Covert Scanning of Low Signature Targets Using High Speed Photon-Counting

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Abstract

This paper describes the design of a scanning time-of-flight system which uses the time-correlated single photon-counting technique to produce three-dimensional depth images of scenes using low light levels. The depth information combined with efficient use of processing algorithms permits accurate location and analysis of low contrast objects at distances up to several kilometres. The data for the scene is acquired using a scanning optical system and a single optimised detector. Frame acquisition times of 1 second are targeted.

Keywords: Laser radar, Single-photon counting, Three-dimensional scanning, Avalanche photodiodes

Introduction

The technique of time-correlated single-photon counting has been used since the 1960's, mainly for the measurement of fast, low-level light signals in, for example, time-resolved fluorescence measurements. The technique measures the time difference (or "micro-time") between an optical input pulse (typically a repetitive laser signal) and a photon event recorded by a single-photon detector. Over many laser pulses, a histogram of the number of photon counts versus micro-time can result in a statistically accurate representation of the actual optical transient signal being measured [1]. This project aims to deliver a lightweight, practical unit using a pulsed diode laser source and semiconductor-based single-photon counting detection which will measure depth images using the time-of-flight approach, to permit accurate location of targets in 3-D. The time-gating and high sensitivity of the time-correlated single-photon counting (TCSPC) approach offers the potential for low light level and eye-safe operation.

System Overview

This project addresses the issue of target scanning – building up a 3-dimensional image of depth with the objective of frame acquisition times of less than 1 second. An optical system is used in which the object plane is scanned continuously, using an inexpensive galvo-mirror assembly, onto a single fibre-coupled high-performance single-photon counting detector. This is in contrast to imaging onto an arrayed detector [2], where parallel readout-out remains a major technological obstacle. In addition, the single-photon counting arrays that are currently available suffer significantly from the deleterious effects of crosstalk between pixels, performance non-uniformity and a general use of non-optimised single-photon detectors. This project is focussing on creating a time-of-flight system based on scanning of the scattered light to a single, optimised single-photon counting detector. Such an approach permits the use of a single high-speed data acquisition module, and the modular construction easily facilitates the use of alternative optimised single-photon detectors, as and when they become available during the project.

The prototype uses state-of-the-art commercially available components and a schematic diagram of the scanning system is shown in Figure 1.

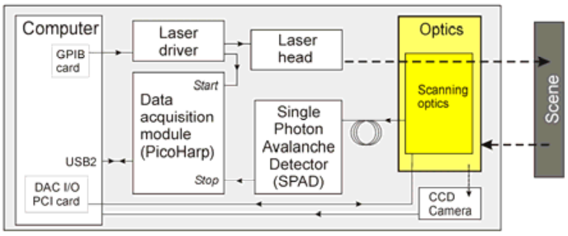

Figure 1: *Schematic diagram showing the key components of the system for the covert scanning of low signature targets using high-speed photon-counting.*

The key elements are:

- Computer: This will run custom software developed in this project. The software will control the scanning of the field and the data acquisition process. It will process the acquired data and enable the user to configure relevant system parameters. It will communicate with the scanning mirrors drive electronics via a digital I/O card and with the photon return data acquisition module via a high-speed USB port.
- Laser head and laser driver: the collimated output of an 850 nm wavelength edge emitting picosecond pulsed laser diode is used to illuminate the scene. The laser and the driver generate low output power pulses, of ≤ 50 µW, at repetition rates varying from 5 to 80 MHz. These are commercially available components available from several vendors.
- Single-photon avalanche detector (SPAD): For the initial work this will be a commercially available, fibre-coupled module from Perkin-Elmer which has a jitter of approximately 400 ps. However, the group will prototype fibre-pigtailed shallow-junction Si SPADs with jitter of <100 ps, as the manufacturers and research collaborators make these available to the project.
- Data acquisition module: The recently-developed PicoHarp unit from PicoQuant is connected to the output from the SPAD. This facilitates high photon-counting acquisition rates with minimal deadtime (<95 ns) after photon events.
- Optics: The optics enable a scene at a range of approximately 1 km to be scanned with the laser output and image the return photons onto a multimode fibre core. The scanning is achieved by using a pair of galvanometer mirrors operated in a closed loop configuration, under computer control.

Optical Design of System

The system uses a single camera-type lens to direct the outgoing laser to the target and to efficiently collect scattered photons returned from the target. Both the outgoing laser beam and the return photons are scanned using the galvo mirror approach – meaning that a single optimised photon-counting detector can be used. Polarisation optics is used to discriminate the outgoing target, and returning signal, beams. A general layout diagram of the optical system is shown in Figure 2.

A commercially available SLR camera lens acts as the system objective and forms an image of the scene. A 35 mm film SLR camera lens, when attached to a camera and focussed on an object, creates a focussed image in the plane of the photographic film. SLR camera lenses are designed to create a flat, well corrected, 42 mm diameter image circle in this plane regardless of the focal length lens used. It is this stationary image, or the required part of it, that is relayed “pixel” by “pixel” onto the fibre core (which is connected to the SPAD) via the imaging optics and computer controlled galvo mirrors. The scanning mirrors, SM1 and SM2, are placed at conjugate planes of the system. If this separated mirror

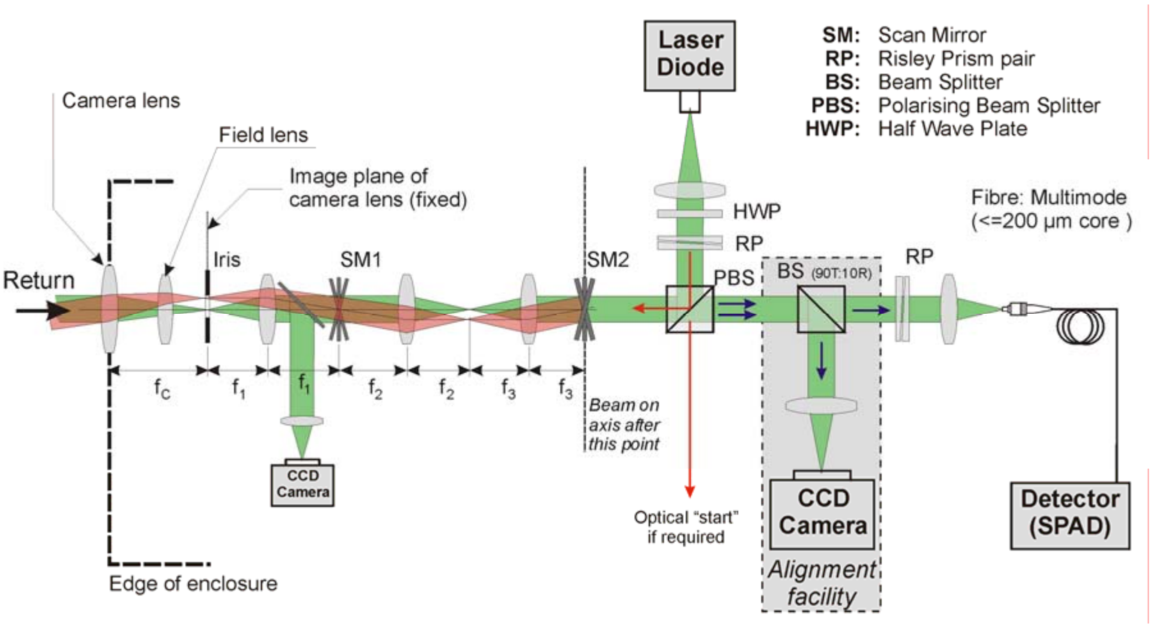

Figure 2: *This schematic shows the optical design of the system.*

scheme is configured correctly, the layout ensures that the beam does not move, or "walk", on the galvo mirrors as the image and laser the beam are scanned. Hence the beam remains almost stationary on the mirrors as they scan the image and there is not a problem with the beam walking on the second mirror as is the case with a closely coupled mirror pair configuration. It also means that the mirrors used can be identical in size.

Field-of-view and Spatial Resolution

It is proposed that the maximum diagonal angle field of view of the system will be approximately 5º. At a distance of 1 km, this equates to a field in object space with a diameter of approximately 80 m. In this sensor, the field-of-view of the *scanned* image is largely determined by the field-of-view of the image presented to the internal system optics by the objective lens. The optomechanical system used for the sensor limits the maximum available clear aperture diameter of the internal optics to 25 mm. This means that an objective lens with a focal length of between 200 to 400 mm is required in order to obtain the desired field-of-view.

The scanning mirrors are computer controlled and therefore the user will be able to set the boundaries of the scanned image, thus directly determining the field-of-view. In order to scan the entire 25 mm diameter image at the fibre plane, the galvanometers are required to move the beam through an angular range of approximately ±10º (depending on the lenses used) which corresponds to a mechanical mirror movement of ±5º. The step angular resolution of the galvanometer positioning is 2^{11} bits for ±20º mirror movement. This equates to a minimum angular step of 0.3 mrad or 0.019º. This means that, theoretically, the galvanometer could move approximately 500 steps in the 25 mm diameter image. Using a 400 mm focal length lens and a target at 1 km, this corresponds to a 250 mm spacing at the target plane when projected to the object (or fibre) plane. The actual spatial resolution achieved will depend on a number of factors including the focal lengths of the lenses, the aberrations of the optics and in particular the size of the fibre core coupled to the detector. An approximation of the spatial resolution can be calculated using the ratio of the fibre core radius to the focal length of the objective. In the initial stages of the project, thick-junction Si-SPADs will be used, and these large-area detectors will allow efficient coupling of light using fibres of up to 200 µm diameter. If we use a fibre diameter of 100 µm, this corresponds to an half-angle of tan^{-1}(50 µm / 400 mm) being subtended by the fibre which equates to a spatial resolution of 250 mm at 1 km range. This corresponds to the minimum step resolution determined by the galvos. We have also constructed a simple model to get a feel for the depth accuracy, based on a number of assumptions, and it shows that a similar depth resolution of 250 mm is achievable when using an objective lens with a collection aperture of 70 mm.

Optomechanics

The sensor consists of a custom-built optomechanical assembly which uses the slotted baseplate approach depicted in Figure 3. An appropriate network of slots of a fixed width is machined in a plate of suitable material. The optical components, or devices, are mounted in cylindrical steel barrels and placed in the slot as shown. The recent baseplates designed, manufactured and used in recent years at Heriot-Watt University have been standardised to the dimensions indicated in the figure. This places the optical axis of the system at 14 mm above the surface of the plate. The components are held in place using either a magnet or clamp. A barrel placed in the slot has four of the six degrees of freedom constrained. This semi-kinematic mount allows accurate adjustment of the two remaining degrees of freedom: (a) the translation of the component along the optic axis of the slot (focus) and (b) the rotation of the component about the axis (roll). Steel plates with magnets offer greater flexibility for prototyping of circuits when the exact positions of components have not been finalised.

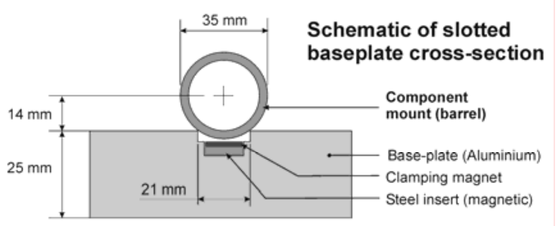

Figure 3: *This diagram shows a cross section of a slotted baseplate and a component mount.*

Sensor Baseplate Design

For this system, we are using an aluminium baseplate with embedded magnetic steel inserts in the base of the slots. This provides us with a lightweight baseplate whilst still allowing flexible magnet, and therefore component, positioning. As mentioned earlier, the baseplate components for this sensor are housed in 35 mm diameter magnetic steel cells which sit in a 21 mm wide machined slot thus placing the optic axis at 14 mm above the baseplate surface. The component cells, or barrels, are held in place on the slot with Neodymium Iron Boron (NdFeB) magnets of grade N38 or greater. An adaptor plate allows for easy interchanging of the objective lens.

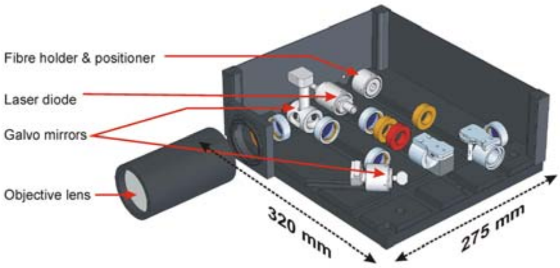

Figure 4: *This a CAD image, from SolidEdge, of the slotted baseplate assembly for the sensor showing the layout of the components.*

The entire assembly has been modelled using a 3D CAD program, SolidEdge, and the post processing carried out using EdgeCAM. A CAD image of the optomechanical assembly is shown in Figure 4 - the plate footprint is approximately 275 x 320 mm.

Data Analysis Algorithms

We have surveyed and compared a number of existing deterministic and stochastic methods to perform peak detection on image data from time-correlated single photon counting systems. These include matched filter and reversible jump Markov chain Monte Carlo (RJMCMC) algorithms [3] specifically aimed at processing the photon count data from the scanning sensor being developed under this project.

Matched filtering is carried out in an efficient way using the Fast Fourier Transform (FFT) algorithm implemented in the frequency domain as this is faster than a typical correlation algorithm [4]. As opposed to RJMCMC algorithms, this approach only gives estimates of the plausible position of the returns. No information at all is given on the uncertainty of these estimates and this approach is likely to fail for small signal-to-noise ratios. Hybrid software/hardware FFTs algorithms can be designed to improve the estimates and to assess uncertainty. Hardware approaches will include the development of specialised digital signal processors (DSPs) to perform certain mathematical operations. Software approaches include hybrid FFT/MCMC algorithms in which the initial values for the MCMC algorithm are given by the FFT algorithm. This will reduce a-priori the number of iterations needed in the MCMC algorithm.

In this paper, we do not deal with the possible hardware solutions to this problem but we focus on the software development. To that end, we have analysed and combined some of these algorithms to optimise the trade-off between speed and accuracy. As the goal of this work is to achieve sub-second processing per image, the choice of the "optimum" algorithm depends on a trade-off between complexity (accuracy) and execution time.

Initial results on synthetic data show that the simplest algorithm that meets the particular time constraints of this project is matched filtering using FFTs. The accuracy of depth measurement on synthetic data (and real data from other sensors) is satisfactory, provided the return can be detected by a suitable threshold, and the execution time for an image of 32 x 32 elements is about 2 seconds according to the different timing and profiling results. This is greater than, but comparable to, the specification of 1 second. The problem of this "excessive" execution time can be handled in one of three different ways. First, for two signals of length N, the complexity of the FFT matched filtering algorithm is of the order of $3N\log_2 N$, thus reducing the length of the signals (currently 4096 time samples), is certainly feasible. Given a-priori knowledge of the position of signal return, this would reduce the processing time with no loss of depth resolution. Second, we could use a computer or other processor designed for digital signal processing (DSP). Third, instead of using the modified version of the FFT algorithm described by [5], we could use other commercial FFT libraries such as the Intel Math Kernel Library (MKL) 9.0 which is composed of highly optimized mathematical functions for math, engineering, scientific and financial applications requiring high performance on Intel platforms. Yet another option is the FFTW (the acronym FFTW comes from "Fastest Fourier Transform in the West") developed by Frigo and Johnson [6] at the MIT Laboratory for Computer Science which suggests significant improvements are possible, even on general purpose machines. A particularly strong feature of the FFTW is the ability to run tests on a particular sized array on a particular processor. These tests determine the fastest method to compute the transform, and this knowledge can be stored in a file or string for later use. Given a large number of transforms to be computed, all of the same size, this method yields a worthwhile gain in speed compared to the default case when FFTW uses a heuristically chosen algorithm. FFTW is licensed under the GNU General Public License. It is also licensed commercially by MIT and is used in the Matlab functions which compute FFTs.

We conclude with the following considerations:

- The FFT matched filter is the only one that will process a 32 x 32 at ~1 frame per second given pure software and the current PC specification.
- If more accuracy is needed, multiple peaks are considered or assessment on the uncertainty of the data is required, RJMCMC algorithms are preferred. However, they are considerably more complex.
- To reduce the execution time, significant hybrid software/hardware design is required.
- The execution time might be reduced if we developed real-time versions of (RJ)MCMC algorithms using parallel and embedded software. To date, there are very few approaches to parallelising them.

Conclusion

This paper describes a scanning time-of-flight system which utilises the time-correlated single-photon counting technique, in conjunction with data analysis algorithms, to produce three-dimensional depth images of scenes using very low light levels. The use of an optical scanning system with a single, optimised single-photon detector has a number of significant advantages over imaging onto detector arrays that are currently available. The optical design of the sensor is consistent with a 25 cm xy spatial resolution, and a similar depth resolution, at a target range of 1 km. The slotted baseplate optomechanical approach that is being used provides a robust yet flexible platform for assessing, testing and fine tuning the sensor performance. A number of peak detection algorithms and approaches have been evaluated with the goal of achieving sub-second processing of the acquired data. The choice of the "optimum" algorithm depends on a trade-off between complexity (accuracy) and execution time.

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