

# REAL-TIME 3D-CAMERA BASED ON LIDAR AND MEMS MIRRORS

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**Abstract** In this study, we describe a Time-of-Flight scanning LiDAR (Light Detection and Ranging) prototype, that leverages MEMS mirrors for agile beam steering and an FPGA-based processing unit for real-time 3D image reconstruction. The proposed 3D-LiDAR system is designed to operate within a range of up to 1 meter with a spatial resolution of  $400 \times 300$  pixels at a frame rate of 30 Hz. Lidar prototype architecture consists of 3 main parts: optomechanical System; Digital Processing Unit (FPGA-based); analog front-end. Processed 3D depth maps are rendered in real-time via an HDMI interface, providing immediate visual feedback. The integration of MEMS mirrors, FPGA-based Time-to-Digital Converter, and an optimized analog front-end resulted in a highly efficient, compact, and real-time depth-sensing platform.

**Keywords:** 3D camera, LiDAR, MEMS Mirrors, Rangefinder, Optical Scanning Oscillator.

## 1. INTRODUCTION

In this study, we introduce a Time-of-Flight scanning LiDAR (Light Detection and Ranging) prototype [1-3], that leverages MEMS mirrors for agile beam steering [4,5] and an FPGA-based processing unit for real-time 3D image reconstruction. The specifications could target both industrial and consumer applications, as illustrated in Figure 1.

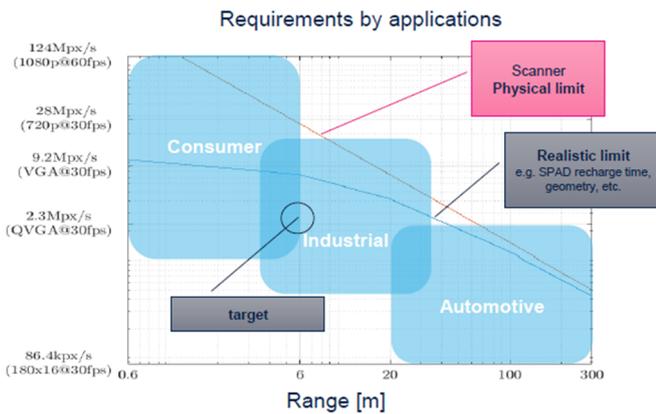


Figure 1. Target project

The proposed 3D-LiDAR system is designed to operate within a range of up to 1 meter with a spatial resolution of  $400 \times 300$  pixels, ensuring high accuracy and detail in environmental reconstruction. Lidar prototype architecture consists of 3 main parts:

- Optomechanical System: encompasses the laser emission source, MEMS mirrors, and receiver optics optimized for efficient signal capture.

- Digital Processing Unit (FPGA-based): manages real-time signal acquisition, Time-to-Digital Conversion (TDC), and dynamic control of MEMS mirror operations.
- Analog Front-End: Facilitates the conditioning of received optical signals, ensuring high fidelity in time-of-flight measurements.

This modular configuration ensures flexibility and scalability, rendering the system suitable for different applications such as autonomous navigation, industrial monitoring, and augmented reality.

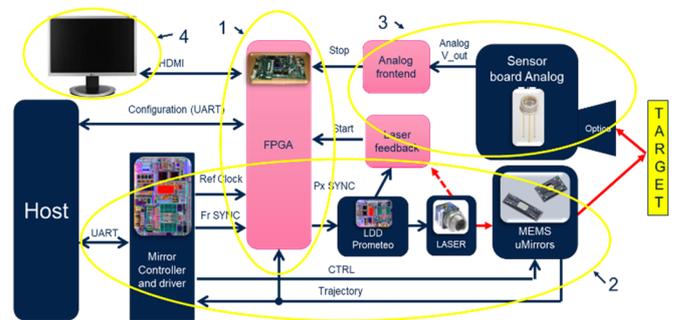


Figure 2. Block Diagram of the Lidar system.

## 2. METHODS AND PROCEDURES

The block diagram of the LiDAR system is shown in Fig. 2, four main systems are interfaced:

1) The information processing and system command module, where we use an FPGA to regulate the laser command system, process incoming information, and manage communication to the outside.

2) The laser driver and micromirror module: the system includes a single fixed laser in which its firing window is defined by the movement of two ST micromirrors, that allow the laser to change the firing point to create a  $24^\circ \times 17^\circ$  acquisition window for a total of  $400 \times 300$  pixels. By varying the micromirror command signals, we can define a specific trajectory for covering the entire field of view.

3) The analog interface module: its task starts from the reception of the light signal reflected from the target, through a PhotoDetector (specifically an MPPC, multi-pixel photon counter), and its processing and conversion into a signal accessible by the receiving FPGA. After the laser pulse hits the target and returns, it is processed and made available to the FPGA through an analog frontend for use.

4) The display module: The signal reconstructed by the FPGA is displayed on the screen through an HDMI interface and can be modified in real-time through a user interface controllable via a HDMI port through a dedicated GUI.

In the actual prototype, the laser pulse has a duration of 8 ns with a repetition rate of 8 MHz, a wavelength of 640 nm (visible for easier alignment) and a peak power of about

100 mW. In a future development, a more powerful infrared laser with shorter pulse durations will be implemented, which will allow for better accuracy in distance measurements. The analog front-end begins with a MPPC photodetector, read by a transimpedance amplifier, optimized for low noise and high bandwidth.

To address timing inaccuracies caused by variations in signal amplitude, a Constant Fraction Discriminator (CFD) was designed (Figure 3). The CFD generates a timing pulse at a consistent fraction of the signal's amplitude, effectively reducing time walk errors and enhancing the precision of time-of-flight measurements [6]. This technique is crucial for maintaining measurement accuracy across a range of signal intensities and distances.

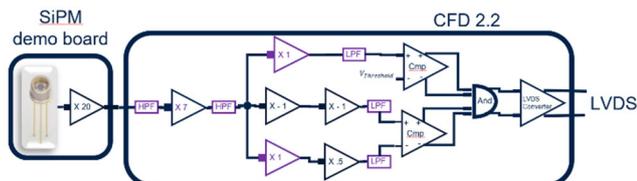


Figure 3. Block Diagram of the Analog Front End with Constant Fraction Discriminator.

Central to the system's digital processing is the Time-to-Digital Converter, implemented on a Xilinx Virtex-7 FPGA, responsible for calculating the time-of-flight. Operating with a resolution of 208 picoseconds, achieved through a 400 MHz clock with a six-phase delay method, the system effectively simulates a 4.8 GHz sampling rate. This precision translates to a distance measurement resolution of approximately 33 mm. The FPGA also orchestrates the synchronization of MEMS mirror movements, generating real-time control waveforms matching the mirrors' resonant and non-resonant drive signals. This ensures that each laser pulse is triggered in tandem with the mirror positions, aligning the pulse trajectory precisely with the corresponding pixel location in the reconstructed 3D image.

Processed 3D depth maps are rendered in real-time via an HDMI interface, providing immediate visual feedback. Additionally, system control and parameter adjustments are facilitated through a HDMI-connected graphical user interface (GUI). The FPGA architecture is designed to handle high data throughput efficiently, ensuring low-latency performance essential for dynamic environments.

### 3. RESULTS AND CONCLUSIONS

After validating all the components of the system in the point-like case, we characterized the overall system. The laser trajectory was priorly simulated through Matlab. In order to verify the uniformity of the measurement in the field of view, and evaluate the consistency of the mirror movement with the simulations, we utilized a setup in which the target constituted a white flat surface. The final prototype is able to reconstruct a 3D image with a resolution of 400x300 on the HDMI output, with a frame rate of 30Hz. As a test example, we used a white teddy bear, positioned in the center of field of view, against a white flat background (figure 4).

The development and validation of the MEMS-based scanning LiDAR system presented in this work represent a significant contribution to the field of compact and high-

resolution three-dimensional sensing. The integration of MEMS mirrors for agile beam steering, an FPGA-based Time-to-Digital Converter for precise time-of-flight measurements, and an optimized analog front-end for signal conditioning resulted in a highly efficient, compact, and real-time depth-sensing platform. Through extensive simulation and experimental validation, the system demonstrated:

- A depth accuracy of about 60 mm, achieved within a 0.2–1.0 m range.
- A scanning Field of View (FoV) of  $24^\circ \times 17^\circ$ , enabled by MEMS mirror actuation.
- A spatial resolution of  $400 \times 300$  pixels, ensuring detailed environmental mapping (angular resolution  $\sim 0.06^\circ$ ).
- Robust FPGA-based real-time processing, supporting frame rates of 30 Hz.

The successful development of this MEMS-based scanning LiDAR system paves the way for a wide range of robotics, automotive sensing, industrial automation, and consumer applications.

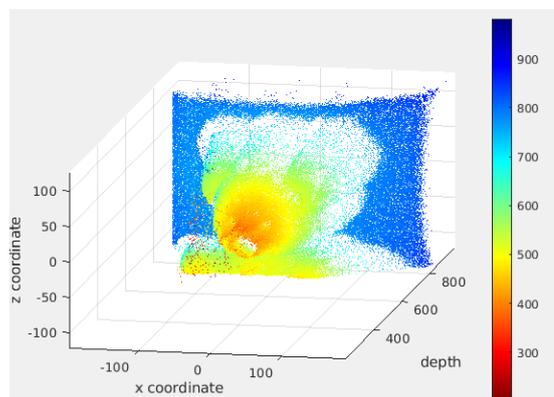


Figure 4. Example of 3D real-time measurement results.

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