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Sub-pixel micro scanning for improved spatial resolution using single-photon LiDAR

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Sub-pixel micro-scanning for improved spatial resolution using single-photon LiDAR

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ABSTRACT

We present a method of improving the spatial resolution of a single-photon counting light detection and ranging system using a sub-pixel micro-scanning approach. The time-correlated single-photon counting technique was used to measure photon time-of-flight from remote objects. The high-sensitivity and picosecond timing resolution of this approach allows for high-resolution depth and intensity information to be obtained from targets with very low average optical power levels. The system comprised a picosecond pulsed laser source operated at a wavelength of 1550 nm and a 32 × 32 InGaAs/InP single-photon avalanche diode detector array. The detector array was translated along two orthogonal axes in the image plane of the receive channel objective lens using two computer-controlled motorized translation stages. This allowed for sub-pixel scanning, resulting in a composite image of the scene with improved spatial resolution.

This paper presents preliminary measurements of depth and intensity profiles taken at stand-off distances of approximately 2.5 meters in laboratory conditions using average optical power levels in the micro-watt regime. A standard test chart was used to evaluate the resolving power of the system for both standard and micro-scanned images to assess performance improvements in spatial resolution. Depth profiles of targets were also obtained to investigate improvements in resolving small details and the quality of target edges.

Keywords: LiDAR, TCSPC, micro-scanning, single-photon, low-light

1. INTRODUCTION

In recent years, the time-correlated single-photon counting (TCSPC) technique has become a prominent candidate technology for light detection and ranging (LiDAR) systems, due to its high level of sensitivity and excellent surface-to-surface resolution. This technique has been demonstrated in a variety of challenging applications such as long-range imaging, non-line-of-sight imaging, through cluttered environments, imaging through high levels of scattering, and underwater imaging. This technique relies on a time-of-flight (ToF) approach where the photon ToF is measured as the time difference between a synchronized start signal from a pulsed laser source and a stop signal from a single-photon detector. This ToF information can then be used to determine the target range with respect to the location of the system and high-resolution depth and intensity profiles of remote targets can be obtained.

Currently, InGaAs/InP single-photon avalanche diode (SPAD) detectors are the most promising candidate for practical and efficient time-correlated single-photon counting at short-wave infrared (SWIR) wavelengths. These detectors are commercially available in both single-pixel formats and as larger format arrays and offer relatively low dark count rates and picosecond timing jitters. SWIR SPAD detector arrays can offer several benefits over their single-pixel counterparts, with the most significant being that their use reduces the need for relatively slow point-and-stare scanning methods. However, current generations of InGaAs/InP SPAD detector arrays tend to have large pixel sizes in array format – typically being 50-100 μm – limiting their spatial resolution when compared to, for example, complementary metal oxide semiconductor (CMOS) SPAD arrays which are used typically in the near-infrared and visible regions. The spatial resolution of a SWIR SPAD detector array can also be improved by creating physically larger format arrays, however, these are not currently available.

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Micro-scanning offers a relatively simple way of increasing the effective spatial resolution of a SPAD array. The micro-scanning technique involves combining multiple images, taken at different pre-determined positions relative to the scene, into a single larger format image with improved resolution. This is a straightforward way of improving the resolution of the final image for a detector array of limited pixel format and large pixel size, albeit at the expense of longer acquisition time.

Micro-scanning has been applied in several applications including: lensless digital holography, imaging from unmanned aerial vehicles (UAVs), and integral Fourier holography. There is also interest in developing faster and more efficient algorithms for the purpose of combining low-resolution images into a single higher resolution image. More recently, sub-pixel scanning at long-ranges using the TCSPC technique has been successfully demonstrated by Li et al., using a single-pixel InGaAs/InP SPAD LIDAR transceiver using a scanning configuration.

In this work we demonstrate preliminary micro-scanned measurements of depth and intensity profiles of targets at a 2.5 meter range obtained with a 32 × 32 InGaAs/InP SPAD detector array.

2. SYSTEM DESCRIPTION

A bi-static single-photon LiDAR system using the TCSPC technique was used to obtain depth and intensity images of two targets. Apart from the micro-scanning capability, the transceiver was broadly similar to the system described by Tachella et al. The sensor used was a 32 × 32 InGaAs/InP SPAD array which was mounted onto two linear translation stages which provided sub-pixel movements in the x- and y-axes. Illumination was provided by a λ = 1550 nm pulsed fiber laser source with a pulse duration of 400 ps and a repetition rate of 150 Hz. The illumination beam was used to flood-illuminate the target area. At the illumination wavelength of 1550 nm, the single-photon detection efficiency (SPDE) of the SPAD array was approximately 25%. Measurements were obtained using a timing bin width of 250 ps, corresponding to a depth increment of 3.75 cm. The focal place array of the sensor has dimensions of 3.2 × 3.2 mm, giving a pixel pitch of 100 μm. Figure 1 shows a schematic diagram of the experimental setup.

![Schematic diagram of the bi-static micro-scanning system](image-url)

Figure 1. Schematic diagram of the bi-static micro-scanning system. The system comprised a Princeton Lightwave Kestrel 32 × 32 InGaAs/InP SPAD array, a λ = 1550 nm fiber-coupled pulsed illumination source, and two Newport motorized linear translation stages for micro-scanning in the x- and y-axes. Optical components include receive channel objective lens (L3); transmit channel lenses (L1, L2); a longpass filter (LP1); bandpass filters (BP1, BP2); a reflective collimation package (RC1); and an ND filter (ND).

Pulsed laser emission from the source is routed to a collimator via a single-mode optical fiber. A 12 nm full-width half-maximum (FWHM) bandpass filter (BP1) with a central wavelength of 1550 nm eliminates any potential out-of-band light and amplified spontaneous emission (ASE) produced by the laser source. The beam then passes through a manually
adjustable telescope arrangement formed by lenses L1 and L2, allowing the divergence of the beam to be altered to ensure consistent flood-illumination at different target distances. Return photons are collected by the receive channel objective lens, L3, and then pass through both a 10 nm FWHM bandpass filter with a central wavelength of 1550 nm (BP2) and a longpass filter with a cut-on wavelength of 1550 nm to reduce ambient background counts. To avoid saturation of the sensitive SPAD array, ND filters were used in the illumination channel to decrease the average optical power level. In this configuration, the detector was not fixed to the objective lens, allowing the translation stages to move the detector freely in the x- and y-directions of the image plane. The illumination channel was mounted on a small rotation stage to allow the beam to be moved across the scene for alignment at different stand-off distances.

Initial experiments were performed in laboratory conditions, with targets placed approximately 2.5 meters from the transceiver location. The system had a field of view of approximately 15.7 × 15.7 cm at this distance. Two targets were chosen to investigate the spatial resolution of the system for both depth and intensity profiles. The first was a standard 1951 U.S. Air Force resolution test chart with dimensions of 7.6 × 7.5 cm and the second was a black and white cow toy with dimensions of approximately 10 × 12 × 6 cm. Photographs of these targets are shown in Figure 2. The USAF resolution test chart was chosen to allow a comparison of the resolving power of the system for a single 32 × 32 image and the improved resolution image obtained via micro-scanning. The cow toy was chosen to investigate how improved spatial resolution affects the depth profile.

![Targets](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Figure 2. Targets used in these measurements. (a) a 1951 USAF resolution test chart measuring 7.6 × 7.6 cm. (b) a black and white cow toy measuring approximately 10 × 12 × 6 cm. These targets were placed approximately 2.5 m from the system.

### 3. IMAGE RECONSTRUCTION ALGORITHM

A significant challenge in micro-scanning is determining the best method of combing the collective images of the scene. For these measurements, as the movements made by the translation stages are significantly smaller (20 μm increments), than the dimensions of each pixel (100 μm), it was decided that the simplest approach would be to place each pixel into the final image according to its relative view of the scene. Figure 3 illustrates the approach used.
As acquired image 2 (represented in yellow) observes a slightly different view of the scene compared to acquired image 1 (represented in red), then the component pixels of image 2 must be distributed according to the movement of the detector, i.e., the yellow pixels see a scene slightly to the right of the red pixels. Therefore, in the final composite image, the yellow pixels are placed to the right of the red pixels and this is repeated until the full 100 µm pixel pitch has been traversed and measurements for each 20 µm increment have been performed. The improvement in resolution achieved through micro-scanning is simply the dimensions of a single, low-resolution image, multiplied by the number of component images taken along each axis.

4. RESULTS

4.1 1951 USAF Resolution Test Chart

The 1951 USAF resolution test chart is a widely accepted standard for measuring the resolving capabilities of an optical system, and so is a useful target for determining the spatial resolution of the system. The USAF resolution test chart was imaged with a micro-scanned format of 5 × 5 measurements (i.e., 160 × 160 pixels in the resultant composite image), each with a 20 µm movement, using an average optical power level of 5 µW at a stand-off distance of ~2.5 meter.

Figure 4 shows intensity profiles of the resolution test chart reconstructed using a simple pixel-wise cross-correlation algorithm with a known system response for (a) single 32 × 32 pixel scans and (b) 160 × 160 pixel scans obtained with micro-scanning. The 32 × 32 pixel single scan was obtained using a 1 second acquisition time. In order to compare this 32 × 32 image with the micro-scanned image at similar photon return levels, the 160 × 160 composite image was obtained with a 0.04 second per image acquisition time, also resulting in a total acquisition time of 1 second for the composite image.
Figure 4. Intensity profiles of the USAF resolution test chart. The results show (a) a single intensity profile of the test chart, with total photon count of $2.19 \times 10^6$. (b) Composite intensity profile of the test chart taken with a $5 \times 5$ micro-scanned format with a total photon count of $2.24 \times 10^6$.

The results in Figure 4 show that, with a similar number of total photons in the measurement, an improved resolution image can be obtained. In Figure 4 (a) none of the elements of the chart could be resolved, however, in Figure 4(b) group -1 element 1 (G-1, E1) was successfully resolved. This gives the system an improved resolving power of approximately 0.5 lp/mm (line pairs per mm) when the micro-scanning technique is used.

In order to investigate the performance of the micro-scanning system at lower acquisition times, measurements taken at total acquisition times of 0.1, 0.01, 0.001, and 0.0001 seconds were obtained. The intensity profiles for both the single
32 × 32 pixel scans and the 160 × 160 pixel scans obtained in these measurements are shown in Figure 5 alongside the average photons per pixel (PPP).

![Image of intensity profiles of the USAF resolution test chart at different acquisition times for a single image (top row) and composite images (middle and bottom rows). Shown also is the average number of photons per pixel (PPP), spatial resolution achieved at the target plane, and the aggregate photon count for each image.](https://www.spiedigitallibrary.org/conference-proceedings-of-spie/1172106)

Reducing the per image acquisition times, as shown in Figure 5, can still provide an improved result over a single 32 × 32 image (shown in Figure 5(a)). To enable a fair comparison between single and composite images, Figure 5 shows composite images with similar levels of PPP (middle row) as well as composite images obtained using an acquisition time \( \frac{1}{25} \) of that used for a single image (bottom row). This was done as a composite image is made up of 25 single images. Although a resolution can be determined from lower acquisition times, the general image quality becomes progressively less clear as...
the average photon per pixel value is reduced. For example, it becomes more difficult to read the numbers labelling the elements.

4.2 Black and White Cow Toy

The cow toy was imaged at a standoff distance of 2.5 meter to ensure that the toy filled the field-of-view of the camera. As the toy had some curvature to it, it was chosen to demonstrate the improvement in spatial resolution in the depth profile. A single $32 \times 32$ pixel scan and a $160 \times 160$ pixel micro-scan were performed using an average optical power level of $1.7 \, \mu W$.

The reconstructed depth and intensity profiles of the target are shown in Figure 6. The single $32 \times 32$ pixel scan was obtained using a 1 s acquisition time and has a total photon count of $2.77 \times 10^6$ over the whole intensity profile and the composite $160 \times 160$ pixel micro-scanned images were obtained using an acquisition time of 0.04 per image (a total acquisition time of 1 second) and has a total photon count of $2.81 \times 10^6$. Both the depth and intensity images show a reduction of aliasing around the head of the toy, providing a smoother more detailed profile of the target. However, the shadow of the toy results in spurious depth estimates. This shadowing can be attributed to the transceiver’s bistatic configuration leading to large angle of the illumination channel with respect to the receive channel at these short target distances. In addition, the sections of the target that are black in color give poor depth estimates. However, as mentioned previously these results were obtained with a computationally simple pixel-wise algorithm and the use of a more advanced algorithm which exploits spatial correlation in single-photon data would result in significantly improved results$^{10,23}$. 


5. CONCLUSIONS

In this paper we have shown preliminary results of measurements taken at stand-off distances of approximately 2.5 m in laboratory conditions obtained with a TCSPC based LiDAR system using a 32 x 32 pixel InGaAs/InP SPAD detector array and a micro-scanning technique approach. The reconstructed depth and intensity profiles obtained using micro-scanning show much improved resolution over the original static images with an approximately five-fold improvement in spatial resolution. Future work in this area will consist implementing the micro-scanning technique in long-range measurements (100s – 1000s meters) in challenging outdoor conditions and through high levels of atmospheric obscurants, optimization of micro-scanning format to evaluate the fewest number of required scanned pixels, and the development and implantation of advanced algorithms allowing continuous, video-rate imaging.
REFERENCES