Room-Scale 3D LIDAR Solution

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I. Introduction

I.I Objective

Since the introduction of the autopilot feature by Tesla in 2016, there has been an explosive interest in autonomous driving. Many companies have since spent large amounts of resources and manpower in this profitable field, especially in the research of 3D Light Detection and Ranging (LIDAR) sensors, one of the more vital aspects of self-driving vehicles [1] (along with countless applications in surveying, movie special effects, sim racing, etc.) This device is utilized to collect the data of a vehicle's surroundings and output an accurate 3D point cloud map so the vehicle can change the direction it is moving accordingly [2]. Because of the growth in popularity of autonomous vehicles, the interest in 3D LIDAR sensors has seen a similar increase among enthusiasts and hobbyists. However, unlike big corporations who have had the ability to obtain industry grade LIDAR technology for years, individuals typically cannot afford the high cost of entry for a 3D LIDAR sensor. To make it easier for hobbyists to explore the self-driving vehicle field, we are developing a system that will provide similar functionalities as the current 3D LIDAR industry solutions utilizing 1D time-of-flight (TOF) sensors while also remaining both affordable and easily obtainable.

The system we build is aimed towards the hobbyist market which has been largely neglected by the market up until now. We plan for the solution's friendly cost of entry to be our main selling point. Instead of using typical single-phase or solid-state 3D LIDAR sensors which cost thousands of dollars, we will build the system based on a TOF sensor (also called 1D LIDAR) that can be a hundredth of the cost. The LIDAR will scan the environment and perform distance measurements on a 2-axis platform with a stepper motor helping to rotate the LIDAR 360-degree on the platform. Meanwhile, another motor will pitch the sensor up and down so the sensor can scan its environments at various height level. The recorded polar coordinates of the measured area will then be converted into Cartesian coordinates and eventually exported as a point cloud file that can be visualized to show the scanned room.

I.II Background

A LIDAR sensor bounces light off a surface and calculates the distance to the surface based on the time it takes to get back to the sensor. A 3D LIDAR system accurately scans its environment using the same principle and measures thousands of points in the sensor's surroundings to obtain their coordinates. These coordinates can then be converted into 3D point cloud data that is a digital sampling of its environment, and even interpolated into a 3D mesh model if needed. LIDAR sensors has been adopted by the majority companies in the autopilot field like Waymo, Uber, and Google.

Apart from these companies, there is also a growing number of hobbyist consumers interested in experiencing the benefits of environmental scanning that 3D LIDAR in various other fields (construction, research, virtual reality, surveying, etc.). However, the cost of such sensors remains prohibitively high, such that there are currently no solutions for the average consumers [3]. The current 3D LIDAR sensor market only contains offerings that target industry level companies with sufficient R&D budget to shell out for top-of-the-line specifications which can include weatherproofing, robust housings, millimeter accuracy, and impressive scanning speeds. Such comprehensive solutions can cost upwards of over $10,000, with more cheaper alternatives still exceeding $1,000 [3][4]. On the other hand, 1D and 2D LIDAR sensors are widely available on the market in addition to being much more reasonably priced. The downside is that such sensors are limited to capturing point to point distance or a top-down layout which is insufficient for most autonomous vehicle purposes. Therefore, the current market has left a void where hobbyists and enthusiasts design, but have no easy ways, to study and expand on this technology [5].

Therefore, by offering a cheap 3D LIDAR system with relatively high functionality, we hope to satisfy the growing interest and needs of enthusiasts and hobbyists. We expect our solution may have lower resolution and a longer scanning period than current industry level scanners, which while unsuitable for the industry, is perfectly suited for individual consumers interested in the field of environment scanning.

I.III Physical Design

Figure 1: Device Physical Design

Our design stuck with the tried-and-true industry design of a revolving sensor. We have striven to keep the physical footprint as small as possible, to make the integration of the sensor to our clients' projects as simple as possible. As such, we plan to integrate a 1/4-20 UNC thread at the bottom of the housing, on axis to the rotation for easy mounting on standard tripods. Though not pictured in this render, the sensor will need a USB connection to the computer as part of the data transfer process.

I.IV High-Level Requirements

- The system can scan the room and output successfully within a time frame of 30 seconds
- The point cloud output by the system will have an accuracy of ±10 cm at a distance of 0.2 to 3 meters.
- The output file will use the industry standard LAS file format specified by the American Society for Photogrammetry and Remote Sensing (ASPRS) and be readable by most external software.

II. Design

II.I Block Diagram

The 3D LIDAR system consists of five major subsystems: primary sensor, vertical rotation, horizontal rotation, control system, and computer. The primary sensor subsystem is responsible for ensuring the accuracy of the environment distance measurements by using a TOF sensor. The vertical rotation subsystem and the horizontal rotation subsystem control the rotational movement of the LIDAR sensor in vertical and horizontal planes, respectively. They work in tandem with the primary sensor subsystem to emulate a scanning effect similar to its 3D LIDAR counterpart. Additionally, these three subsystems are regulated by the control system allowing the sensor to scan an indoor room with an approximate dimension of 10x10x5m in 30 seconds with an accuracy of ±10 cm at a distance of 0.2 to 3 meters. After the control system receives the measurement data from the sensor under the I2C communication protocol, it will convert the 3D polar coordinates to Cartesian coordinates then pass the processed data to the computer subsystem from which the python software can output a 3D point cloud file of the scanned room.

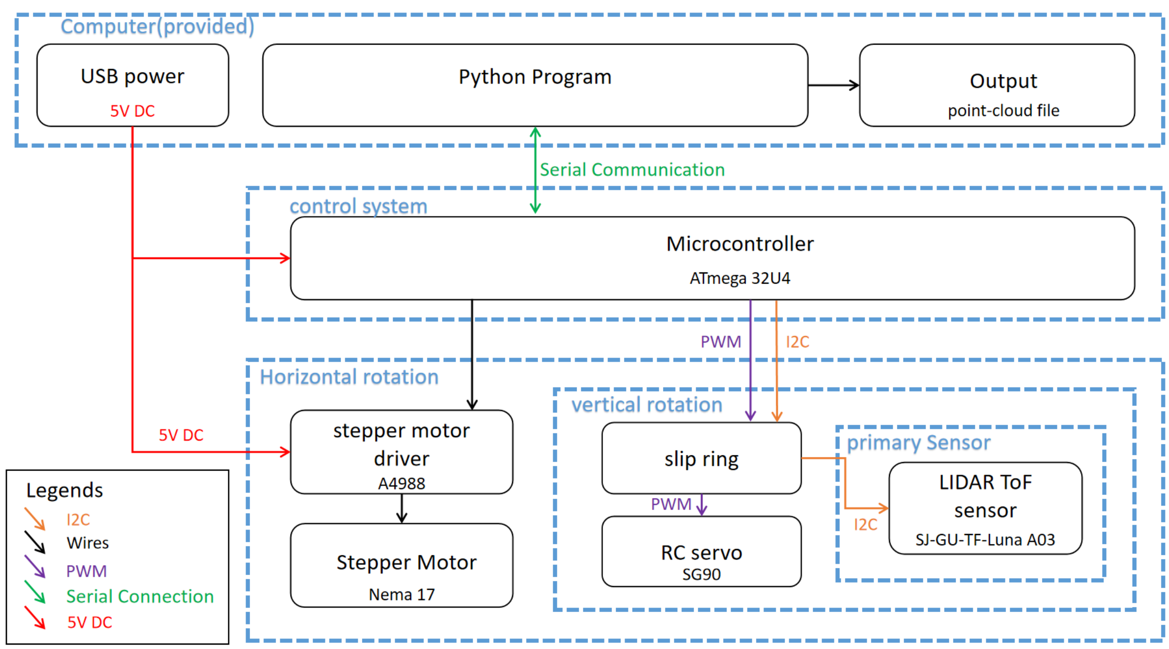

Figure 2: Block Diagram

II.II Functional Overview and Block Requirement

II.II.I Control System

The Microcontroller coordinates all the different subsystems so that the rotation of the two different axis is coherent, systematic, and repeatable enough for the TOF sensor to obtain meaningful measurements. The Control System is responsible for moving the horizonal rotation to its next position after the TOF sensor receives a reading and pitching the sensor to the next vertical angle after one revolution of the horizontal rotation.

Requirement 1: The program successfully converts the raw data into a LAS file within the 30 second period specified as a high-level requirement.

II.II.I.I (ATmega32U4)

We decided to go with ATmega32U4 microcontroller as it has been very well documented and supports all the communication protocols that are needed. The microcontroller will have to talk to the A4988 chip to control the stepper motor, maintain I2C communication with the TOF sensor to obtain the distance reading, PWM output to the RC servo to set the angle of the sensor, and establish a serial connection to the client's computer streaming the coordinates of different points all simultaneously. The controller is also in charge of converting the polar coordinate space that the LIDAR system is running into Cartesian coordinates so the data can be understood by the python program to properly convert into the LAS file format.

Requirement 1: Simultaneously maintain I2C and serial communication while controlling the A4988 motor driver and PWM servo without timing / interruption issues.

Requirement 2: Convert the polar coordinates into Cartesian coordinates at a rate faster than 250Hz (refresh rate of TOF sensor.)

II.II.II Primary Sensor

The primary sensor subsystem consists of a TOF sensor. The subsystem references the environment through the sensor by taking 1D point-to-point distance measurements from the environment. It receives DC power and sends digital signal from and to the computer subsystem through the USB port. The voltage needs to be kept between 3.7 to 5.2V to ensure the sensor can function reliably. In addition, the power supply should be adequate to ensure the sensor can work for at least 30 seconds to take a full scan of the environment.

Two signal wires run between the sensor and the microcontroller subsystem. The wire runs under I2C protocol and is responsible for sending collected data to the control subsystem to be processed. It starts from the sensor, passes through the slip ring and finally goes to the microcontroller.

If we connect the sensor tightly to the slip ring, with the help from the vertical rotation subsystem, the combined system can achieve a 3D scan of an indoor room (such as living room, classroom etc.)

Requirement 1: The subsystem can have enough power supply ranging from 3.7 to 5.2V to ensure the sensor can work in normal condition for at least 30 seconds.

Requirement 2: The subsystem should send the data smoothly to the control subsystem through a wire under I2C protocol.

II.II.II.I Primary TOF Sensor (SJ-GU-TF-Luna A03)

We will use the SJ-GU-TF-Luna A03 LIDAR module as the TOF sensor. The TF-Luna LIDAR product was our choice of sensor after researching options available. It has the smallest footprint and the lowest cost of entry while maintaining an 8-meter range and 250 Hertz refresh rate. The sensor will have a 360-degree continuous rotation and take distance measurements in every direction in a 2D plane with the help of the stepper motor to the precision of ±10 cm at 0.2 to 3 meter distance. In addition, the RC servo will pitch the TOF sensor up and down to ensure the sensor can reach various height levels allowing for 3D environment of dimension 10x10x5m to be scanned. The TOF sensor's frame rate will be adjusted so it can fully scan the room in 30 seconds to leave enough time for the point cloud file generation.

Requirement 1: The sensor should be tightly connected to the slip ring to ensure a precision of ±10 cm at 0.2m to 3m distance.

Requirement 2: The sensor should have an operating range that enables it to scan a room with a dimension of 10x10x5m.

II.II.III Vertical Rotation

The Vertical Rotation block is in charge of pitching the sensor up and down so the sensor can scan the various horizontal planes at different heights. It consists of a slip ring and a RC servo. When the scan process begins, the RC servo will pitch the 1D sensor up and down under the PWM control from the control block, thus the sensor can access different height levels. On the other hand, the control signal and the data collected by the sensor will be transferred past the slip ring to the microcontroller in the control block. In addition, the servo will receive DC power supply ranges from 5 to 5.5V from the computer block in USB wire passing through the slip ring to keep it functions normally.

Requirement 1: The RC servo must receive a DC power supply ranges from 5 to 5.5V from the computer block to make it function normally.

Requirement 2: The slip ring should make sure the PWM and I2C signals are not compromised under constant rotation.

II.II.III.I Slip Ring

The slip ring inside the block is connected to the TOF sensor in the primary sensor block on one side, and the microcontroller on the other. It makes sure the wire does not get twisted when the sensor is rotating so that the stepper motor in the horizontal rotation block can rotate infinitely to ensure the sensor's continuous scan. The slip ring acts to maintains the signal integrity of three components. 2 of the leads will supply 5V DC power to the electronics within the vertical rotation and primary sensor block. The communication between the TOF sensor and the Control System is run through the slip ring and is under the I2C protocol. The PWM signal coming from the microcontroller into the RC servo also passes the slip ring.

Requirement 1: The noise induced by the slip ring must not interfere with the I2C signal sent from the primary TOF sensor or the PWM signal going to the RC servo.

Requirement 2: The 5V DC power coming out of the slip ring must be smoothed out enough to fit the 3.7 to 5.2V requirement of the TOF sensor.

II.II.III.II RC Servo

We will use SG90 9G Micro Servo as the RC servo in this subsystem. The servo, which is regulated by the control system through PWM, can pitch the sensor up to 90 degrees so that the TOF sensor can aim up and down. The servo receives a DC power from the computer block through the USB wire and the power needs to be between 5 to 5.5V to ensure the servo functions normally. Since the angular resolution of the LIDAR TOF sensor is 2 degrees, the accuracy of the servo needs to be kept around 1 degree to guarantee accuracy and repeatability. We expect the servo to be able to rotate 40 to 50 degrees in 0.1 second under 5V DC power supply to ensure that the whole system can finish scanning in 30 seconds.

Requirement 1: The servo must be able to rotate the system 40 to 50 degrees in 0.1 second under a continuous 5V DC power supply.

Requirement 2: The servo must be able to repeatably go to a certain angle with an accuracy of ±1 degree.

II.II.IV Horizontal Rotation

The Horizontal Rotation block, which consists of a stepper motor driver and a stepper motor, rotates the sensor in the horizontal plane so the sensor can scan the horizontal plane. It works with a vertical rotation block and the primary sensor block to make sure we can have a 360-degree scanning of an indoor room with an approximate size of 10x10x5m by a 1d LIDAR sensor. The stepper motor driver receives DC power ranges from 3 to 5V from the computer block through the USB wire and receives control signal from the microcontroller in the control block. When the scanning process begins, it will control the stepper motor to rotate the system horizontally to ensure that the sensor can have 360-degree scanning of the horizontal plane.

Requirement 1: The subsystem must work in synchronous with the vertical rotation subsystem and the primary sensor subsystem to make sure the system can do a 360-degree scanning for an indoor room(10x10x5m) in 30 seconds.

Requirement 2: The subsystem must be repeatable enough to maintain spacial awareness over 30 rotations.

II.II.IV.I Stepper Motor Driver & Stepper Motor

We will use a Nema 11 stepper motor as our stepper motor. The motor will rotate the sensor in the primary sensor block horizontally at the speed 50 to 70 RPM under the control of the stepper motor driver, which is under the control of the control block.

Requirement 1: The stepper motor should be able to run at the speed 50 to 70 RPM to make sure that the scanning process can be done in 30 seconds with the precision of ±10 cm at 0.2m to 3m distance.

II.II.V Computer

The Computer subsystem is fed in a continuous serial data stream from the microcontroller of converted measurements from the TOF sensor. The data will be collected and converted into the LAS point cloud file format through a python program.

II.II.V.I USB Port

5V DC are output from the computer via a USB type A port, which will power the microcontroller, the servo motor, the TOF sensor, and the stepper motor to handle the rotational movement. Since the entire system is powered via a singular port, the scan/convert process is heavily reliant on a consistent output from the port.

Requirement 1: The USB port can continuously output 5V/500mA to the rest of the system.

II.II.V.II Python Program

The python3 program is fed a stream of 1D measurement data that has been converted from polar to cartesian coordinates by the microcontroller. By utilizing the laspy and numpy python libraries, a LAS file is generated and output. The LAS file type is an open format specified by the American Society for Photogrammetry and Remote Sensing (ASPRS) and the standard for the "interchange of 3-dimensional point cloud data" [6]. Once in this format, the point cloud can be imported and visualized into numerous different software.

Requirement 1: The program successfully converts the raw data into a LAS file within the 30 second time period specified as a high-level requirement.

II.III Risk Analysis

After reviewing the different subsystems, our team believes that the TOF sensor carries the most risk towards the successful completion of our project. Since the sensor is the main input that is required for the generation of the point map, it functioning properly is vital to the entire system.

Even a slight variation in refresh rate could mess up the syncing of the sensor and the rotating motor enough to create aliasing in the data. On the other hand, if the reported versus actual error of the sensor differs too much, our accuracy based high-level requirement will not be met. Since the sensor uses infrared light to obtain the distance, outside interference, direct sunlight for example, might also be enough to disturb the measurement under some circumstances.

To try and combat the aforementioned issues, our team will test multiple TOF sensors to determine the most reliable and cost-effective option for the final product. At the same time, we will attempt to continuously maintain the same environment and testing conditions of the system to minimize any potential variations.

III. Ethics and Safety

Our project aims to lower the cost of entry into the light-based scanning field. By minimizing the construction cost and streamlining the assembly, setup, and maintenance processes, we hope to allow for the better "understanding...of conventional and emerging technolog[y]"[7] that is 3D LIDAR.

In the efforts to "protect the privacy of others" [7] following section I-1 of the IEEE Code of Conduct, after heavy deliberation, we do not believe there are any privacy concerns from a user data perspective. This is based on the fact that all data that the system collects is stored offline.

As stated in the IEEE Policies section 7.6, the "safety, health, and welfare of the public" [8] is to be held paramount. With the TOF sensor utilized in our design, there is an 850 nm laser that has the potential to cause damage to the human eye. With this wavelength of light, humans cannot distinguish its intensity and can easily be injured as a result [9]. To account for this, our team will utilize special safety laser goggles that protect against the laser and will include a safety warning to any consumers.

Taking into account other possible safety concerns such as system voltage, we have concluded that there is no issue to worry about as the maximum voltage used by the system of 5.5 volts is not enough to cause significant harm [10].

It is important to note that a cheaper cost of entry for 3D LIDAR systems could make it easier for an individual to conduct more precise attacks via an unmanned device. Already, higher complexity LIDAR systems are already being utilized by the US military. "...military scientific research institutes in the United States have developed...LIDAR seekers with specific algorithms have the ability of automatic target recognition [11]." Though our project does not exist to promote such uses, there remains a definite possibility of a third party utilizing our system alongside others to threaten public safety which also contradicts section 7.6 mentioned above.

There does not seem to be a good way to proactively counteract such utilization of our 3D LIDAR solution as the use case of general surrounding scanning is too broad and mostly innocuous to try and police. Any sort of countermeasures integrated into the system would most likely detriment the user experience significantly. With this in mind, we acknowledge the slight possibility of our system being used for unintended purposes that could breach the IEEE code, however in the efforts to maintain device functionality and given the low probability of misuse, the system will not be designed to counteract this specific concern.

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