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Fully digital intensity modulated LIDAR

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Abstract

In several applications, such as collision avoidance, it is necessary to have a system able to rapidly detect the simultaneous presence of different obstacles. In general, these applications do not require high resolution performance, but it is necessary to assure high system reliability also within critical scenarios, as in the case of partially transparent atmosphere or environment in presence of multiple objects (implying multiple echoes having different delay times.) This paper describes the algorithm, the architecture and the implementation of a digital Light Detection and Ranging (LIDAR) system based on a chirped optical carrier. This technique provides some advantages compared to the pulsed approach, primarily the reduction of the peak power of the laser. In the proposed architecture all the algorithms for signal processing are implemented using digital hardware. In this way, some specific advantages are obtained: improved detection performance (larger dynamics, range and resolution), capability of detecting multiple obstacles having different echoes amplitude, reduction of the noise effects, reduction of the costs, size and weight of the resulting equipment. The improvement provided by this fully digital solution is potentially useful in different applications such as: collision avoidance systems, 3D mapping of environments and, in general, remote sensing systems which need wide distance and dynamics.

Keywords: CW-IM LIDAR; Chirp; Laser Obstacle Avoidance

1. Introduction

LIDAR based on laser beam scanning can be applied to several detection and ranging fields, including obstacle avoidance in aerospace navigation [1] as well as real-time surveillance of restricted areas. For example, LIDAR can be used in port areas security to detect crafts in rapid approach, which are not easily revealed by passive optical systems at night, also considering that RF Radar systems can fail in case of non-conductive or small boats.

Many laser modulation techniques can be applied, obtaining different measurement ranges and resolutions:

1) Continuous wave amplitude modulated [2], based on the sinusoidal modulation of the laser beam intensity (sub-millimetrical resolution, single echo and small distance);
2) Pulsed LIDAR [3] (long distance, multiple echoes);
3) Pulse compression [4,5] (long distance and multiple echoes)
4) Continuous wave frequency modulated (CW-FM) technique (long distance and multiple echoes) [6,7].
5) Continuous wave intensity modulated [8], based on the laser beam intensity modulated by a chirped signal.

The CW-IM-technique is generally implemented by using analog electronic circuits or optical system. Despite its greater operative frequency which can allow a higher resolution, the use of an analog implementation reduces the flexibility and the robustness of the obtained equipment, and does not enable the application of powerful processing techniques that can improve the performance in presence of multiple echoes with very different amplitudes. On the contrary, a digital approach is able to exploit these techniques, increases the integration and reduces the complexity of the assembling [9]. As a consequence, the resulting devices have reduced costs and increased reliability.

For these reasons during the last years, the authors developed different versions of a fully digital processing system for LIDAR. This system is able to measure the times of flight of the optical wave also in presence of multiple echoes. The system has been developed in a collaboration between ENEA and University of Rome "Tor Vergata".

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All the above versions of the electronic circuits for the LIDAR have been designed and tested; one of these has also been actually applied to an optical laser probe.

This paper describes the CW–IM algorithm used in the experimental equipment, the architecture of the hardware and firmware developed, the test performed and their results.

The paper is organized as follows: in Section 2 the algorithm is briefly discussed, while in Section 3 the architecture of the fast prototype is illustrated. Section 4 contains a discussion on the digital implementation of the proposed algorithm. Section 5 describes the experimental results of a first version of the LIDAR electronic system, while Section 6 contains the preliminary electrical test of the second release. The last section contains the conclusions and the possible future activities.

2. CW-IM algorithm

CW-IM LIDAR technique is based on linear complex chirp signal

$$R(t) = \mathrm{e}^{i(2\pi f_{\mathrm{r}} \cdot t)t} = R_{\mathrm{I}}(t) + iR_{\mathrm{Q}}(t)$$

where $f_{\mathrm{r}} = \Delta freq/T$ is the increasing rate of chirp frequency, T is the sweep duration and $\Delta freq = stop\_freq - start\_freq$ is the chirp bandwidth.

The laser beam is modulated with the component

$$R_{\mathrm{Q}}(t) = \sin[(2\pi f_{\mathrm{r}} \cdot t) \cdot t]$$

The echo signal *S(t)* at the output of the photodiode that receives the lights backscattered from the targets is given by

$$S(t) = A_{\mathrm{R}} \cdot R_{\mathrm{Q}}(t - \Delta t) = A_{\mathrm{R}} \cdot \sin[2\pi f_{\mathrm{r}}(t - \Delta t) \cdot (t - \Delta t)]$$

S(t) corresponds to $R_{\mathrm{Q}}(t)$ delayed by time of flight $\Delta t = 2 \cdot D/C$ (where D is the target distance and C is the speed of light). The amplitude of the echo A_{R} depends on the target material, the angle of incidence and the distance.

For sake of simplicity, in this discussion additional phase shifts in the echo have not been considered; this assumption does not affect the final results.

The product $C(t) = R(t) \cdot S(t)$ can be expressed as

$$C(t) = C_{\mathrm{I}}(t) + iC_{\mathrm{Q}}(t) = C_{\mathrm{IL}}(t) + C_{\mathrm{IH}}(t) + iC_{\mathrm{QL}}(t) + iC_{\mathrm{QH}}(t)$$

where

$$C_{\mathrm{IH}}(t) = \frac{1}{2} A_{\mathrm{R}} \sin\left(4\pi f_{\mathrm{r}} t^2 + 2\pi f_{\mathrm{r}} \Delta t^2 - 4\pi f_{\mathrm{r}} \Delta t \cdot t\right)$$

$$C_{\mathrm{IL}}(t) = \frac{1}{2} A_{\mathrm{R}} \sin\left(2\pi f_{\mathrm{r}} \Delta t^2 - 4\pi f_{\mathrm{r}} \Delta t \cdot t\right)$$

$$C_{\mathrm{QH}}(t) = -\frac{1}{2} A_{\mathrm{R}} \cos\left(4\pi f_{\mathrm{r}} t^2 + 2\pi f_{\mathrm{r}} \Delta t^2 - 4\pi f_{\mathrm{r}} \Delta t \cdot t\right)$$

$$C_{\mathrm{QL}}(t) = -\frac{1}{2} A_{\mathrm{R}} \cos\left(-2\pi f_{\mathrm{r}} \Delta t^2 + 4\pi f_{\mathrm{r}} \Delta t \cdot t\right)$$

The high-frequency terms C_{IH} and C_{QH} are 2 chirps with double chirp rate and different start and stop frequency with respect to *R(t)*. The most of C_{IH} and C_{QH} signals are removed from the *C(t)* signal using a complex low-pass filter, as shown in Fig. 1. The remaining low-frequency terms C_{IL} and C_{QL} are 2 sinusoids at frequency $2 f_{\mathrm{r}} \Delta t$, they depend on the time of flight Δt.

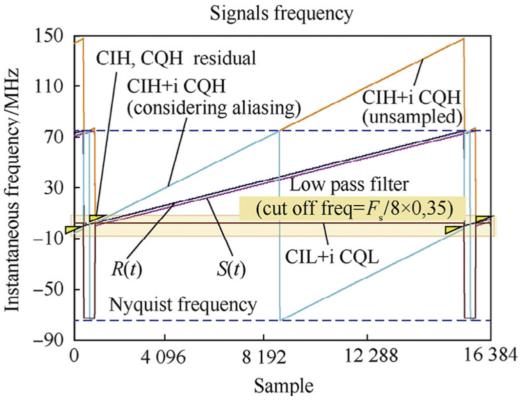

Fig. 1. Trend of the signals frequencies during the chirp period.

The instantaneous frequencies of the previously described signals are shown in Fig. 1.

In case of multiple echoes with different delays Δt_i, it is possible to know the amplitude $A_{\mathrm{R}i}$ of the single echo by analyzing the module of the Fast Fourier Transform (*|FFT|*) of the *(*C_{IL}*+i* C_{QL}*)* signal.

3. Architecture of the fast prototyping system

Two fully digital CW-IM LIDAR electronics have been developed starting from Field Programmable Gate Array (FPGA) fast prototyping system [10].

The first release (see Fig. 2) is based on Stratix II EP2S60 DSP Development Board presenting the following characteristics:

1) Altera Stratix II EP2S60F1020C4 FPGA;
2) 100 MHz system clock;
3) Two 12-bit 125 Msps A/D (model AD9433BSQ) converters used in interleaved mode to obtain a 150 Msps analog to digital conversion;
4) 14 bit 165 Msps D/A converter (model TI DAC904);
5) An Ethernet MAC/PHY;
6) A JTAG interface.

Moreover, the hardware contains a signal conditioning circuitry and an optical interface composed by a laser diode and a photoreceiver.

4. Implementation of CW-IM LIDAR algorithm on digital hardware

The proposed algorithm has been implemented through the digital processing of the signals; the main limitations are due to the sampling frequency (F_{s}) of the A/D converter. If compared with the conventional analog implementations we obtain the following advantages:

1) Simplification of the system and lower cost due to the absence of critical analog parts;
2) The digital generation of the quadrature complex chirp signal (with frequency in the range *0-*$F_{\mathrm{s}}/2$) corresponds to