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High-Resolution Optical Rangefinder for Industrial Monitoring

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***Abstract* –The proposed work aims to improve one of the most used telemetry techniques to make absolute measurements of distance: the time of flight telemetry. The main limitation of the low-cost implementation of this technique is the low accuracy (some mm) and measurement rate (few measurements per second). In order to overcome these limits we modified the typical setup of this rangefinder exploiting low-cost telecommunication transceivers and radiofrequency synthesizers. The obtained performance are very encouraging, reaching a standard deviation of a few micrometers over the range of some meters.**

I. INTRODUCTION

The industrial demand of absolute length measurements over long distances is increasing, and the specific demanding are always more stringent for resolution, accuracy and measurement speed. There are different field of applications of distance measurement, from the aviation industry, requiring three-dimensional measurements with range up to 100 m for wing structures, to measurements for space environment, to real time control of satellites dynamic, for geodesic monitoring, e.g. for earthquake prediction, or decision on storing toxic waste. For an absolute distance measurement, the optical Time Of Flight (TOF) method is widely used: the distance is obtained by measuring the time taken by light to cover the distance to measure usually in round trip [1-3]. Using optical pulses, the ultimate limit is given by the resolution time of the detectors, for example, time resolutions of 10 ps corresponds to a distance resolution of 1.5 mm (1.5 10^{-5} on a range of 100 m). To improve the resolution, the standard solution consists in modulating the laser source, and measuring the phase-shift of the reflected light [2]. Other techniques, less used, are based on interferometry [4], but they are limited to the coherence length of the laser source [3] and typically exhibit too-high cost for industrial applications. Other techniques are based on the synthetic wave method [4-5], for example, using a femtosecond comb as an amplitude modulated source [4]. This very particular optical source allows interesting measurement performances, but with very-high costs.

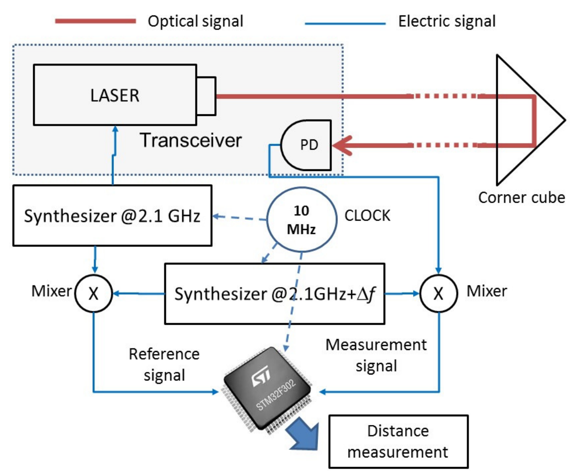

Fig. 1. Sensor scheme.

The proposed technique for distance measurement is based on TOF, with a high frequency modulation, in order to reach micrometric-resolution performances, but realized with commercial telecommunication electronics, in order to keep the system low-cost.

In a previous work [7], we demonstrated very good performances, obtained through a pulsed mode-locked laser, by measuring the heterodyne down-conversion of a high-harmonics at about 2 GHz. The drawback of that realization are the complexity of the source and of the elaboration electronics. In this work, we propose to directly modulate a low-cost optical transceiver at about 2 GHz, reaching performances similar to [7], without wasting power in all the unused harmonics.

The ultimate limit in accuracy for this kind of measurement in air is still the knowledge of the air refraction index along the optical path, because it involves a correction to the measurements, but it is easy to compensate its effect to about 10^{-6}. The presented approach aims to achieve a relative accuracy better than 10^{-5} and a resolution of about 5 μm, at a measurement rate of 1 kHz. These performances are well adequate to different industrial monitoring applications.

Fig. 2. Optical receiver and emitter, linked by an optical fiber to the transceiver.

II. INSTRUMENT SETUP

The system setup of the realized rangefinder is described in Figure 1. The instrument core is a commercial transceiver (model FTLF1519P1 by Finisar), including laser diode and photoreceiver, both working at about 2.1 GHz. The radiofrequency section is composed by two electronic integrated synthesizers ranging from 2.04 GHz to 2.45 GHz (Analog Devices ADF4360-1) and two frequency mixer (MiniCircuits ZEM-4300+) performing downconversion from 0.3 GHz to 4.3 GHz. The whole system is managed by a microcontroller STM32F303. It drives the two synthesizers, samples the downconverted signals and executes all the needed elaborations for real time measurement. Large-beam fiber collimators, as shown in Fig. 2, implement the optics for emitter and receiver. The link to the transceiver is realized by connectorized fibers. Finally, the cooperative target is a corner cube.

III. RADIOFREQUENCY SYSTEM

In order to calculate the distance the system measures the phase shift between the modulation of the transmitted light, and the modulation of the received light. The transmitter is directly modulated at f_m = 2.1 GHz by the first frequency synthesizer (see Fig. 1). The second frequency synthesizer operates as local oscillator for the down-conversion of the signal received by the photodiode (measurement signal), and by the other synthesizer (reference signal). It generates a frequency of 2.1 GHz + Δf=1 MHz. In this way, the downconverted signals are at 1 MHz. The heterodyne conversion retains the phase shift, while expanding the time scale.

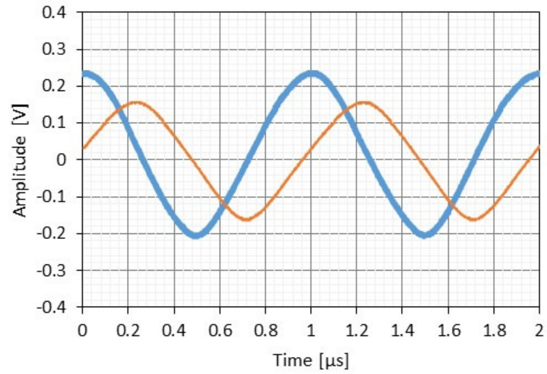

Fig. 3. Reference signal (blue thick line) and measurement signal (red thin line).

The two signals at 1 MHz are amplified and sampled by the microcontroller by two ADC working at 3.5 MSa/s. Fig. 3 shows an example of the two downconverted signals, acquired by a digital oscilloscope. Their phase shift $\Delta\varphi$ is a linear function of the absolute target distance *D*:

$$\frac{\Delta\varphi}{2\pi} = \frac{D \cdot f_m}{c \cdot n} + \varphi_0 \tag{1}$$

where *c* is the speed of light, *n* is air refraction index, and φ is the initial phase shift due to the different fiber lengths and electronics delays between the two paths (transmitter and receiver). When measuring $\Delta\varphi$ between 0 and 2π, we have to take into account the ambiguity in the result, due to the periodicity of the signal, therefore the distance results measured by:

$$D = \frac{1}{2} \cdot \left(\frac{\Delta\varphi}{2\pi} + i \right) \cdot \frac{c \cdot n}{f_m} + D_0 \tag{2}$$

where D_0 takes into account all the not-optical phase shifts, while *i* is the integer number of phase periods. The factor 2 at the denominator of eq. (2) is due to the outward and return path of the light. In the case of f_m = 2.1 GHz, the spatial periodicity is equal to about 7.14 cm.

Both the two synthesizers and the microcontroller are driven by the same clock at 10 MHz, in this way the frequency errors are strongly reduced, because all the realized frequency are correlated.

IV. SIGNAL ELABORATION

In order to measure $\Delta\varphi$, the two downconverted signals (reference and measurement channel) are sampled simultaneously: the STM32F303 microcontroller has two 12 bit ADC embedded, and they can be synchronized. The sampling frequency is set to 3.5 MHz, and the system acquires 1050 samples for both channels. The phase shift is measured by digitally calculating the Fourier coefficients at 1 MHz (phase and quadrature) for both signals. The number of samples is chosen in order to avoid bin leakage errors [8]: 1 MHz correspond exactly to the bin number 300 in the discrete Fourier transform. The microcontroller performs the sampling and the whole elaboration in less than 0.5 ms. In this first prototype, the output is fed to a PC through an USB connection, and the final measurement rate is about 1 kHz. A custom-made LabVIEW program allows to display and store the measurement results.

In order to overcome the problem of distance ambiguity (the number i in eq.(2) is generally unknown), the microcontroller starts the measurement process setting modulation frequencies shifted by 5 MHz: f_{m0} = 2.1 GHz+5 MHz. After this first measurement, the frequencies of both synthesizers are set back to the normal values. Through a vernier approach [2], it is possible to measure exactly i, because 5 MHz of frequency shift extends the not-ambiguity distance to about 30 m. The shifted-frequency measurement is made only at the system reset, in order to speed-up the measurement. After the reset, the absolute distance is estimated by imposing the continuity to the target movement. In the case of beam interruption, the operator needs to reset the instrument for retrieving the correct absolute distance.

V. MEASUREMENT RESULTS

The radiofrequency system was preliminary tested as shown in Fig. 4: the optical path was substituted by a direct electric connection.

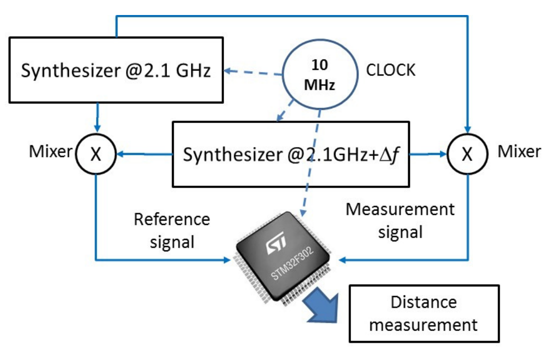

Fig. 4. Characterization scheme for the radiofrequency electronics.

In this way, we can estimate the measurement uncertainty contribution due to the radiofrequency system. Reported in equivalent-distance, the measured standard deviation is equal to about 2 µm. The second characterization setup is realized by a direct fiber connection between transmitter and receiver. The standard deviation in this case is close to 3 µm. The slight worsening is due to the insertion of the optical transceiver.

The final characterization was made with fiber collimators (Fig. 2) and corner cube as reflecting target, placed at different distances between a few centimeters to about 2 m. Fig. 5 shows the distance measurement made at about 2 m, not compensated by the ambiguity index $i = 27$. The short-time standard deviation is still very good, about 4 um, while the stability over some minutes is limited to a peak-to-peak variation lower than 40 um.

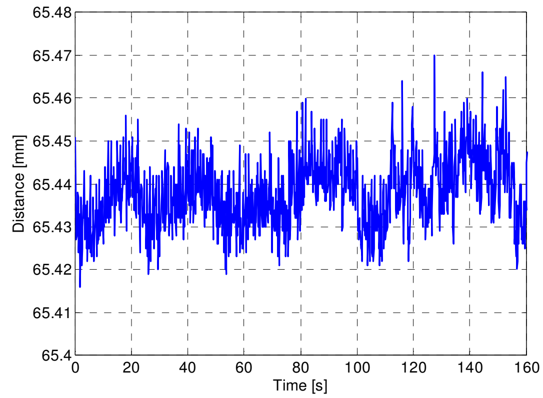

Fig. 5. Distance measurement at about 2 m. The reported measurement is not corrected by the distance ambiguity.

This stability performance is reached after about 5 minutes of warm up time, when the temperature of the laser transponder is stable: we noticed that a temperature change of about 10°C influences the absolute distance measurement of about 0.2 mm. Fig. 6 shows the measurement made at about 20 m, at the system start-up. This measurement drift can be ascribed to the system laser-photoreceiver, that slightly changes its frequency response with temperature, and therefore adds a different initial phase shift at the radiofrequency signal.

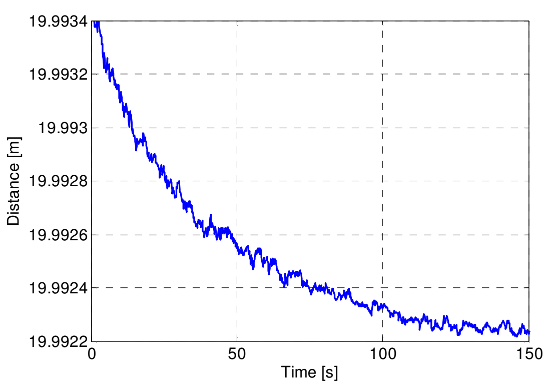

Fig. 6. Thermal transitory of the distance measurement at the system start-up.

Considering that the measurement rate is about 1 kHz, the obtained performances are adequate for a number of industrial monitoring applications.

VI. CONCLUSIONS

We have designed and preliminary tested a high-accuracy time of flight telemeter for demanding industrial applications. Using commercial telecommunication components, the instrument can keep low costs, while reaching very-high measurement performances. The system is now under complete measurement characterization. After temperature compensation of the air refractive index, the expected accuracy should be better than 100 µm for measured distance up to 30 m, at a measurement rate higher than 1 kHz. A possible industrial application is for the testing of steel tubes [9].

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