Laser Distance Measuring and Image Calibration for Robot Walking Using Mean Shift Algorithm

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***Abstract*—In this research, we have measured the physical distance between the robot and its surroundings using a laser distance measuring device that we have developed, designed controllers for, and tested operationally. We will record the distance using the USB camera and integrate the LDMSB board into the laser distance measuring design. We will fasten these two parts to the robot's underside. Developing the experiment in LabVIEW is the next step. The mean shift method enables us to move the robot's position by relocating a laser-based distance measurement device and capturing a photo at that location. In order to record that area, we will perform a perspective camera calibration. This will allow us to set up or adjust the camera system's value, or provide visual assistance to ensure that the viewing angle is precisely aligned with the intended view angle. The laser measurement results ranged from one to fifteen meters. A device that makes use of lasers has 99.25% accuracy. Every calibration location throughout the 10 has a precision rating of 94.03%.**

Keywords—Laser distance; image calibration; mean shift algorithm; LabVIEW

I. Introduction

The mobile robot education process at Rajamangala University of Technology Lanna's Faculty of Engineering, Electronic Engineering, and Automation Control Systems Program, Chiang Mai Province, includes measuring a robot's walking distance. This field holds great promise for the development of precise and long-range robots. However, a variety of issues, including measurement error, sensor data rectification, various settings, and adaptability, make determining a robot's walking distance difficult.

There is more to using a laser to measure distance than simply speed and ease. Nonetheless, the technique is very accurate and widespread. Consequently, it might be a useful tool in many facets of everyday life. This covers a wide range of industries, including commercial and medical applications, engineering, and building construction. The advantage of lasers is 1) High degree of accuracy: The laser exhibits a high degree of accuracy in measuring distance and is capable of precisely transmitting laser signals to the designated measurement location. Laser sensors provide precise data in a variety of situations. This makes it appropriate for uses where a high degree of precision is required. The laser can quickly calculate the separation between the two locations. The laser's quick light transmission allows for instant viewing of the experiment findings. 2) This makes it an ideal choice for tasks that require quick thinking, such as data storage and production management. 3) It has the ability to adapt to challenging situations. Lasers are used in harsh environments like cold and dusty ones because they can withstand harsh conditions. 4) Versatility in Application Lasers possess a wide range of potential applications. It has a wide range of potential uses, including in commerce and research, as well as in the field of measuring distances in medicine.

To conduct this study investigation, we set up a laser distance measuring and imaging device. Writing and testing control software in LabVIEW is a crucial step in tracking the robot's location and determining the distance to the objective. One of the main purposes of lasers in robots is to detect distance accurately [1]. This enables robots to carry out their work with the same diligence and precision as people. Robots can gain a better understanding of their environment and adjust their behavior by employing laser distance measurement to gather information about it and adjust their behavior. The use of lasers in robotics creates new opportunities for the creation of innovative and useful robots, suitable for various human endeavors such as navigation, obstacle avoidance, and precision placement tasks. These robots have applications in all fields of human endeavor. These robots can support industrial applications, conduct surveys and research, or serve both purposes [2].

Most people agree that one of the most powerful tools for software development and engineering is the LabVIEW application [3-4]. A graphical programming environment called LabVIEW uses representations of the signal type [5]. LabVIEW allows users to create programs by simply dragging and dropping components into block diagrams. This simplifies operations and creates an easy-to-use interface. Furthermore, because it can interface with a wide range of devices, LabVIEW may be used in software applications that require automation in the domains of measuring, controlling, and testing. There are several uses for LabVIEW software, some of which include industrial, scientific, and engineering research and development. Because of its intuitive design, LabVIEW is a tool that allows users to create and modify programs to any degree of customization without facing any limitations. This study uses the board to compute the robot's distance. Its hardware is the Laser Distance Measuring Signal Board (LDMSB). We use the mean shift approach to track objects [6].

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The difficulties in object tracking include many types of occlusions, including occlusion by background objects, other target objects, or self-occlusion (produced by components of the object itself). The tracking procedure becomes more difficult due to these partial or complete occlusions. Significant difficulties are also presented by the target object's changing appearance, particularly in surveillance applications. Inconsistent illumination over wide regions or rotations of the object along axes other than the imaging system's optical axis often cause these alterations. Improving the accuracy and resilience of object tracking systems requires addressing these problems.

This research report explains the camera calibration process and the creation of a laser distance measurement device. For this, we wrote driver software and tested it with LabVIEW. This crucial step enables us to calibrate the camera before recording the robot's location using the Mean Shift method, a crucial tool for precise and thorough distance measurement. Laser distance measurement may benefit robots that can detect and adjust their behavior in different situations. We have organized this job to involve traversing a space, avoiding obstacles, or performing tasks that require precise placement. Section III describes the study technique, while Section II reviews some relevant prior research. Section V brings the article to a close. Section IV presents and examines the findings.

II. Literature Review

The various methods and designs discussed in these books simplify the calculation of the distance between two lasers. A low-tech laser sensor using triangulation achieves outstanding spatial resolution [7]. Another approach suggests using a heterodyne interferometer, renowned for its high accuracy, for absolute distance measurement. A new method for laser distance measurement employs least squares and triangular-wave amplitude modulation to enhance the signal-to-noise ratio [8]. Additionally, a unique distance-measuring device utilizing microfabricated scanning micromirrors demonstrates various configurations for distance estimation [9]. Overall, these methods and technologies offer a wide range of laser distance measurement techniques that can be adapted to meet different application needs and accuracy standards [10].

These studies provide new perspectives on robotic walking using laser distance measuring. One study addresses the calibration of laser range finders for legged robots to achieve the accuracy needed for terrain mapping and foothold selection [11]. Another explores integrating inertial measurement units (IMUs) with laser scanners for real-time, safe calculation of minimal distances between humans and robots. Research also highlights the utility of 3D laser distance measurements for accurate pedestrian tracking, particularly in unstructured environments with occlusions and sensor noise [12]. Additionally, a mobile robot equipped with a laser range finder combines a walking motion model with the geometric characteristics of human legs to ensure precise tracking and a better understanding of human gait [13]. Collectively, these studies demonstrate the advantages and potential of laser distance measurement in walking robot applications [14].

The essays in this collection offer valuable insights into the use of LabVIEW for laser distance measuring. One study emphasizes the importance of LabVIEW in evaluating the reliability of femtosecond laser light sources for distance measurements [15]. Another explains a LabVIEW-based software architecture for assessing laser divergence angles [16]. A further method demonstrates the utility of LabVIEW in a laser beam profile scanning interface. Additionally, a high-precision optical distance meter based on a mode-locked femtosecond laser is presented, capable of measuring distances up to 240 meters with a detection accuracy of 0.01 meters or better [17]. Together, these papers highlight the effective and versatile application of LabVIEW in various laser distance measuring components [18].

III. Methodology

The main program of the suggested algorithm is shown in Fig. 1.

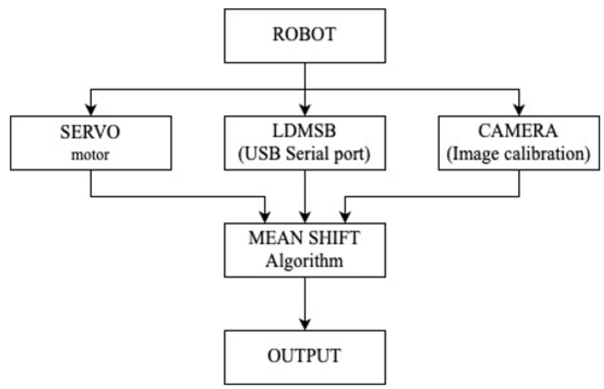


Fig. 1. Distance-measuring walking laser robot block diagram.

Fig. 1 illustrates the process for calculating the robot's travel distance. By following the instructions, one may accomplish the many stages involved. The LDMSB board is situated precisely adjacent to the wheel section at the bottom of the moving robot. The LDMSB board is ready to perform its function as a distance measuring device. The technique then moves on to attaching two USB cameras to the mobile robot. We will proceed to the next step. Establish a serial port protocol connection between the LDMSB board and the USB camera. We test the robot's distance calculation and image calibration skills using LabVIEW's Mean Shift approach. The purpose of these tests is to verify the accuracy of the results.

A. LDMSB

Laser Distance Measuring Signal Board (LDMSB) is a board used in the design to measure distance with laser in this research article. Fig. 2 shows the various components of the LDMSB board. When a lens transmits laser light, it is called a laser transmitting lens. Similarly, a laser receiving lens is a laser receiving lens. Holes or indentations drilled into any material or component to install or secure an object, such as an electronic board or component, so that it may be installed or connected to other apparatuses or buildings, are known as mounting holes. An information processing and perception system or technology is referred to as vision. Pin locations, for instance, are used to link pins in circuits or structures when DC power is needed to power them. Utilizing sensors is necessary for tasks pertaining to various systems' eyesight and perception. A USB

(Universal Serial Bus) system connection establishes the circuit connection between the LDMSB board and the USB interface. This implies that the system will automatically detect USB-powered devices when they are inserted into a port. It is perfect for connecting devices that need full-duplex communication since it can transmit both transmission (TX) and reception (RX).

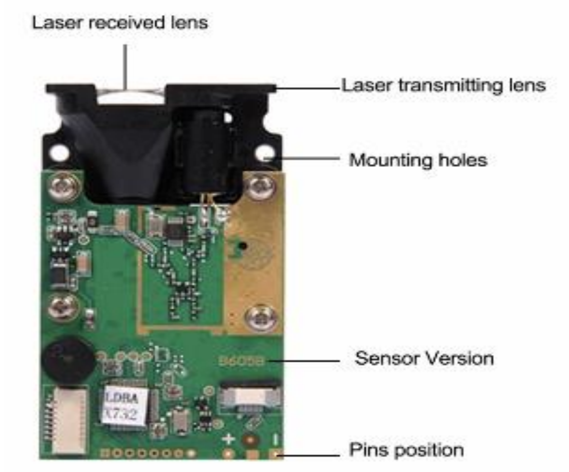


Fig. 2. Components of the LDMSB board.

The goal is to create a device that will be utilized for evaluating the functionality of a laser distance measurement system after identifying the target position in order to measure the Z-axis distance that has to be measured and gathering picture data according to the position. In order to do this, a servo motor that can be adjusted in one-degree increments will be used to rotate the X and Y axes. The desired appearance of the gadget as per its design is seen in Fig. 3.

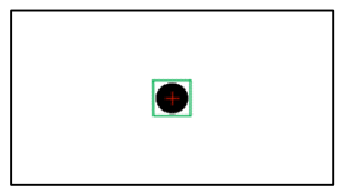
Fig. 3. Laser distance measuring functional testing equipment.

After that, it may be used with mobile robots, where the USB camera and LDMSB board are mounted in the bottom of the robot. The robot can use the laser to measure and record distances thanks to the placement of these parts.

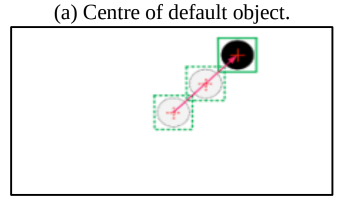
B. Mean Shift Algorithm

The working principle of the object tracking algorithm is based on a methodology akin to template search [19]. The process of matching object photos to templates involves searching for templates that enable things to be located inside a user-defined area or throughout the entire image. This technique, similar to object tracking, looks for an object template in an area that either anticipates or is close to the item's position from the previous frame. This reduces false searches and boosts processing efficiency, making it ideal for labor-intensive activities. The article monitors objects by approximating their position and appearance using the mean shift [20]. The kernel method estimates the mode of the probability function to assess the condition of an item. The rival object's position is estimated using target object motion data from the previous frame. Comparison of the appearance characteristic model of an object with the previous frames to increase the likelihood of its location Assign a new competitive position to the outcome. Increase the frequency of the position estimate until either the user-defined repetition criterion is met or the competing position converges to the final value.

Next, the model will be updated for the following frame when the target object's location has been calculated. After several iterations, the target item's position is estimated using the initial frame. The middle of the rectangle determines the round position of the competing item. In Fig. 4, the arrows in (a) display the mean shift vector, which indicates the amount that the center of mass of the target object changed from the prior frame. The center of the moving item as it gets closer to the target is the starting object (b).



(a) Centre of default object.



(b) Point of movement toward objective.

Fig. 4. Mean shift object tracking.

During tracking, the target object contour model that tracks mean shift fixes the target object forms. The image's target object's center of mass is shown by the telematic model's parameters [21]. The center of mass's pixel location is all that is needed to monitor mean-shift objects in the model. When the subject in the next frame travels slowly, this works. There are two different types of objects tracking algorithms that employ the Mean Shift technique: target object tracking and target object modelling. These two categories represent various aspects of the application.

The mean shift update equation for tracking an object at position x can be formulated as follows:

- Initial Position of Object: Start with an initial position $^{(0)}$ of the object in the current frame.

- Kernel Density Estimation: The pixel weights are assigned using a kernel function K, usually according to the pixels' distance from the center. Although other kernels, such as Gaussian, may also be employed, the Epanechnikov kernel is a popular option. The weighted mean position is determined with the use of the kernel $K(x)$, which concentrates on pixels nearer the center.

- Mean Shift Vector: For each iteration t, vector m(x(t)) is computed to shift towards the mean of the region with the highest density from Eq. (1).

$$m(x^{(t)}) = \frac{\sum_{i=1}^{n} x_i\, K(x_i - x^{(t)})}{\sum_{i=1}^{n} K(x_i - x^{(t)})} \tag{1}$$

Where x_i represents the positions of pixels within a region around the current location and $K(x_i - x^{(t)})$ gives the weight based on the distance from $x^{(t)}$

Position Update: The object's new position is updated by shifting to x(t+1) from Eq. (2).

$$x^{(t+1)} = x^{(t)} + m(x^{(t)}) \tag{2}$$

Convergence: Repeat the iteration until the mean shift vector $m(x^{(t)})$ is sufficiently small (below a threshold), indicating that the peak (mode) has been found.

As illustrated in Fig. 5, it regulates the blending parameter and the maximum percentage of rotational size and shape changes.

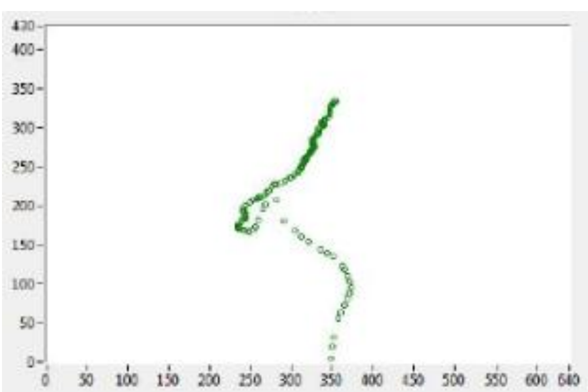


Fig. 5. Adjusts mixing settings and maximum rotation size and shape.

C. LabVIEW

One object tracking technique that is accessible in LabVIEW 2019 is the Mean Shift algorithm, which utilises both the NI Vision Assistant and the NI Vision Library feature. This approach is perfect for monitoring a single target object and is made to work with LabVIEW 2019 [22-23].

This technique replicates the distance of a laser measurement using LabVIEW programming by employing the mean shift method to move an object based on the mouse's position. Fig. 6 displays the accessible front-panel interface of the LabVIEW program. The first stage in improving the accuracy of devices or systems, such as offset, sensitivity, or scale factor, is to calibrate the x- and y-axes. As a result, you can trust that the system will precisely determine an object's position or movement. The next step is to employ a method to figure out how big the object (PEN) is in order to depict the laser point and the object's movement. The final step of the procedure entails analyzing the program to determine if the coordinates of x and y (red objects) on the Axis Mouse are following the mean shift approach as they move along the mouse frame. For the application, LabVIEW has produced a block diagram (graphic programming). We will be able to move more effectively with the help of a servo motor if we move at an angle along the x and y axes. We will correctly apply the mean shift algorithm.

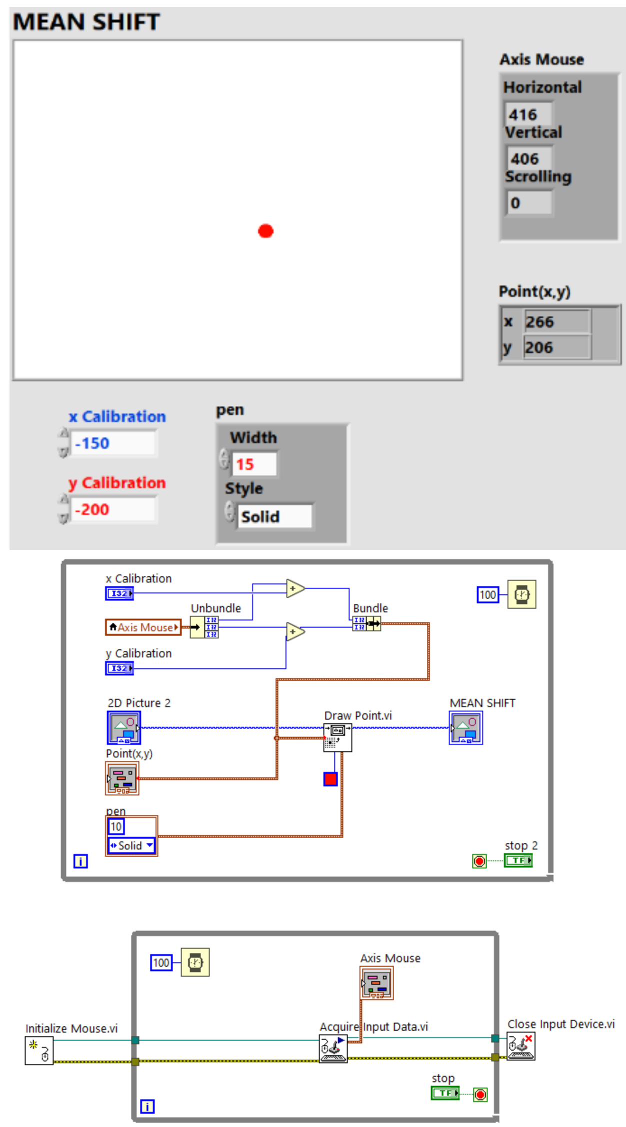


Fig. 6. LabVIEW front panel and block diagram via mean shift algorithm.

We have developed a laser distance measurement design and captured pictures of the distances for the robot's use during its travels. To shoot a picture, one must perform a procedure known as perspective calibration. Adjusting or changing the camera system or imaging equipment settings is necessary to ensure that the picture's angle is true to the desired perspective or the proper theoretical point of view [24], as Fig. 8 illustrates.

The calibration perspective achieves several objectives. 1) Assist in ensuring the accuracy of the camera system or picture equipment according to visual theory and metrics; 2) guarantee that the results are theoretically sound and consistent with the visual model. It also helps to minimize deflection errors, reflection, and visual distortion. 3) Measure or closely inspect photos. Gathering both intrinsic and extrinsic camera system characteristics is necessary to ensure that the produced picture is accurate and does not tilt or distort due to an incorrect angle, and also to assist in optimizing the camera or imaging equipment. Then, using LabVIEW, we created a front-panel user interface for capturing photos and measuring distances, as shown in Fig. 7.

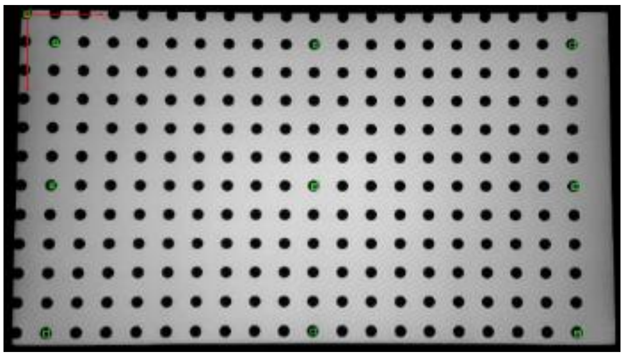


Fig. 7. Perspective 10-point calibration.

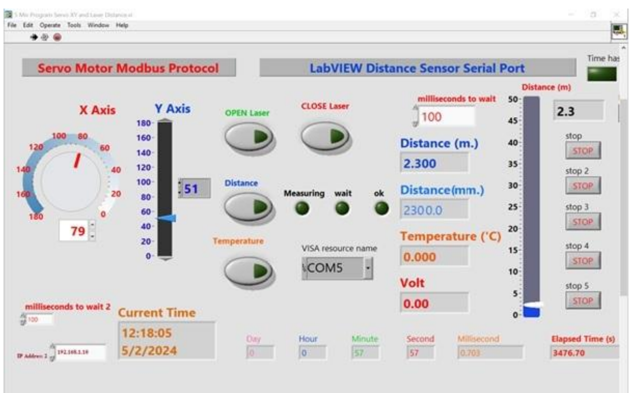


Fig. 8. Images and laser distances LabVIEW front panel.

The user interface seen in Fig. 8 was created through programming. The robot design attaches the LDMSB board and a USB camera to its bottom, enabling the software to perform its planned tasks. The software allows you to turn the laser on and off at will. The software allows you to measure distances in millimeters and meters, as well as save photos. You can monitor the temperature and voltage of the laser.

This method locates a controlled circular point in motion with a radius of 20 millimeters, using a source image at the X and Y axes. The experiment used an LDMSB board with a laser to measure distance. Additionally, we connected a USB camera to the distance measurement board to capture pictures. We then projected the picture onto a 100-inch display for the exercise. We must create an angle to shift the position from point 6 (P6) to point 7 (P7). Fig. 8 illustrates the process of mean shift image tracking and laser distance measurement.

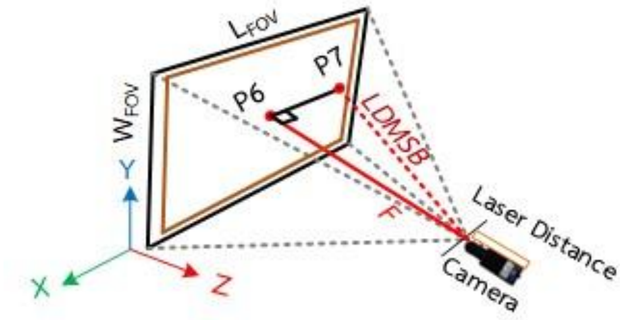


Fig. 9. The laser uses a mean shift from position 6 (P6) to point 7 (P7) to track pictures and calculate distance.

In Fig. 9, this case involves the transfer of the post. In order to calculate the distance caused by P6 to P7, use the formula $c = \sqrt{a^2 + b^2}$, where *a* is the distance between the camera and laser device and the monitor, or point P6, *b* is the distance between the points P6 and P7 along the X axis, and *c* is the distance between the camera and laser device and the monitor, or point P7, that results from comparing the calculated value with the actual value that was measured by the laser. When we speak to the camera's field of vision (*FOV*), we mean the range of pictures it can record. We refer to the scope the camera records as *FOV*, the scope it records by width as W_{LOV}, and the scope it records by length as L_{FOV}. The formula $FOV = W_{LOV} \, x \, L_{FOV}$ may be used to get the value, where *FOV* stands for the scope that the camera records.

IV. Results and Discussion

We separate the experimental findings from the laser odometer and the picture recording from the mean shift algorithm into three distinct design experiment components, each of which consists of the specific elements listed below:

A. Laser Distance Testing

We must measure the separation between two spots using our own laser technology. We designed these stages to evaluate the accuracy of the laser apparatus. The laser distance determines the example's result, as Table I illustrates.

The data presented shows the measurements of distances in meters, with five repetitions for each distance. The average values for each distance are very close to the expected values, indicating a high level of accuracy in the measurements. The percentage error remains minimal across all distances, with the largest error observed at the 0.1-meter distance, which has a 6.67% error. As the distance increases, the percentage error decreases, reaching 0% for several measurements, including 1 meter, 2 meters, 3 meters, and 10 meters, among others. This suggests that the measurement process is highly reliable, particularly at greater distances, where the error becomes negligible. Overall, the data indicates that the measurement system or method used is highly precise and consistent across a wide range of distances. Table I displays the results of five separate experiments conducted at distances ranging from 10 cm (0.10 m) to 50 m, along with the average of each test. 99.25% accuracy is the average for measuring distance.

TABLE I. LASER DISTANCE TESTING

Distance (meters)	#1	#2	#3	#4	#5	%Error
0.1	0.10	0.10	0.10	0.12	0.12	6.67
0.2	0.20	0.21	0.21	0.21	0.21	0.33
0.3	0.30	0.30	0.30	0.30	0.30	0.11
0.4	0.40	0.40	0.40	0.40	0.40	0.00
0.5	0.50	0.51	0.51	0.51	0.50	1.00
1	1.00	1.00	1.00	1.00	1.00	0.00
2	2.00	2.00	2.00	2.00	2.00	0.00
3	3.00	3.00	3.00	3.00	3.00	0.00
4	4.00	4.00	4.00	4.00	4.00	0.00
5	5.01	5.00	5.02	5.00	5.00	0.10
10	10.00	10.00	10.00	10.00	10.00	0.00
20	20.00	20.00	20.00	20.01	20.00	0.01
30	30.00	30.00	30.00	30.00	30.00	0.00
40	40.00	40.00	40.03	40.01	40.01	0.02
50	50.00	50.00	50.00	50.00	50.00	0.00

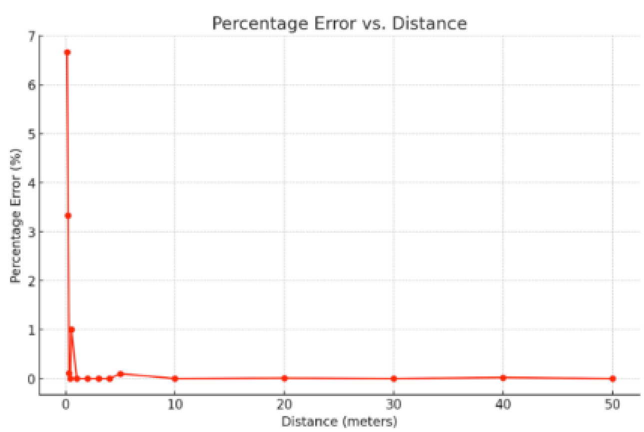


Fig. 10. Percentage error decreases with distance.

In Fig. 10, According to the line chart, the percentage error increases initially at shorter distances but then levels out and stabilizes as the distance grows. This implies that when one moves farther away from the subject, especially beyond 0.4 meters, where the error is almost nil, the measurements get more precise.

B. *Image Calibration*

While the robot is moving, it is a good idea to take images and measure the distances. The following list displays the results of the 10-point perspective (CP) calibration. The camera or other photographic equipment must have ten calibration points to ensure that the final image is accurate and suitable for the intended angle of view. You can see these calibration points in Fig. 11.

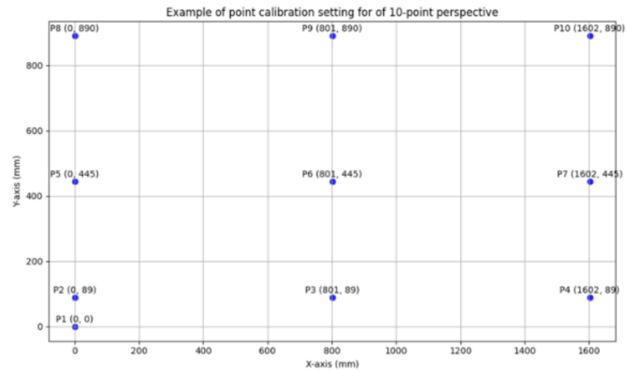


Fig. 11. The 10-point perspective's calibration results.

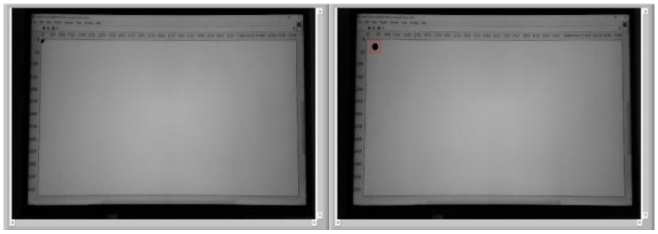
We examined the calibration using a USB camera with a pixel resolution of 1280x720. An LED screen measuring 100 inches in size displays the image. Ten points, each with a value on both the X and Y axes, make up the calibration.

TABLE II. RESULTS OF THE 10-POINT PERSPECTIVE CALIBRATION

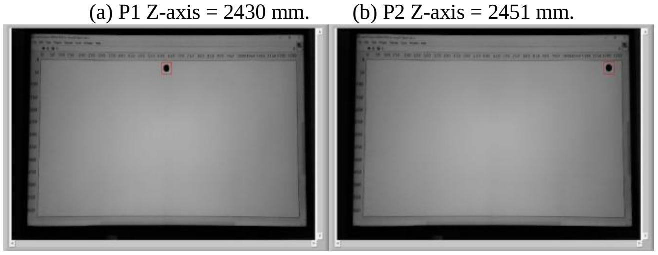
CP (10 POINT)	X-axis (mm.)	Y-axis (mm.)	Z-axis (mm.)
P1	0.00	0.00	2,430.00
P2	0.15	84.93	2,451.00
P3	800.85	89.16	2,328.00
P4	1,599.78	85.78	2,451.00
P5	1.87	443.34	2,430.00
P6	798.93	443.89	2,300.00
P7	1,598.77	442.54	2,426.00
P8	0.98	800.56	2,442.00
P9	799.53	797.4	2,324.00
P10	1,601.58	800.82	2,444.00

Table II demonstrates that both the distance measurement value from the laser and the number of photos taken there are relevant. Z represents the value that the laser determined. The X and Y axes represent the point's value. We will conduct the experiment in 10 distinct locations for this study.

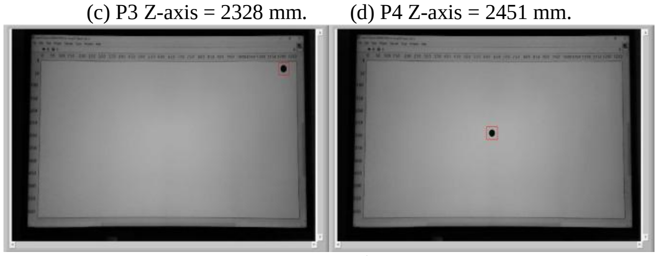
After measuring the distance, we used the mean shift technique to track the locations of all 10 dots in the picture. At last, this picture was produced. We calculate the distance between the point of the laser measuring and recording device and the projected screen. A distance of 2300 mm separates the two locations (P6). The Z-axis measurements provided for points P1 through P10 reveal varying levels of displacement, with values ranging from 2300 mm to 2451 mm. Notably, points P2 and P4 both reach the highest Z-axis value of 2451 mm, while point P6 records the lowest at 2300 mm. The data suggests that while some points, such as P1, P5, and P7, remain close to 2430 mm, others like P3, P9, and P6 show significant deviations. This variation in Z-axis measurements illustrates the spatial differences captured during the tracking process, as depicted in Fig. 12, which shows the outcomes of the tracking mean shift algorithm's picture recording.



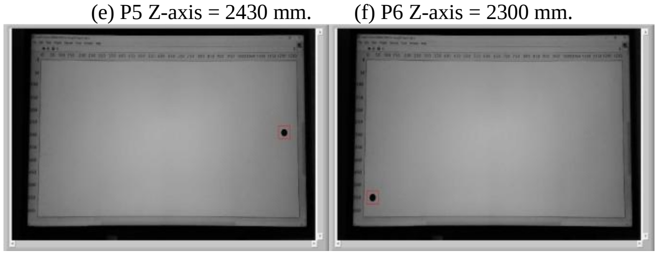
(a) P1 Z-axis = 2430 mm. (b) P2 Z-axis = 2451 mm.



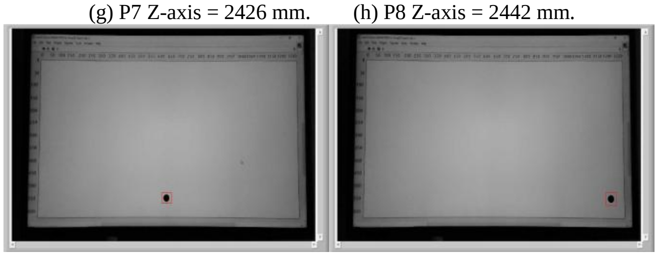
(c) P3 Z-axis = 2328 mm. (d) P4 Z-axis = 2451 mm.



(e) P5 Z-axis = 2430 mm. (f) P6 Z-axis = 2300 mm.



(g) P7 Z-axis = 2426 mm. (h) P8 Z-axis = 2442 mm.



(i) P9 Z-axis = 2324 mm. (j) P10 Z-axis = 2444 mm.

Fig. 12. Example of the tracking mean shift algorithm's picture recording outcomes, such as P6 Z-axis = 2300 mm.

TABLE III. COMPARING LASER MEASUREMENTS WITH CALCULATED VALUES

CP	*a*	*b*	$c = \sqrt{a^2 + b^2}$	%Error
P1	0	2,430	2,430.00	0 .00
P2	0	2,451	2,451.00	0.00
P3	801	2,328	2,461.95	5.44
P4	1602	2,451	2,928.11	16.29
P5	0	2,430	2,430.00	0.00
P6	801	2,300	2,435.49	5.56
P7	1602	2,426	2,907.21	16.55
P8	0	2,442	2,442.00	0.00
P9	801	2,324	2,458.17	5.46
P10	1602	2,444	2,922.25	16.37

A comparison between the values produced by the computations and the values measured by the laser instrument is shown in Table III. The comparison's outcomes are shown. The average accuracy percentage of the numbers derived from the calculations was 94.03%.

The data presented highlights a series of measurements (b) associated with various CP points, alongside calculated values (c) and the corresponding %Error. A few notable observations emerge from the analysis, as shown in Figure 13.

- Consistency in Measurements: For several data points, such as P1, P2, P5, and P8, the values of b and c are identical, resulting in zero error. This suggests that these measurements are precise and match the expected values perfectly.
- Significant Deviations: Other points, particularly P3, P4, P7, and P10, show notable deviations between the b values and the calculated c values. The error percentages at these points range from 5.44% to 16.55%, indicating considerable discrepancies. This variation implies the possibility of underlying measurement process issues or the presence of conditions or anomalies not adequately represented by the expected values.
- Trend Analysis: The plot of b values against CP points reveals that while most values are relatively stable, certain points exhibit substantial variation. For instance, P4 and P7 show the largest errors, with discrepancies of 16.29% and 16.55%, respectively. We may attribute these higher error rates to measurement inaccuracies, external factors, or inherent variability in the system under study.
- Implications and Recommendations: The presence of large errors in specific measurements warrants further investigation. It would be beneficial to review the data collection methodology and consider any external influences that could impact accuracy. Additionally, analyzing whether these errors are systematic or random could provide insights into improving measurement precision. Understanding and addressing these discrepancies will enhance the reliability of the results and ensure more accurate conclusions in future analyses.

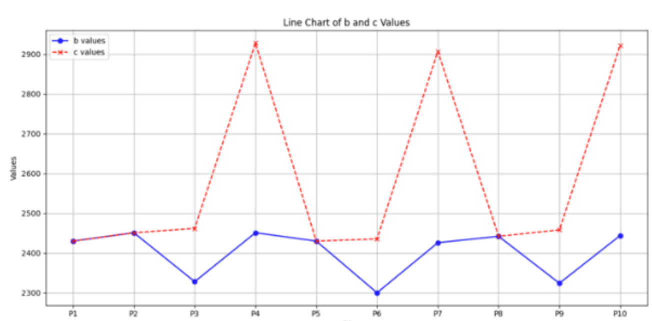


Fig. 13. A comparison between calculated values and laser measurements.

V. CONCLUSION

We use the LDMSB board to build the laser distance measuring system for the experiment. We program the device using LabVIEW and record the distance using the USB camera. Before moving on to the next phase, we use an algorithm to modify the distance, measure it with a laser, and then take a picture there. To make sure the picture is exactly at the specified distance, we calibrate the camera using ten different perspective points. The findings are suitable for use with mobile robots due to their high accuracy in both measurement and recording.

In order to verify the laser distance measurement against theoretical estimations, we carried out ten distinct calibration and distance measuring experiments. The results indicate that over 15% of the points were incorrect. P4, P7, and P10 are located at the right angle of the projected image. The device's perpendicular base warps when the servo motor vibrates, projecting the picture from the initial point and rotating it to succeeding places. The device's use of a coordinating system is mostly the responsibility of the servo motor.

The advancetage of Mean Shift method is effective for tracking deformable objects that change shape, size, or appearance, including rotations on non-optical axes or articulated motions. However, a limitation arises when using a servo motor for camera rotation, as insufficient motor speed can cause the target to slip out of the tracking frame, compromising the process.

Future work in the development of military robots should enhance laser-based targeting precision, adaptability, and efficiency. Advances in sensor fusion, low-power lasers, and energy-efficient designs could improve target detection and extend operational duration. Refining autonomous decision-making to address ethical concerns and developing collaborative robot networks for real-time coordination can significantly improve battlefield strategies.

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