, and scalable solutions to simultaneously measure depth and velocity in a wide field of view.

CMOS cameras have found wide spread use in many applications and economies of scale have brought down the cost significantly over the last few decades. The motivation in this project is to investigate the possibility of using a cheap CMOS camera with minimal optical components to obtain reliable depth and velocity information in a wide field of view as alternatives for LIDAR and Time of Flight (TOF) cameras.

2 Related Work

Measuring the depth of a scene based on time of flight measurements can be accomplished with optical interferometric techniques. In optical interferometry, a laser beam is separated into two different beams; a reference and an object beam. The object beam is directed to the target and interferes with the reference beam upon reflecting and returning to the image sensor [1]. The reference beam is up-shifted in frequency by a phase modulator to allow heterodyne detection of the interference pattern recorded by the CMOS sensor. Due to the micron scale wavelength of light, however, the unambiguous depth range is limited to the wavelength of light, which is on sub-micron levels. By sending different frequencies to the target and measuring the phase (or, equivalently, the frequency response), the depth of the scene can be estimated to an accuracy that depends on the spanned temporal bandwidth. This technique is commonly referred to as stepped frequency continuous wave radar (SFCW) in the radar community [2]. To extend the unambiguous range in optical interferometry, synthetic wavelength interferometry technique is used [3]. Multiple closely spaced laser frequencies are simultaneously sent to a target and the returning beams interfere with multiple different reference beams with different frequencies to map each frequency channel into a different temporal frequency. This method has been demonstrated to achieve meter level unambiguous depth range with micron level accuracy using a complex optical setup consisting of multiple lasers and a ToF module. Another work uses the orthogonality of sinusoids to estimate the velocity of objects in a scene [4]. Using a ToF camera, either the depth or velocity of objects can be estimated by amplitude modulating an incoherent light source and having on sensor modulation in the ToF camera. Velocity and depth can be estimated using this method by rapidly capturing sequential images and varying the sensor reference signal.

3 Project Overview

In this project, I will implement a multi-heterodyne time of flight and velocity imaging system. The system will allow simultaneous velocity and depth information to be extracted, unlike previous works which either only measure depth or need to multiplex between depth and velocity mode when using a single sensor. The system will only consist of a standard CMOS camera as the detector. The object beam will be phase modulated to achieve multiple frequencies, similar to synthetic wavelength interferometry. The object beam will also be phase modulated to achieve another set of multiples frequencies. Upon reflection from the target, the object beam with the different frequencies will each carry a different phase and will be frequency shifted based on their amplitude modulation frequency. The frequency spacings will be adjusted, using ideas from orthogonal frequency division multiplexing (OFDM) [5] to make more efficient use of the temporal bandwidth of the CMOS camera. The phase and Doppler shift information will be used to simultaneously extract the motion and depth in the field for each pixel simultaneously, only requiring a handful of frames.

4 Milestones, Timeline, and Goals

4.1 Week 1

Fully derive the theory for multi-frequency measurements. Frequency separations, amplitude ratios, QAM demodulation, and OFDM techniques.

4.2 Week 2

Simulate the established theory in MATLAB to test the validity. Revise the methods or relax the problem if simulation does not hold. Derive confidence bounds and prepare tables and plots of SNR vs. measurement distance, number of synthetic frequencies, relative amplitudes. Find the necessary equipment (beam splitters, phase modulators, laser, camera, interference filter, focusing lens) to conduct the experiments the following week.

4.3 Week 3

Start conducting preliminary experiments to make sure the setup is configured and basic measurement results are consistent with the theory and simulation results. Use one frequency rather than multi-frequency if multi-frequency approach fails. Conduct more advanced measurements demonstrating full capability if possible.

4.4 Week 4

Keep working on experimental results to demonstrate full capability of the system as predicted by theory and simulation. Finish poster and report.

5 References

1. A. Kadambi, and R. Raskar, "Rethinking Machine Vision Time of Flight With GHz Heterodyning", *IEEE Access*, vol. 5, November 2017

2. J. M Weiss, "Continuous-Wave Stepped-Frequency Radar for Target Ranging and Motion Detection", MICS, 2009

3. C. Weimann, M. Fratz, H. Wolfel Schneider,W. Freude, H. Hofler, and C. Koos, "Synthetic-Wavelength interferometry improved with frequency calibration and unambiguity range extension", *Applied Optics*, vol. 54, No. 20, July 2015

4. F. Heide, W. Heidrich, M. Hullin, and G. Wetzstein, "Doppler Time-of-Flight Imaging", *ACM Transactions on Graphics*, vol. 34, July 2015

5. Y. Li, and G. L. Stuber, "Orthogonal Frequency Division Multiplexing for Wireless Communications", *Springer*, 2006

6. A. A. Dorrington, M. J. Cree, A. D. Payne, R. M. Conroy, and D. A. Carnegie, "Achieving sub-millimetre precision with a solidstate full-field heterodyning range imaging camera", *MEASUREMENT SCIENCE AND TECHNOLOGY*, July 2017

7. R. M. Conroy, A. A. Dorrington, R. Kunnemeyer, and M. J. Cree, "Range imager performance comparison in homodyne and heterodyne operating modes", *Proc. SPIE 7239, Three-Dimensional Imaging Metrology*, January 2019