Terrestrial LiDAR: Principles, Development, and Hardware

1 Introduction

Terrestrial LiDAR (Light Detection and Ranging), or Terrestrial Laser Scanning (TLS), is a ground-based remote sensing technology that uses laser pulses to create high-resolution 3D point clouds. It is used in surveying, structural monitoring, archaeology, and forestry, achieving centimeter-level accuracy. This document explains TLS principles, development steps, hardware components, and references relevant research.

2 Theoretical Principles

TLS primarily uses the Time-of-Flight (ToF) method, with phase-shift as an alternative. Key equations include:

2.1 Time-of-Flight Distance

$$d = \frac{c \cdot t}{2} \tag{1}$$

- d: Distance (m)
- c: Speed of light (3×10^8 m/s)
- t: Round-trip time (s)

2.2 3D Coordinates

$$x = d \cdot \cos(\phi) \cdot \sin(\theta) \tag{2}$$
$$y = d \cdot \cos(\phi) \cdot \cos(\theta) \tag{3}$$
$$z = d \cdot \sin(\phi) \tag{4}$$

- x, y, z: Coordinates (m)
- θ, ϕ: Azimuth and elevation angles (radians or degrees)

2.3 LiDAR Equation

$$P_r = \frac{P_t \cdot \rho \cdot A_r \cdot \eta_{\text{atm}} \cdot \eta_{\text{sys}}}{4\pi d^2} \tag{5}$$

- P_r, P_t: Received and transmitted power (W)
- ρ: Reflectivity (0–1)
- A_r: Receiver aperture area (m^2)
- $\eta_{\text{atm}}, \eta_{\text{sys}}$: Efficiencies (0–1)

2.4 Range Resolution

$$\Delta d = \frac{c \cdot \tau}{2} \tag{6}$$

- Δd: Range resolution (m)
- τ: Pulse width (s)

2.5 Angular Resolution

$$\Delta \theta = \frac{\beta}{2} \tag{7}$$

- $\Delta\theta, \beta$: Angular resolution and beam divergence (radians or degrees)

2.6 Atmospheric Attenuation

$$\eta_{\text{atm}} = e^{-2\alpha d} \tag{8}$$

- α: Attenuation coefficient (m^{-1})

3 Hardware Components

Building a TLS system requires:

- **Laser Source**: Pulsed laser diode (e.g., 905 nm, Osram SPL PL90) or fiber laser (1550 nm).
- **Scanner and Optics**: Mechanical (rotating mirror), MEMS, or Optical Phased Array (OPA).
- **Photodetector**: Avalanche Photodiode (APD, e.g., Hamamatsu S14645) or Silicon Photomultiplier.
- **Timing System**: Time-to-Digital Converter (TDC) or ADC, implemented on FPGA (e.g., Xilinx Zynq-7020).
- **Positioning**: GPS (e.g., u-blox NEO-6M) and IMU (e.g., MPU-6050) for mobile TLS.

- **Data Processing**: Embedded system (e.g., Raspberry Pi 4) for point cloud generation.
- **Power Supply**: Battery (e.g., 5000 mAh LiPo) or mains.
- **Mounting**: Tripod for static TLS; vehicle or handheld for mobile TLS.

4 Development Steps

1. **Design**: Choose ToF or phase-shift; define wavelength, FOV, and resolution.
2. **Assemble**: Integrate laser, scanner, photodetector, and timing system using FPGA.
3. **Software**: Write firmware (C/C++, Python) for control and data acquisition; use PCL for point cloud processing; implement SLAM for mobile TLS.
4. **Calibrate**: Adjust laser, scanner, and photodetector using a target board.
5. **Test**: Validate in controlled environments, ensuring <1 cm accuracy.

5 Challenges

- **Cost**: High-precision components are expensive.
- **Noise**: Quantum and amplifier noise reduce accuracy.
- **Environment**: Rain or fog attenuates signals, especially at 1550 nm.
- **Data Storage**: Large point clouds require efficient formats (e.g., .LAS).

6 Research Papers

- Vosselman, G., & Maas, H.-G. (2010). *Airborne and Terrestrial Laser Scanning*. CRC Press. ISBN: 978-1904445-87-6.
- Olsen, M. J., et al. (2010). "Terrestrial Laser Scanning-Based Structural Damage Assessment." *Journal of Computing in Civil Engineering*, 24(3), 264–272. DOI: `10.1061/(ASCE)CP.1943-5487.0000028`.
- Bauwens, S., et al. (2016). "Forest Inventory with Terrestrial LiDAR." *Forests*, 7(12), 127. DOI: `10.3390/f7120127`.
- Shao, J., et al. (2020). "SLAM-Aided Forest Plot Mapping." *ISPRS Journal of Photogrammetry and Remote Sensing*, 163, 214–230. DOI: `10.1016/j.isprsjprs.2020.03.008`.
- Poulton, C. V., et al. (2019). "Coherent Solid-State LIDAR with Silicon Photonic Optical Phased Arrays." *IEEE Journal of Selected Topics in Quantum Electronics*, 25(6), 7700108. DOI: `10.1109/JSTQE.2019.2931050`.

7 Units Summary

Variable	Description	Unit
d	Distance	Meters (m)
c	Speed of light	Meters per second (m/s)
t	Round-trip time	Seconds (s)
x, y, z	Coordinates	Meters (m)
θ, ϕ	Angles	Radians or degrees
P_r, P_t	Power	Watts (W)
ρ	Reflectivity	Dimensionless (0–1)
A_r	Receiver area	Square meters (m^2)
$\eta_{\text{atm}}, \eta_{\text{sys}}$	Efficiencies	Dimensionless (0–1)
β	Beam divergence	Radians or degrees
τ	Pulse width	Seconds (s)
α	Attenuation coefficient	Per meter (m^{-1})

Table 1: Summary of variables and units.

8 Conclusion

Terrestrial LiDAR enables high-precision 3D mapping using laser-based distance measurements. Developing a TLS system involves integrating laser, scanner, photodetector, and processing components, guided by ToF or phase-shift principles. Challenges include cost, noise, and environmental factors. Referenced papers provide further insights into TLS development and applications.