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Recent advances in dental optics – Part II: Experimental tests for a new intraoral scanner

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ABSTRACT

The object of this paper is testing the performance of a new device for 3D oral scanning: a two channel PTOF (pulsed time-of-flight) laser scanner, designed for dental and industrial applications in the measurement range of zero to a few centimetres. The application on short distances (0–10 cm) has entailed the improvement of performance parameters such as single shot precision, average precision and walk error up to mm-level and to μm-level respectively.

The single-shot precision (σ-value) has resulted to range from 43 to 63 ps (9–10 mm), having considered the measurement range (6.5–10 mm) corresponding to 1–2 V signal; this result agrees well with estimates made from simulations. The average precision has resulted to be dependent on the number of measurements and can reach a value equal to ± 25 μm, whenever the measurements frequency is sufficiently high. For example, if the required scanning speed is 1000 points/s and the required average precision is ± 25 μm, then a pulses frequency of 30–50 MHz is needed, considering signal amplitude varying between 1–2 V.

On the whole, the performance of this new device, based on PTOF has proven to be adequate to its employment in the field of restorative dentistry.

1. Introduction

Three-dimensional scanning of the mouth is required in a large number of procedures in dentistry such as restorative dentistry and orthodontics. The aim of the 3D mapping of the oral cavity is to create *digital impressions*. Restorative dentistry is of course the main field which requires the application of very accurate 3D intraoral scanners. In fact, the realization of any dental prosthesis requires building the three-dimensional mathematical model of dentition, performing a reverse engineering procedure; the prosthesis can be designed on this model and it can be realized by means of CAD/CAM systems [1].

This work is focused on a new intraoral PTOF laser scanner [2]; previous articles [3, 4] have reported an extensive review of existing techniques for reverse engineering; PTOF can represent an interesting alternative because these systems are capable of covering a large volume of the scene in a single image or few images and accuracy does not depend by target distance, unlike other sensors.

However the application of PTOF to dentistry implies a measurement range of zero to a few centimetres; therefore the device employed for industrial measurements needs to be redesigned in order to achieve improved single-shot precision and accuracy.

This work introduces this new system and describes its main components; the performances of this new system are first calculated on the basis of analytical formula, and then are experimentally tested on a prototype. The possible impact of this new device is finally discussed.

2. Materials and methods

This paragraph summarizes main steps followed for the design of the 3D PTOF laser scanner.

Abbreviations: APD, avalanche photodiode; *B*, bandwidth; CAD/CAM, computer aided design/computer aided manufacturing; CFD, constant fraction discriminator; $F(M)$, excess noise factor of APD; *G*, laser gain; GBW, gain-bandwidth product; λ, wavelength; LVPECL, low voltage positive emitter-coupled logic; LVTTL, low voltage transistor-transistor logic; *M*, multiplication factor of APD; NEP, noise equivalent power of APD; PD, photo-diode; PECL, positive emitter-coupled logic; PTOF, pulsed time of flight; *q*, charge of electron (1.6×10^{-19} C); $R(\lambda)$, spectral responsivity of APD; rms, root-mean-square; RX, receiver; S/N or SNR, signal-to-noise ratio; SR, slew rate; SSP, single shot precision; TDC, time-to-digital converter; TOF, time-of-flight; t_r, rise time (10–90% of full pulse amplitude); t_f, fall time (90–10% of full pulse amplitude); TX, transmitter; V_{n-amp}, noise of electronics (amplifiers); V_{out}, voltage of the pulse in the timing point; *Z*, gain of a transimpedance amplifier

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Table 1
Target performance parameters of the new PTOF system.

Performance parameters	
Minimum scanning speed	1000 pts/s
AP	±25 μm
Walk error	±25 μm
Measurement range	1–10 cm
Mean measurement distance	5 cm

2.1. Specifications

The required performance parameters (Table 1), which could make the new PTOF laser rangefinder suitable for dental applications, have been established on the basis of the performances exhibited by the other intraoral scanning devices [1,5] and on the basis of the requirements, in scientific literature.

2.2. Main components

The basic structure of the PTOF laser range finder is presented in Fig. 1 and the components are listed below:

1. Oscillator or signal generator (STANDFORD RESEARCH SYSTEM, model DG535);
2. noise generator (own designed circuit);
3. oscillator or signal generator (AVTECH AVPP-1-C);
4. laser driver or pulse generator circuit (own designed circuit);
5. START timing discriminator (own designed circuit);
6. pigtailed laser diode (Thorlabs LP660-SF40, 660 nm and Thorlabs LP405-SF10, 405 nm);
7. pigtailed aspheric collimator (Thorlabs CFS2-532-FC);
8. tube;
9. 50/50 glass beam splitter;
10. Visible Achromatic Doublet Pairs (Thorlabs MAP107575-A);
11. target;
12. Receiver Avalanche photodiode unit (Thorlabs APD110A2/M), which embeds a transimpedance preamplifier and a current feedback postamplifier;
13. STOP timing discriminator (Analog Devices EVAL-ADCMP 573 and own designed circuit);
14. TDC circuit with evaluation kit (ACAM ATMD-GPX Evkit);
15. IBM-compatible PC.

This is a two channel PTOF system with a single-axis optic.

2.3. Electronics

The aim of the jitter circuit (or noise generator circuit) is avoiding the synchronization of the oscillators of the transmitter and of the time measuring unit, by adding random noise to the oscillator of the transmitter. If the single-shot measurements are repeated n times and the oscillators, used in the transmitter and in the time measuring unit, are not synchronous (the single-shot measurements are independent of each other), the precision of the averaged result is improved by a factor equal to $\sqrt{n}$, compared to the single-shot precision.

Two laser diodes have been chosen to be tested in this work: Thorlabs LP405-SF10 and Thorlabs LP660-SF40. The laser driver circuit has been home-made. The circuit has been fed with the input signal generated by the oscillator.

The receiver channel is composed of the avalanche photodetector Thorlabs APD110A2/M which embeds a silicon APD and a ultra-low noise transimpedance preamplifier and a current feedback post-amplifier.

The main specifications of Thorlabs APD110A2/M are disclosed in Table 2.

The main performance parameters of an APD are the multiplication factor M and the excess noise factor F(M), and are defined by the following equations:

$$M=\frac{1}{1-\left(\frac{V}{V_{br}}\right)^{r}} \tag{1}$$

$$F(M)=k_r M+\left(2-\frac{1}{M}\right)(1-k_r) \tag{2}$$

where V is the bias voltage, V_{br} is the breakdown voltage, r is a coefficient depending on the material [6], and k_r is the ionization ratio, depending on the material [7].

The APD delivers an output voltage, which is a function of incident light power P_{opt}, detector responsivity $R(\lambda)$, multiplication factor M and transimpedance gain Z, given by

$$V_{out}=P_{opt}R(\lambda)MZ\ [\mathrm{V}] \tag{3}$$

The timing discriminator bears the following functions:

- it changes the analog pulses to logic level pulses, which are fed to the time measuring unit,
- it separates the timing pulses from the noise pulses.

The most important property of the timing discriminator is to keep the timing event at the same point independently from the amplitude of the incoming pulse.

The pulse shape in laser range finders usually remains stable and only the amplitude changes as a function of the distance and of the reflectivity of the target [2]. The pulse shape may change if

- the target surface is almost parallel to the measurement beam;
- the measurement beam hits two targets located at different distances at the same time; and
- the amplifier or the attenuator has a nonlinear behavior.

The performance of a timing discriminator can be expressed in terms of its walk error, drift and precision.

The most critical is usually the walk error, produced by changes of the averaged amplitude or of the shape of the incoming pulses. If the walk error is small enough and the dynamic range of the input pulse amplitude does not overcome the linear range of the amplifiers, an adjustable electrical or optical attenuator is not needed.

The STOP CFD is composed of the comparator Analog Devices ADCMP573, its evaluation board (Analog Devices EVAL-ADCMP 573), working as a timing comparator, and of a home-made noise comparator [8].

The time to digital converter circuit is ACAM AM-GPX with the evaluation kit ACAM ATMD-GPX. The ATMD-GPX evaluation system consists of a motherboard together with the AM-GPX plug-in module, mounted in a metal case. It is connected to the ATMD-PCI interface card (mounted in the PC) by a SCSI-type cable [9].

The TDC AM-GPX has four operating modes: I, G, R and M-mode. The laboratory tests have been performed using R-mode and sometimes M-mode when the desired minimum frequency per channel was 1 MHz and the best resolution was to be achieved. According to [10], the features of each mode are the following:

- R-mode
  - 2 channels with 27 ps resolution.
  - Differential LVPECL inputs, optional LVTTL.
  - Measurement range 0 μs up to 40 μs.
  - 5.5 ns pulse-pair resolution with 32-fold multi-hit capability = 182 MHz peak rate.