FMCW Laser Ranging with FPGA Closed-Loop Control

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Abstract

A laser ranging system (Lidar), based on the frequency-modulated continuous-wave (FMCW) method is built. It consists of a DFB laser and an asymmetric Mach-Zehnder interferometer. Linear tuning of the laser frequency via current modulation creates a beat signal at the interferometer output. The frequency of the beat signal is proportional to the optical path difference in the interferometer. Since the laser frequency-to-current response is nonlinear, a closed-loop feedback system is designed to improve the tuning linearity, and consequently the measurement resolution. For fast active control, an embedded system with FPGA is used, resulting in a nearly linear frequency tuning, realizing a narrow peak in the Fourier spectrum of the beat signal. For free-space measurements, a complete system with an additional Michelson interferometer is built.

FMCW Ranging System

Advances in autonomous driving and robotics are creating high demand for inexpensive and mass-producible distance sensors. For precise, fast and flexible distance sensing, light detection and ranging (Lidar) can be used. However, the relatively high costs of current Lidar technology are the main factor preventing its utilization as off-the-shelf products. In comparison to the most commonly used time-of-flight ranging systems, where high-speed photodetectors are needed, a FMCW ranging system [1] is a valid choice for inexpensive systems because of its comparatively low-cost components [2].

FMCW laser ranging systems transmit and receive back-scattered frequency-modulated laser light. The signal received interferes with a portion of the transmitted light creating an interference signal, which contains the traveling time information. This technique requires a swept-frequency single mode laser as a source.

Figure 1 shows the ideal linear modulation scheme of laser frequency vs. time. The time-dependent frequency of the laser source is:
The so-called chirp-rate is defined as $\alpha$.

$$f(t) = f_c + \frac{df}{dt} t = f_c + \alpha t$$

For a given target distance $x$, the time-delay $\tau$ results in the beat frequency:

$$f_b = \alpha \tau = \frac{2x}{c}$$

The optical frequency of the DFB laser is tuned via injection current modulation in triangular waveform. This ideally linear laser frequency-tuning generates a certain constant beat frequency corresponding to a certain target distance. DFB lasers however have a non-linear laser-frequency-to-current response \[3\]. This causes a spectral broadening of the beat signal. Therefore, a feed-back loop (FBL) is needed in order to predistort the current modulation waveform to compensate the non-linear frequency response. A phase-locked loop is implemented on an embedded FPGA system.

**PLL on Embedded FPGA System**

Phase-locked loops (PLL) are negative feedback control systems that force a voltage-controlled oscillator (VCO) to follow the phase of a reference oscillator. Since frequency is the time-derivative of phase, the frequency of the VCO locks to the frequency of the reference oscillator in the closed state of the control loop. Hence, a PLL can be used as a control loop to create a constant beat-frequency in an interferometer with a fixed delay \[4\].
The PLL is implemented on a LabVIEW RIO Evaluation Kit System. A diagram of the FPGA program is shown in Figure 2. The input beat signal is converted to a rectangular signal by a comparator. Then the error signal is created by a XNOR mixer by mixing the input with a reference oscillator. The scaled error signal and the integrator offset are added and integrated. After scaling the signal is used for laser current modulation. The initial triangular waveform is created using the integrator offset. For rising and falling slopes, the sign of the integrator input is periodically inverted.

Setup and Results

The complete setup, as shown in Figure 3, consists of the linearly frequency-swept DFB diode laser source the output of which is split by a 90:10 coupler. The ranging part is implemented as a Michelson interferometer with a fixed reflector arm and a sample arm. A balanced photodiode and a spectrum analyzer are used to determine the frequency peak, which is proportional to the target distance. In the FBL, the beat signal is generated by a reference Mach-Zehnder interferometer with a fixed delay length of 1 m. The electrical beat signal generated in the photodetector is fed into the FPGA control system. The FPGA provides the pre-distorted current modulation waveform to linearly tune the laser frequency.

![Figure 3](image)

*Figure 3: The complete measurement setup consists of two interferometers.*

With the FBL control, the optical chirp of the laser could be linearized to a high degree. Figure 4 shows the beat spectrum of a free-space measurement with enabled FBL. The FWHM of the frequency peak is ~50 Hz, which results in an absolute resolution of 2 mm (~3.6 ‰) accuracy at 560 mm target distance.

Figure 5 compares the beat-signal spectra over time in the reference interferometer for a deactivated and an enabled FBL. Without FBL, the beat frequency periodically varies, resulting from the characteristic laser tuning response to the triangular current waveform. Since the delay length in the reference interferometer is fixed, the reference beat frequency should stay constant. This is achieved by closed-loop operation.
Figure 4: Beat spectrum in free-space interferometer with enabled FBL

Figure 5: Spectrograms of the reference interferometer beat signal with uncompensated non-linearity (top) vs. closed-loop (bottom) compensation

Summary

For an improvement of the chirp linearity and therewith the measurement resolution, an optical PLL feed-back loop system was successfully developed and implemented as a “digital circuit” on an FPGA board. Using the FPGA is practical because of its flexibility, reconfigurability and performance. Considering the cost of components, this is a successful result with a high potential of reducing costs when moving from current laboratory equipment and parts of known high cost to an industrial-scale assembly.
References


