Simulation and Analysis of Laser Triangulation for Non-Contact Range Finding in a 3D Environment

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***Abstract* - This project explores the application of Laser Triangulation for non-contact distance measurement in a 3D simulation environment using Zemax OpticStudio 20.1 software. By projecting a laser spot onto an object and capturing the backscattered light with a CCD camera, distances can be calculated based on angle measurements. A Python program is developed to calculate the centroid of the reflected laser beam spot on image plane. The project successfully achieves its objectives, although challenges arise when dealing with out-of-focus laser beams on the image plane and the transition from 2D to 3D calibration. Nevertheless, the simulation demonstrates promising results for distance measurement within certain ranges, offering valuable insights into Laser Triangulation applications.**

***Keywords* — Laser Triangulation, Gausian Beam, 3D Simulation Model, Image Processing, Callibration**

I. INTRODUCTION

Human vision's stereoscopic nature allows us to perceive a sense of three-dimensional shape from visual inputs, relying on two-dimensional images from each eye to form a 3D vision. However, replicating this process using cameras to gather distance-related information presents challenges. Non-contact distance measurement techniques play a vital role in various applications, with Laser Triangulation being one of the most popular methods for such measurements.

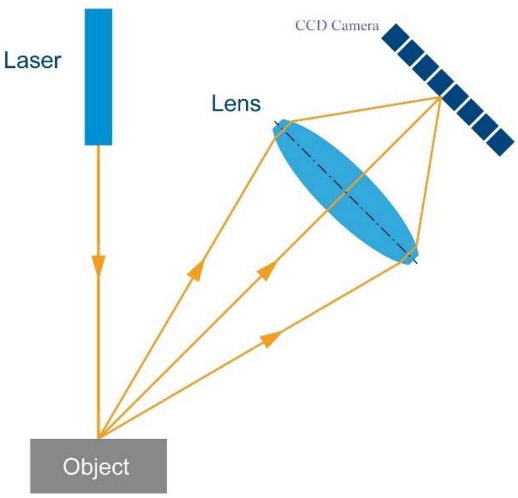

Figure 1: Functional principle of laser triangulation [1]

Triangulation involves calculating distances based on angle measurements, where a laser spot is projected onto an object, and a CCD camera captures the backscattered light through a focusing lens, forming an image. This project explores Laser Triangulation in a 3D simulation environment using Zemax OpticStudio 20.1 software.

II. METHODOLOGY

Triangulation is the process used to determine the location of a point by forming triangles with known points. It involves only angle measurements instead of directly measuring distances to the point. In the figure 2, PI, P2, and P3 represent the reference point camera, laser source, and the target point respectively.

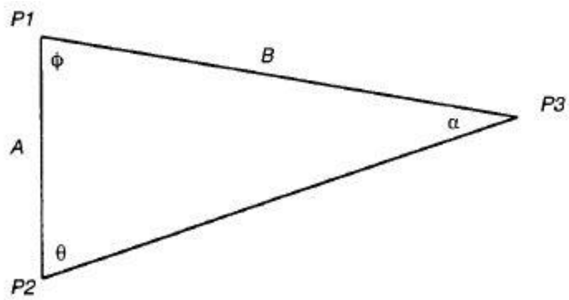

Figure 2: Configuration for triangulation ranging [2]

Theoretical calculations use the baseline distance between the source and the sensor, as well as the sensor and source angles, to determine distance via triangulation. The range B can be determined using the values of the baseline separation A and the angles α and θ, applying the law of sines.

$$B = A\frac{sin\theta}{\sin\alpha}$$

However, accurately measuring the baseline separation and angles is difficult. Hoa G. Nguyen and Michael R. Blackburn demonstrated a technique for obtaining range information via laser triangulation without knowing the values of A and the angles in the paper titled "A Simple Method for Range Finding via Laser Triangulation," published in 1995. The same method is used in the simulation of this project. [2]

The setup for Nguyen and Blackburn's approach for triangulation is shown in figure 3.

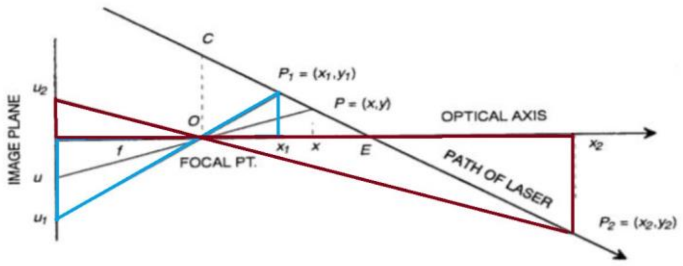

Figure 3: Configuration for Laser and Camera

In this setup, the camera position is represented by the image plane; the laser is exactly above the camera. The point of interest is represented as P, and CE is the path of the laser, intersecting the optical axis at point E. The point u represents the vertical projection of point P on the camera. X1 and X2 are the vertical projections of points P1 and P2 on the optical axis, which are two points used in the calibration to find the range of the object. Here, u1 and u2 are also the projections of P1 and P2 on the Image Plane.

To find out the value of x, we can write the following equations from the similar triangles shown in the highlighted part of figure 3.

$$\frac{y_1}{x_1} = \frac{u_1}{f} \text{ and } \frac{y_2}{x_2} = \frac{u_2}{f}$$

The slope *(m)* of the laser path and the y-intercept (c, the height of point C) are:

$$m = \frac{y_2 - y_1}{x_2 - x_1} \text{ and } c = y_2 - mx_2 \qquad (2)$$

Substituting equation 2 into equation 3 to eliminate v; and *y2*, we have:

$$m = \frac{u^2x^2 - u_1x_1}{f(x_2 - x_1)} \text{ and } c = \frac{u_2x_2}{f} - mx_2 \qquad (3)$$

Now solving for x and y,

$$y = \frac{ux}{f} \qquad (4)$$

The laser beam path from the figure is given by,

$$y = mx + c \qquad (5)$$

After solving equations 4 and 5 and using equation 3, we get

$$x = \frac{N}{ud - k} \qquad (6)$$

After calibration process we get,

$$\left.\begin{aligned} d &= x_2 - x_1 \\ k &= u_2x_2 - u_1x_1 \\ N &= (u_1 - u_2)x_1x_2 \end{aligned}\right\} \qquad (7)$$

Using these equations, we can get the distance X of the object from the camera with the help of those calibrated projection points u_1 and u_2.

III. MEASUREMENT APPROACH

The measurement approach for ranging via laser triangulation is shown in figure 4. Firstly, a simulation setup is designed in Zemax software to perform ray tracing and data collection. The centroid of the tracing beam spot on the image plane will be calculated by python program.

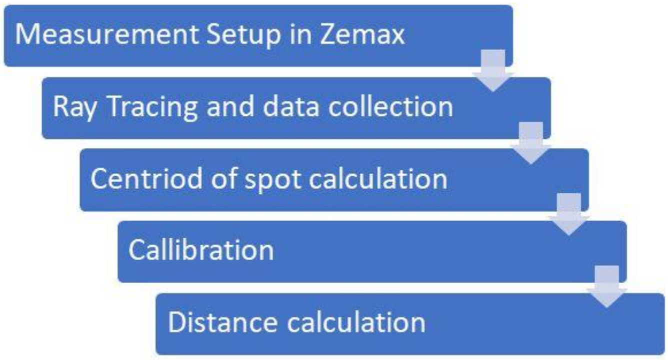

Figure 4: Distance Ranging Approach

A. SIMULATION SETUP

The measurement setup comprises the following components:

1. Laser Source
2. Object Under Test
3. Focusing Lens
4. Image Plane

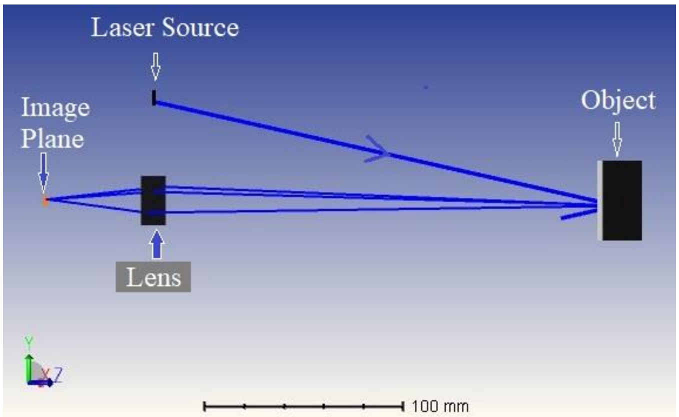

Figure 5: Simulation Setup in OpticStudio

In the OpticStudio software, the setup (figure 5) includes a Gaussian Laser source, Object under test, Lens, and Image plane. The Lens and Image plane together represent the CCD camera mentioned in Nguyen and Blackburn's method for Range finding using Laser Triangulation. In this setup, the laser beam is focused on the object under test, and the scattered laser beam returns to the image plane through the

Lens. The object under test is placed on the same axis as the Focusing lens and Image plane.

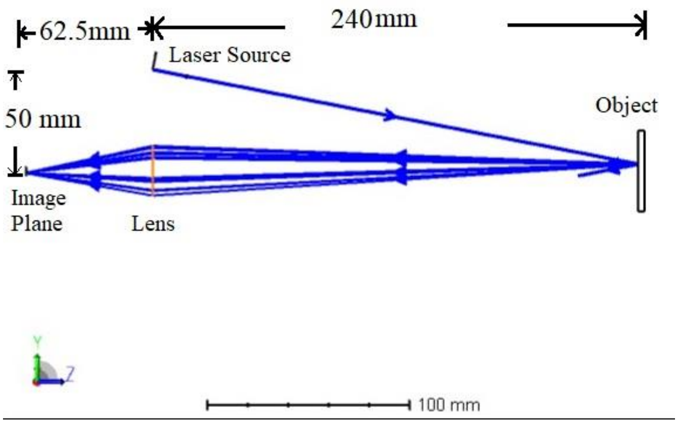

Figure 6: Distances among the Components

Figure 6 shows the distances among the components of the Laser triangulation setup on Zemax. The initial position of the Object under test is considered the reference point (0, 0, 0) for the Laser Source and Lens, while the position of the lens is the reference point for the Image plane. The setup uses a Gaussian source type laser with a beam size of 0.5 and power of 1 watt. The Object Under test is a rectangular volume with size (40x40) mm and a Mirror material type. The Lens is a Paraxial type with size (25x25) mm, and the Image Plane is a Detector rectangle with an Absorb material type and size (5x5) mm. The positions of the components are listed in table 1.

Table 1: Positions of the Components

Device Name	**Type**	**Position(X, Y, Z)**	**Tilt (X, Y, Z)**	**Size (X half width*Y half width)**
Laser Source	Source Gaussian	0, 50, -240	11, 0, 0	(Beam Size 0.5)
Object Under test	Rectangular Volume	0, 0, 0	0, 0, 0	20*20
Lens	Paraxial Lens	0, 0, -240	0, 0, 0	12.5*12.5
Image Plane	Detector Rectangle	0, 0, -62.5	0, 0, 0	2.5*2.5

B. Ray Tracing and Centroid Calculation

The scattered rays from the Object under test are captured on the Image Plane through the lens by ray tracing. Figures 7 shows the laser beam spot on the image plane at different z positions. It is evident that with the change of Object position to the negative direction, the beam spot moves in the negative direction of the Y-axis (downward), and with the change of Object position to the positive direction, the beam spot moves in the positive direction of the Y-axis (upwards).

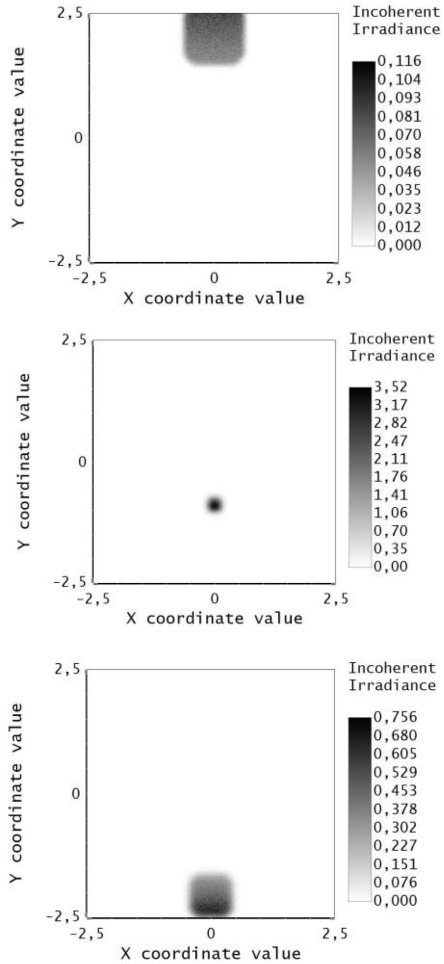

Figure 7: Z positions 70, 0, and - 20 (from top to bottom)

The centroid of the spot needs to be calculated for each corresponding position of the Object.

C. Calibration

Nguyen's Theory provides a calibration equation based on the idea of similar triangle theory (equation 7). However, in 3D, there is a slight change in the coordinate system: Z → X and Y → U. The Simulator's coordinate system is shown in Figure 8.

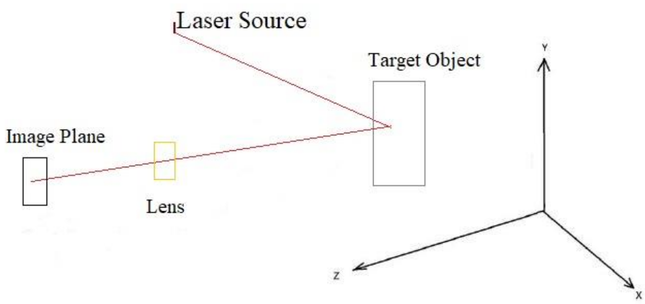

Figure 8: Coordinate System in Simulation

The object's distance is calculated using several calibration positions to find better calibration positions X_1 and X_2. The system is calibrated using two z-positions within the measurement range. Different calibration points of z-positions are used to measure the same object position (shown in table 2), and the deviation is compared. The calibration points X_1 = 235 mm and X_2 = 255 mm are selected to calibrate the system due to their minimal deviation in measurement.

Table 1: Calibration Data

Position for Calibration		**DUT (at X = 0)**		**Deviation**
X1	X2	X_S (mm)	X_{th} (mm)	
-5	5	239.982	240	-0.0179
-5	**15**	**240.0027**	**240**	**0.0027**
-5	20	240.0057	240	0.0057
-5	30	240.0295	240	0.0295

Calibrated data:

X1 = 235 mm, U1 = -1.1622807017543857 mm.

X2 = 255 mm, U1 = -0.0927734375 mm.

IV. RESULT

The Object under test is moved along the Z-axis, and the laser beam spot on the image plane is recorded. The centroid of the beam spot is calculated through a python program. Using the calibration equation 7 and range finding equation 6, the distance is calculated as follows:
Xth = Object position - (-240). The measurement error is also calculated by $X_S - X_{th}$.

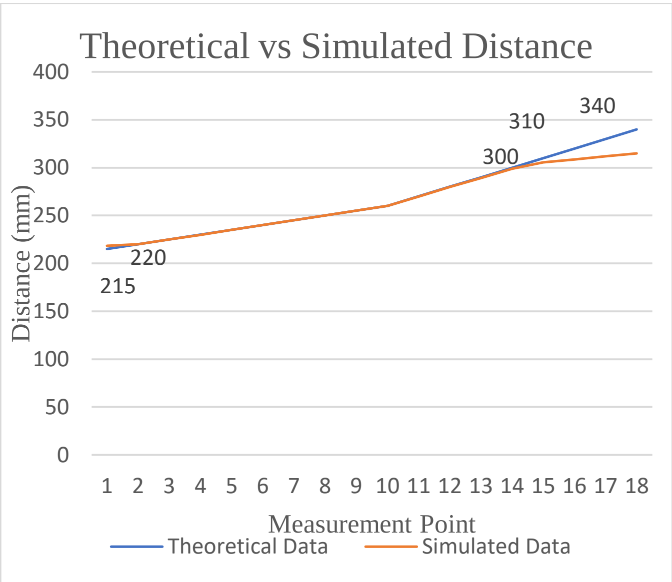

Figure 9: Theoretical vs Simulated Distances

A comparison of the theoretical distance and simulated distances is depicted in figure 9. The theoretical distance and the measured distance are almost the same from 220 mm to 300 mm. However, above 310 mm, the measured distances decrease in comparison to theoretical distances.

To find out the deviation, the measured Error of simulation vs. theoretical distance is shown in Figure 10. It is evident that below 220 mm and above 300 mm, the deviation increases rapidly. Therefore, the measurement range of this Laser Triangulation setup can be considered as 220 mm – 300 mm. Error = X_S - X_{th}.

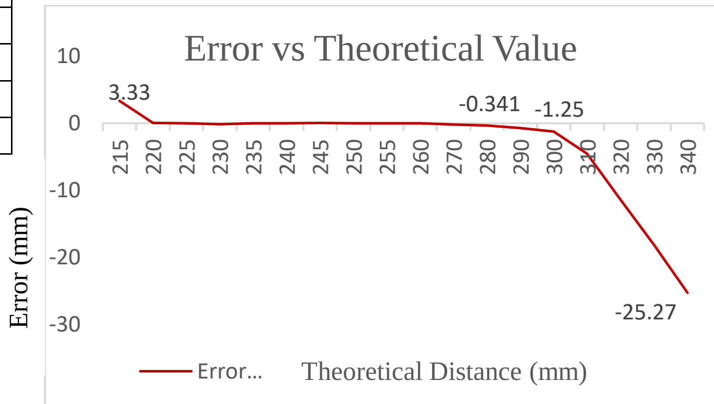

Figure 10: Simulated Error vs Theoretical Distance

V. CONCLUSION

Based on the laser triangulation ranging simulation project conducted in Zemax OpticStudio, the most effective setup for accurate measurements was achieved using a mirror-type target and capturing scattered light through the lens within the range of 220 mm to 300 mm. When the test object was positioned farther away, a change in distance perpendicular to the ray resulted in a relatively small angle change for the light hitting the detector. It was noted that deviations increased when the scattered laser beam through the lens was out of focus on the image plane. Ensuring precise calculations of the centroid of the spot formed by the reflected beam on the detector was crucial for accurate distance measurements, and the distance measurement range could be adjusted based on the configuration.

VI. ACKNOWLEDGMENT

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[2] 200Hoa G. Nguyen, Michael R. Blackburn, A simple approach for Range Finding via Laser Triangulation, Jan. 1995