Laser depth measurement based on time-correlated single-photon counting

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A method for acquiring range data based on time-correlated single-photon counting is described. This method uses a short-pulse (≈10-ps) laser diode, a detector based on a silicon single-photon avalanche diode, and standard photon-counting timing electronics. The accuracy of the technique has been measured as ≈ ±30 μm in a laboratory experiment and corresponds closely to the results of a theoretical simulation.

Laser depth-measurement systems can be divided into two broad classes: triangulation and time-of-flight (TOF), which were reviewed extensively by Besl.[1] In the former case, a spot, stripe, or other laser pattern is projected onto a surface. The image of the pattern is detected by an imaging sensor from a different viewpoint, and simple geometric calculation leads to the determination of the (x, y, z) coordinates. Typical systems can provide submillimeter accuracy at standoff distances of the order of 0.5 m. On a smaller scale, optical heads can be placed on coordinate-measuring machines in place of a contact probe to provide local accuracy to at least 0.01 mm. However, triangulation systems require very accurate calibration and are subject to occlusion. They also have problems disambiguating true from spurious reflections.

In the TOF system a laser signal is projected toward a target and then reflected and received by a coaxial detector. The depth is proportional to the measured time delay between the target and a reference signal. Potentially, such systems are attractive because they can focus on narrow fields of view, are not subject to occlusion, and do not depend on complex geometric calibration.

TOF systems can be divided into pulsed, e.g., amplitude-modulated (AM), and frequency-modulated (FM) systems. In each case the critical limiting factor is the measurement of the go and the return paths of the laser beam, which is dependent on the time response of the transmit and receive devices and the associated electronics. In a pulsed system a range resolution of ±2 mm at ranges up to 30 m is typical (see, for example, Ref. 2). One other example of a pulsed system is the gated detector system used by McLean *et al.*[3] for constructing three-dimensional images in turbid water. In an AM system the phase change between a continuously modulated laser reference and the target signal is measured, resulting in a typical accuracy of ±1 mm or slightly better over a similar range.[4] In a typical FM system a laser diode's optical frequency is modulated, and again the range is proportional to the measured phase change between the reference and the target signals during a round trip.[5] This appears to give the most accurate results to date, although acquisition times can be long, for example, a resolution of ±0.1 mm with a time of 30 s for each point.[6]

In this Letter we present a new approach to laser distance measurement based on a short-pulse TOF technique and using time-correlated single-photon counting[7] (TCSPC). TCSPC is a statistical sampling technique with single-photon detection sensitivity and capable of picosecond timing resolution. It has been used to good advantage in time-resolved fluorescence and photoluminescence experiments in which optical decay-time constants of tens of picoseconds can be resolved,[8] as well as in optical time-domain reflectometry with optical fibers.[9] Here we present the results of a short experimental study to demonstrate the feasibility of applying the technique to precise surface measurement and show good agreement between the results of a simulation and actual distance measurements obtained from a simple planar, reflecting target at short range.

Optical ranging using the TCSPC technique relies on the ability to measure single-photon events with a timing accuracy of the order of the interrogating-pulse duration. One can improve this timing accuracy by repeating the measurement 10^4 to 10^6 times and then averaging to achieve the desired precision. The object under study (target) is irradiated by a high-repetition-rate pulsed laser source, and the scattered signal that arrives back at the detector is attenuated such that the probability of detecting one or more photons is ≤5% per pulse. Under these conditions, if the timing process is repeated over many laser pulses, the time distribu-

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tion of the single-photon events being recorded gives an accurate measurement of the distance to the scattering surface. This process is facilitated with timing pulses that are fed from the laser and detector to the start and stop inputs of a time–amplitude converter, which generates an analog output pulse with an amplitude proportional to the time difference between the start and stop inputs and can have a resolution of ≤ 5 ps. The signal is then digitized by an analog–digital converter and used to add a single count to the corresponding channel of a multichannel analyzer. After many laser pulses the analyzer data correspond to a plot of the backscattered optical signal versus time. In practice, the accuracy of an absolute measurement of the distance will be degraded by drift in the timing electronics; however, we can overcome this by introducing a second reflecting surface (reference) and making relative measurements of the distance between this and the target surface.

If the error on a single timing measurement is σ, then the error, $\overline{\sigma}$, on the mean of N such measurements, assuming random (uncorrelated) errors, will be given by

$$\overline{\sigma} = \sigma/\sqrt{N}\,. \tag{1}$$

Thus, we can improve the accuracy of the timing measurement by increasing the data-acquisition time and hence the number (N) of timing measurements made. As an example, if $\overline{\sigma} \approx 40$ ps and $N = 5 \times 10^5$ for each of the target and reference measurements, then $\overline{\sigma} \approx 80$ fs, which corresponds to a positional accuracy of $\approx 12\ \mu$m. With a currently achievable data-acquisition rate of $\approx$1 MHz, this could be achieved in $\sim$1 s.

A schematic of the experimental system is shown in Fig. 1. The laser source was a passively Q-switched laser diode[10] emitting $\approx$10-ps pulses of energy of $\approx$6 pJ at a wavelength of 850 nm. The detector was a silicon single-photon avalanche diode,[11] which together with standard photon-counting timing electronics gives an instrumental response width of $\approx$50 ps FWHM. The laser repetition rate was $\approx$1 MHz, and the detected photon rate was ≤ 50 kHz. Both the target and the reference were diffuse-scattering metal plates clamped to an optical table and separated from the detector–receiver head by distances of ≈ 0.5 and ≈ 1.5 m, respectively. The reference surface only partially overlapped the optical beam, permitting the rest of the light to continue to the target. Figure 2 shows an example of a plot obtained from the photon-counting system and represents the number of detected photons versus time. The two peaks correspond to light scattered from the reference and the target (as indicated) and are displaced by twice the transit time of light over the separation distance (x in Fig. 1). One important feature of this system is that the small-area single-photon avalanche detector has an active diameter of $\sim$7 μm.[11] This, in conjunction with the $f/1$ collimating lens, gives an angular field of view of only $\pm$0.5 mrad. Thus, light scattered from outside the target area and coming from secondary reflections is, in general, not detected.

To determine the accuracy of the system, we made a set of 20 measurements, each having the same fixed distance between the reference and the target and having the same total number of counts, N. We then calculated the displacement of the peaks by measuring the separation of the centroids of the autocorrelation function. The error on the measurement was determined from the standard deviation of the data about the mean. This process was repeated for various values of the total count N.

In addition, the experimental data were modeled by a Monte Carlo simulation, using a function of the form

$$f(t) = A + Bi(t) + Ci(t - \tau)\,, \tag{2}$$

where A is the background noise, τ is the peak separation, and B and C are the relative magnitudes of

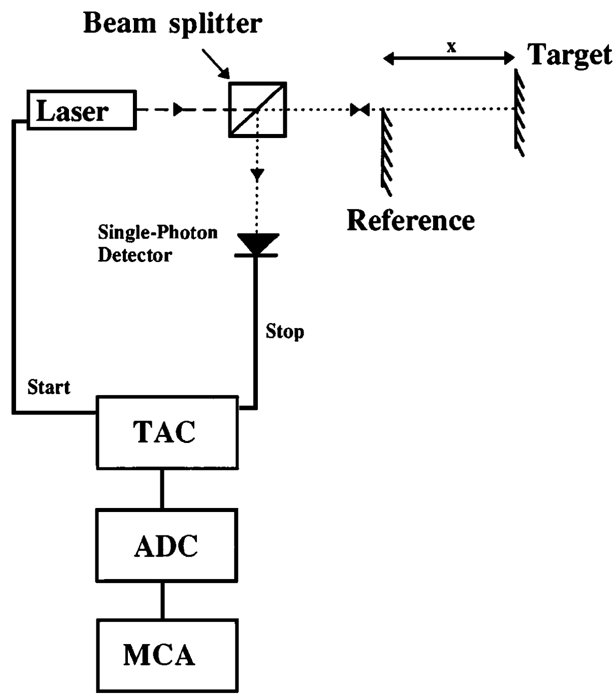

Fig. 1. Schematic diagram of the experimental system: TAC, time–amplitude converter; ADC, analog–digital converter; MCA, multichannel analyzer.

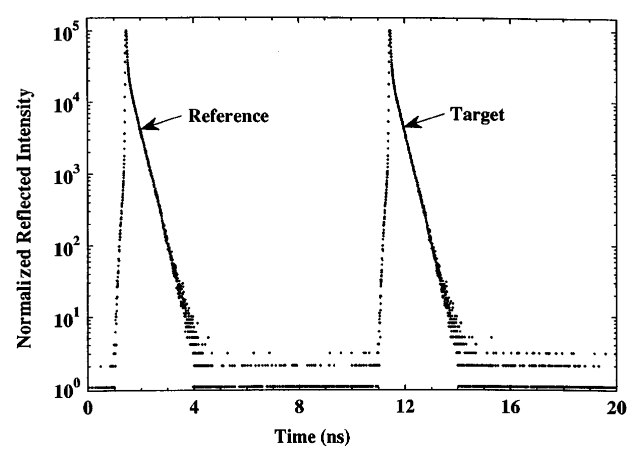

Fig. 2. Plot of received photons from the single-photon avalanche diode detector, showing light scattered from the target and the reference.

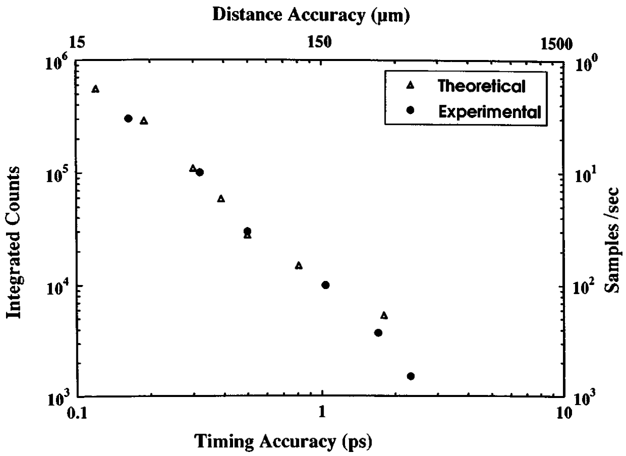

Fig. 3. Comparison of the simulated and the experimental results for depth resolution as a function of accumulated photon returns. The top axis gives the corresponding positional accuracy. The right axis gives the number of positional measurements that could be performed per second, assuming a modest upgrade of the photon-counting system to allow data acquisition at a rate of $\approx$1 MHz.

the target and the reference signals, respectively. The function $i(t)$ was the instrumental response of the system obtained experimentally when the laser source was scattered off a single metal surface. The standard deviation for the reference–target separation was determined from a set of 20 simulations, each run using different seed values for the random number generator. The same autocorrelation program used for the experimental analysis was used to fit the simulated data, and the process was repeated for various values of N. Figure 3 shows a plot of the experimental and theoretical results obtained and indicates a close correspondence between the predictions of the simulation and the results from the experiment. The gradient of the log–log plot gives a slope of ≈ -0.5, as expected from Eq. (1) for this type of measurement. It can be seen that for a total number of photon counts in the range 10^3 to 10^6 the timing accuracy lies in the range 0.2 to 10 ps. This permits measurements with a precision down to ≈ 30 μm. Positional accuracy can be traded off against total acquisition time. Thus, assuming a data-acquisition rate of $\approx$1 MHz, positional measurements with a precision of, say, 150 μm could be made at a rate of $\approx$100 per second. The high accuracy and rapid acquisition times mean that this technique is applicable to several engineering tasks, such as the accurate profiling of surfaces for reverse modeling of precise machine parts. The high sensitivity of the technique has the potential for long working distances, which means that it could be used, for example, to aid in the assessment of the structural integrity of large aerospace components (i.e., $>$10 m).

In conclusion, we have demonstrated both experimentally and by simulation the use of a time-of-flight ranging system, based on TCSPC, for the measurement of distances to an accuracy of ≈ 30 μm. The system uses semiconductor source and detection systems and has single-photon detection sensitivity, which makes it particularly suited for studying weakly reflecting or distant surfaces.

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