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Continuous-wave light detection and ranging (LiDAR) using image-reject homodyne detection and PRBS modulation

Katie A. P. Ward[1,2,3], James T. Spollard[1,2,3], Lyle E. Roberts[1,2,3], David C. McClelland[1,2], and Daniel A. Shaddock[1,3]

[1]Research School of Physics and Engineering, Australian National University, Canberra ACT 2601, Australia
[2]OzGrav-ANU, Centre for Gravitational Physics, The Australian National University, Canberra, ACT, Australia
[3]EQUS-ANU, Centre for Gravitational Physics, The Australian National University, Canberra, ACT, Australia

ABSTRACT

We present a continuous wave Light Detection And Ranging (LiDAR) sensor that instantaneously measures distance and radial velocity with strong immunity to interference (e.g., other LiDAR sensors, glare). By automatically prioritising measured information based on velocity and range, our aim is to reduce the processing time required to execute safety-critical decisions in autonomous applications.

Keywords: LiDAR, coherent detection, cross-correlation, digital signal processing, FPGA

1. INTRODUCTION

LiDAR describes a class of technologies used to create high-resolution three-dimensional maps of the environment. It is considered a crucial technology for autonomous vehicles but is also used in a wide range of other applications including terrain profiling, wind velocimetry and Doppler altimetry. The distance to an object within a scene can be inferred by measuring a time varying attribute of light (e.g., modulation of frequency, amplitude or phase) to determine the round-trip time-of-flight. Radial velocity of an object can be measured by analysing Doppler-induced frequency shifts in the reflected light.

The sensor presented here measures distance by encoding the phase of the light with a pseudo-random bit sequence. Velocity is extracted by observing the Doppler frequency shift of the received light relative to a reference local oscillator. The sensor utilises commercially-available telecommunications-grade hardware, as well as the latest generation of system-on-chip (SoC) field-programmable gate-array (FPGA) technology. By combining flexible, electronically controlled optical hardware with the signal processing power of FPGAs, the behaviour and performance of the sensor is entirely software-defined.

A lab-based proof-of-concept has demonstrated ranging with 5 meter precision, limited by the availability of high-bandwidth electronics. A system capable of better than 10 cm resolution using dedicated high-bandwidth electronics is in development.

2. SYSTEM DESIGN

Light from a 1550 nm fiber laser is separated into two arms using an asymmetric fiber coupler (Fig 1). The weak arm is used as a local oscillator and is connected directly to a 90-degree optical hybrid. The high powered arm passes through an electro-optic modulator where the phase of the optical carrier is encoded with a pseudo-random bit sequence. This light is then sent out and steered to the target using a 2-axis galvanometer. The received light is coupled into the signal port of the 90-degree optical hybrid where it interferes with the local oscillator at two photodetectors. The 90-degree optical hybrid performs in-phase and quadrature projections of the received signals electric fields with respect to the reference.

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Signal processing is performed on a Field-Programmable Gate-Array (FPGA) for high-throughput real-time extraction of distance and velocity. The FPGA is connected to two analog-to-digital converters which digitise the signals from the photodetectors. High-speed digital outputs are used to drive the electro-optic phase modulator with the PRBS code. High accuracy, low-bandwidth digital-to-analog converters are used to drive the two galvanometers.

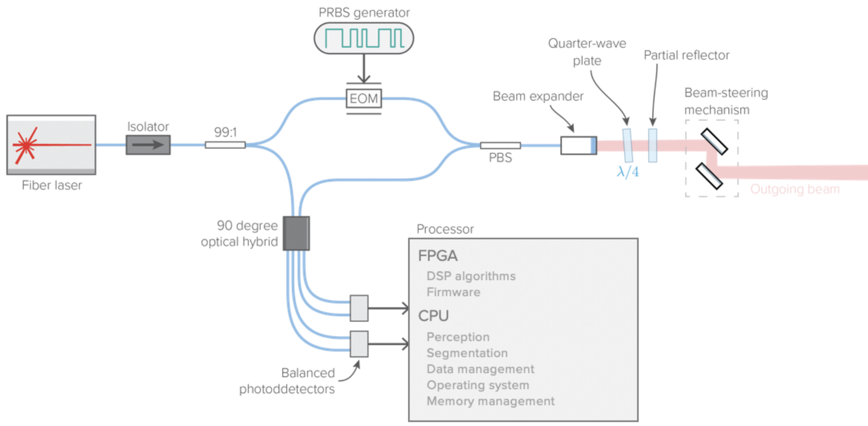

Figure 1. Schematic of the optical and FPGA implemented digital signal processing systems.

3. RANGE AND VELOCITY MEASUREMENT

A Pseudo-Random Bit Sequence (PRBS) is encoded onto the phase of the outgoing beam in order to provide a measurable time-varying attribute. The PRBS has excellent auto-correlation properties which can be exploited to measure round trip time-of-flight (i.e., the total time taken for light to reach the target and scatter back to the sensor) and therefore distance. Correlation is performed efficiently on an FPGA using cross-spectral analysis between the received signal and a local template. Since the received electric field may be shifted due to Doppler, it can degrade the performance of the correlation algorithms if not taken into account. The Doppler frequency is thus determined first and then used to update a local template for correlation. The principle of using PRBS phase encoding for ranging is inspired by digitally enhanced heterodyne interferometry, a technique which can be used to isolate interferometric signals based on their unique time-of-flight within an optical system.[1]

The Doppler frequency is extracted using cross-spectral analysis on the in-phase and quadrature projections of the received signal with respect to the reference local oscillator. This is made possible by using a 90-degree optical hybrid. Cross-spectral analysis between the two independent measurements of the in-phase and quadrature signals will reveal any Doppler shifts in the imaginary axis of the resulting cross-spectrum (since the two signals are out-of-phase by 90 degrees). This technique, called image-reject homodyne velocimetry, was initially proposed in 2014 by Cyrus F. Abari for wind velocimetry.[2] We have extended Abari's technique to also measure distance.

The absolute Doppler frequency is extracted by identifying the frequency bin belonging to the highest magnitude spectral feature in the imaginary axis of the cross-spectrum. The direction of the Doppler shift (i.e., positive or negative) is determined by observing whether or not the highest magnitude peak in the first half of the imaginary axis of the cross-spectrum is positive or negative. This enables us to unambiguously detect Doppler shifts without requiring an intermediate frequency shifter such as an expensive and fragile Acousto-Optic Modulator (AOM). Using this technique, velocity can be measured with better than 10 cm/s resolution.

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