Single-Photon LiDAR Lab-bench Construction

Project Documentation

1 Introduction and Motivation

One of the primary challenges in LiDAR research and development is the notable scarcity of comprehensive raw datasets. The limited availability of such datasets hinders algorithm development, system optimization, and accurate evaluation of LiDAR performance. Existing substitutes, such as mathematical modeling and synthetic simulators, fall short in accurately replicating real-world scenarios, further highlighting the need for authentic LiDAR raw datasets.

To address this gap, this project establishes a dedicated optical setup that emulates the precise functioning of LiDAR technology and faithfully captures the intricate details of target objects and environments. This setup enables the construction of a comprehensive repository of diverse and realistic LiDAR raw datasets. Unlike purely synthetic methods, our optical system provides data that reflect the physical phenomena, hardware artifacts, and noise characteristics encountered in practical applications.

The availability of such datasets is critical for a range of tasks:

- Noise characterization and analysis of photon-limited signals.
- Evaluation of compression and data-processing methods.
- Depth estimation and reflectivity reconstruction.
- Training and validation of machine learning algorithms for LiDAR-based applications.
- Assessment and validation of algorithm performance under real-world conditions.

By generating authentic datasets, the project not only addresses the shortage of LiDAR data but also enables the research community to deploy algorithms in real-world applications with increased confidence in their robustness and accuracy.

2 System Architecture and Components

The LiDAR system is built upon Time-Correlated Single-Photon Counting (TCSPC) principles. High-resolution depth mapping is achieved by synchronizing a pulsed laser with a sensitive single-photon detector and precision scanning optics. The overall system arrangement is illustrated in Figures 1 and 2.

The main hardware components required for the lab-bench setup are summarized in Table 1. This combination ensures flexibility in data acquisition and supports the generation of comprehensive LiDAR datasets with varying signal-to-noise ratios.

3 Optical and Electrical Setup

3.1 Optical Path and Beam Scanning

The laser emits short optical pulses at a fixed repetition rate, directed toward the scene through free-space optics. A galvanometric mirror (Thorlabs GVS012) enables two-dimensional beam scanning. Backscattered photons are collected and focused onto the SPAD detector.

Figure 1: Arrangement of the physical SP-LiDAR lab-bench setup.

Table 1: System Component Cost Breakdown

Item	**Manufacturer**	**Price (USD)**
TCSPC PicoHarp 300 Module	PicoQuant	$20,000.00
PDM SPAD Module	Micro Photon Devices	$5,500.00
Laser PILAS 510nm (0-40 MHz)	NKT Photonics	$13,000.00
Scanning Module GVS012	Thorlabs	$3,500.00
Power Supply Unit GPS011-US	Thorlabs	$600.00
USB 6003 DAQ	National Instruments	$800.00
Additional Connectors and Equipment	Thorlabs	$1,500.00
Total System Cost		**$45,000.00**

3.2 Electrical Synchronization

Precise timing is critical for TCSPC-based LiDAR. Synchronization is implemented as follows:

- The laser sync output connects to the `SYNC` input of the PicoHarp 300.
- The SPAD output connects to the `STOP` input of the PicoHarp 300.
- The PicoHarp measures the time difference between laser pulses and detected photon arrivals.

The galvanometric mirror is driven by analog signals from the NI-DAQ USB-6003, synchronized with the TCSPC acquisition so that each photon is associated with a spatial position.

3.3 System Control and Programming

The system is controlled using vendor-provided drivers along with a custom MATLAB program. The NI-DAQ generates raster-scan waveforms to drive the galvanometric mirrors. Scan patterns can be customized according to the desired spatial resolution, scanning speed, or specific regions of interest, allowing flexible control over the acquisition process.

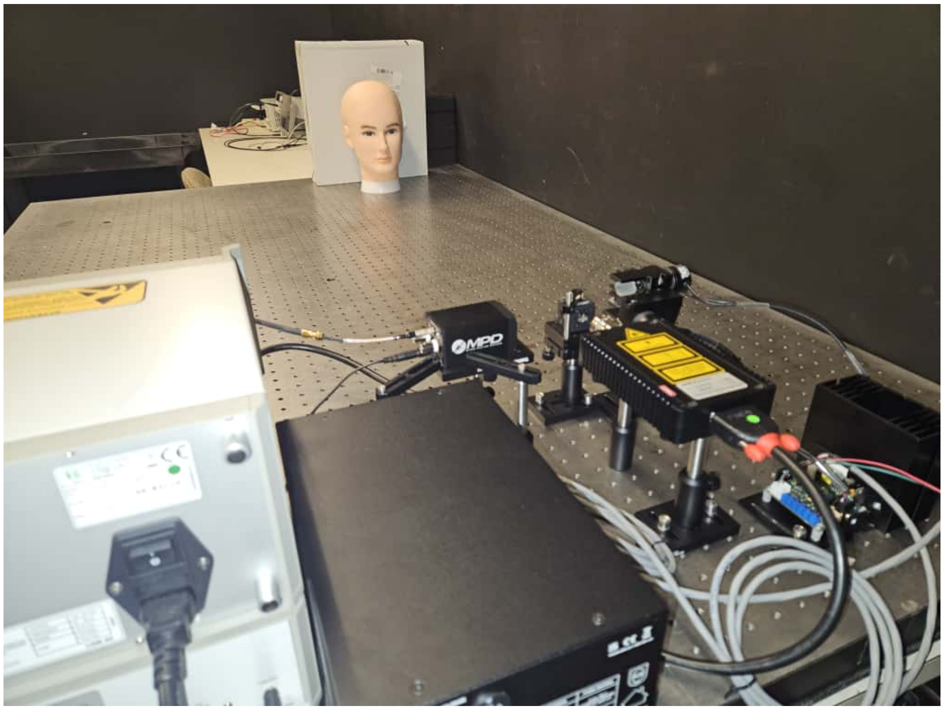

Figure 2: The SP-LiDAR lab-bench setup fully prepared for data acquisition.

The PicoHarp 300 API allows configuration of timing resolution, histogram binning, and acquisition duration. For each galvo position, a histogram of photon arrival times is recorded, producing a 3D data cube indexed by spatial coordinates (x, y) and time bins (t).

3.4 Alignment and Calibration

Optical alignment ensures the laser is normal to the galvo mirror and properly propagates through the transmit optics. Receive optics are adjusted to focus backscattered photons onto the SPAD detector. Alignment is verified by observing photon counts on a high-reflectivity planar target.

Depth calibration is performed using targets at known distances. The relationship between time delay and distance is:

$$z = \frac{c\,\Delta t}{2},$$

where c is the speed of light and Δt is the photon time-of-flight. Instrument response function (IRFs) is measured by directing the laser onto a mirror to capture the temporal impulse response, used for matched filter-based depth estimation algorithms.

4 Dataset Generation

Raster scanning produces a three-dimensional histogram cube (x, y, t), where x, y are spatial coordinates and t is photon arrival time. This raw data includes physical noise and hardware artifacts, which are crucial for developing algorithms robust to Poisson noise inherent in single-photon detection. Post-processing accounts for background noise, dark counts, and dead-time effects.