INVESTIGATION OF THE RADIOMETRIC BEHAVIOUR OF A LOW-COST AUTOMOTIVE LIDAR SENSOR

Z. Zhang, Z. Zeng, J. Boehm*

Department of Civil, Environmental and Geomatic Engineering, University College London, Gower Street, London, WC1E 6BT UK – {zian.zhang.21, zichao.zeng.21, j.boehm}@ucl.ac.uk

KEY WORDS: Terrestrial LiDAR, Radiometry, Low-Cost.

ABSTRACT:

Terrestrial LiDAR is an established method for 3D data acquisition in close-range applications. A new category of low-cost LiDAR sensors for autonomous driving has become available with similar specifications. However, these new sensors lack the guarantee of survey-grade performance. Initial experiments have broadly confirmed the specification of one such low-cost sensor but have also raised issues with the radiometric behaviour. This study investigates through practical experiments how the intensity information of the Livox-Mid40 laser scanner is influenced by time, reflectance, distance and angle of incidence. The quantitative analysis of the experiments shows an expected relationship between surface reflectance and recorded intensity. However, the result indicate that intensity can significantly influence the distance measurement at very close ranges.

1. INTRODUCTION

Terrestrial Light Detection and Ranging (LiDAR), or terrestrial laser scanning, is an established method for acquiring three-dimensional (3D) data (Vosselman and Maas, 2010) for more than two decades. Its applications span various fields, such as topographic applications, construction monitoring, asset management and heritage recording (Backes et al., 2014). Several generations of survey-grade instruments were commercially developed and academically studied. With the recent emergence of autonomous driving a new category of low-cost LiDAR sensors has become available (Ortiz Arteaga et al., 2019). The nominal specifications of these sensors are often similar to terrestrial LiDAR sensors. However much less is known about their performance characteristics.

LiDAR provides not only geometric information through point cloud data but also offers additional insights into the reflectance behaviour of the scanned objects via laser intensity returns. Intensity data enriches point cloud data by providing radiometric information perfectly aligned with the geometric information. This is valuable for scene classification and analysis (Scaioni et al., 2018). Consequently, intensity data has been used for a wide array of applications for example building material recognition (Wehr et al., 2006), marker-less registration (Böhm and Becker, 2007) and stochastic modelling (Wujanz et al., 2018).

The intensity recorded by an instrument is the relative strengths of the reflected laser at a particular wavelength of laser light (Vosselman and Maas, 2010), rather than the absolute reflectance of the object. Such relative intensities can be corrected to absolute intensities (Sanchiz-Viel et al., 2021). The correction of the intensity requires an in-depth study of the equipment and the availability of a sufficient number of scanned targets with accurate reflectivity.

There are several parameters that can affect the measured strength and for ease of description, this study uses the classification of Kashani et al. (2015). The first category is target surface characteristics, which include reflectance and roughness. Reflectance is influenced by the object's composition, colour, and material absorbance, while rough surfaces cause diffuse reflection and smooth surfaces result in specular reflection (Sanchiz-Viel et al., 2021, Godin et al., 2001). Lambertian reflectors have uniform reflectance in all directions, while surfaces with specular reflection can lead to detector saturation (Sanchiz-Viel et al., 2021, Kashani et al., 2015). The second category is data acquisition geometry characteristics, specifically the angle of incidence and distance. The distance may cause light attenuation, but its effect is more pronounced in aerial laser scanning than in terrestrial laser scanning (Pfeifer et al., 2007, Kashani et al., 2015). Other parameters, such as the presence of multiple targets in the laser path, can also impact intensity. The scanning instrument itself can introduce gain or shrinkage in the intensity data during post-processing, making it challenging to investigate instrument-specific effects (Kashani et al., 2015, Kaasalainen et al., 2011). Lastly, environmental factors like atmospheric attenuation, humidity, and temperature can influence intensity measurements, but their significance varies depending on the experiment conditions and the specific instrument used (Höfle and Pfeifer, 2007, Kaasalainen et al., 2009). The time required for the scanner to reach thermal equilibrium is also an important consideration for accurate intensity measurements (Sanchiz-Viel et al., 2021, Errington and Daku, 2017).

The effects of the categories mentioned above have been intensely studied for survey-grade scanners (Boehler et al., 2003, Voegtle et al., 2008, Hartmann et al., 2023). Modern commercially available terrestrial LiDAR instruments are individually calibrated and often compensate for these effects. However, the aforementioned new class of low-cost automotive scanners is much less investigated. Initial studies have shown issues with the recorded intensities (Ortiz Arteaga et al., 2019). This study therefore provides an investigating the radiometric behaviour of the Livox Mid-40 LiDAR sensor, a low-cost automotive LiDAR. This study quantifies the effect on intensity of different parameters with practical experiments. The parameters include distance, angle, time and reflectivity. The influence of intensity on range measurement will also be quantified.

* Corresponding author

2. METHODOLOGY

2.1 Equipment

2.1.1 Low-cost LiDAR In this study, the experimental equipment will use the Livox Mid-40, a next-generation LiDAR system introduced by Livox in 2019 shown in Figure 1. Priced at $599, it offers a significantly lower cost compared to most LiDAR systems used in surveying. The unique scanning pattern of the Livox Mid-40 is attributed to the use of Risley prisms instead of conventional reflectors in the scanner (Ortiz Arteaga et al., 2019, Brazeal et al., 2021). By internally setting the rotation rate and direction, the two wedge-shaped prisms generate different scanning patterns (Marshall, 1999). The manufacturer's manual states that the point cloud density within the field of view (FOV) increases over time, with a higher density in the middle area (Livox, 2019).

Figure 1. The Livox Mid-40 LiDAR sensor.

Two studies (Ortiz Arteaga et al., 2019, Glennie and Hartzell, 2020) have been conducted to assess the measurement accuracy of the Livox Mid-40, and the angular and distance errors are generally consistent with the manufacturer's accuracy specifications, with a range of 20 mm and an angular error of less than 0.1°. However, one study has reported the presence of ripple noise artifacts that affected angle and distance measurements (Ortiz Arteaga et al., 2019), while other studies have not observed this phenomenon (Glennie and Hartzell, 2020).

Regarding intensity measurements, one study has suggested that the Livox Mid-40 had difficulty distinguishing between reflections from materials with similar colour but different material (Ortiz Arteaga et al., 2019). This finding raises questions about the suitability of the target materials used in the experiment, such as reflectance and roughness, at the Livox Mid-40's operating wavelengths (905 nm). The study also mentions that intensity changes over time and influences the distance measurement during the experiment, with lighter targets appearing closer and darker targets farther away.

2.1.2 Scanning target Ideally a perfect Lambertian reflector with known absolute reflectivity, such as Spectralon coated material, is used for experiments on radiometry (Sanchiz-Viel et al., 2021). However, it has prohibitively high cost for this study and thus a photographic reference target is used.

The scanning target used in this experiment is a ColorChecker 3-Step Grayscale produced by Calibrite (Figure 2). This target consists of three areas of different colours: black, white, and 18% gray. It is specifically designed to maintain colour stability

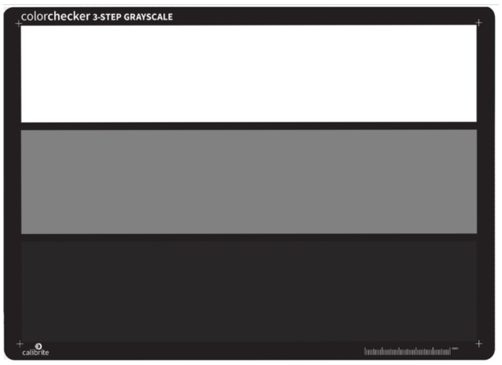


Figure 2. ColorChecker 3-Step Grayscale produced by Calibrite.

in various lighting conditions and is commonly used for photographic calibration (Varghese et al., 2014). However, the experiment conducted in (Crowther, 2018) revealed that products from the same manufacturer do not exhibit consistent reflectance across different wavelengths, although they are expected to perform better than ordinary materials like printed paper.

2.2 Experiments

The experiments are conducted in a controlled indoor laboratory. To ensure the stability of the Livox Mid-40 during the experiments and minimize errors caused by uncertain angles, the scanner is securely fixed on a tripod. A level is used to ensure its horizontal alignment. The scanner is connected to a converter box provided by the manufacturer for testing, using its dedicated cable.

The experiments are carried out to investigate the influence of four parameters: Time, Reflectance, Distance, and Angle of Incidence.

2.2.1 Time The target used in the experiment is affixed to a wall at a horizontal distance of approximately 4.6 meters from the LiDAR system. The front face of the laser scanner is positioned parallel to the wall. The experiment investigates the impact the instrument warming up has on the intensity measurements. Thus, the variation of intensity over time is recorded. Intensity recordings are taken at 1 minute, 5 minutes, 15 minutes, and 30 minutes after the instrument is powered on. The recording of the point cloud stream starts immediately. We choose a maximum duration of 30 minutes for the experiment because if a steady state for the intensity measurements cannot been reached within this timeframe, we would not consider the sensor to be suitable for intensity measurements.

2.2.2 Reflectance In this and subsequent experiments, a warm-up period of at least 30 minutes is employed for the laser scanner to mitigate the impact of temperature on its performance. In this particular experiment, the target remains affixed to the wall, but it was re-positioned closer to the centre of the LiDAR's FOV. The point cloud data is then recorded from this new position. Two additional retro-reflective targets with different colours are added to the scene close to the centre of the FOV. These targets are specifically included to assess the sensor's performance on retro-reflective material.

2.2.3 Distance In this experiment, the scanning target is no longer affixed to a wall but instead attach to a movable rectangular object. This allow for measurements to be taken at different distances. The target is still maintained perpendicular to the ground, as it is when fix to the wall. Moreover, the target remains positioned at the centre of the LiDAR's FOV.

To ensure accurate distance measurements, a tape measure is used to mark the distances in front of the scanner where the target is placed. The chosen measurement distances are 1 m, 2 m, 3 m, 4 m, and 5 m. The selection of 1 m as the lower limit is based on it being the officially stated minimum detection distance. Due to space limitations in the indoor testing environment, this experiment primarily focusses on examining the effects of shorter distances on intensity measurements. Point cloud data is recorded at each distance.

The outcomes of this experiment will also be analysed to determine if there is any correlation between intensity data and range measurements.

2.2.4 Angle of incidence In the angle of incidence experiments, the horizontal distance between the target and the laser scanning instrument is approximately 3.7 m. Similar to previous experiments, the target is positioned at the centre of the LiDAR's FOV. The selection of this distance is influenced by the presence of a parallel reference line on the ground at the same distance. Aligning the target along this reference line enable more precise angle measurements.

The point cloud data is recorded at three distinct angles of incidence: 0 degrees (directly perpendicular to the target), 30 degrees, and 60 degrees. These angles are chosen to investigate the effect of different incident angles on the intensity measurements.

3. RESULTS

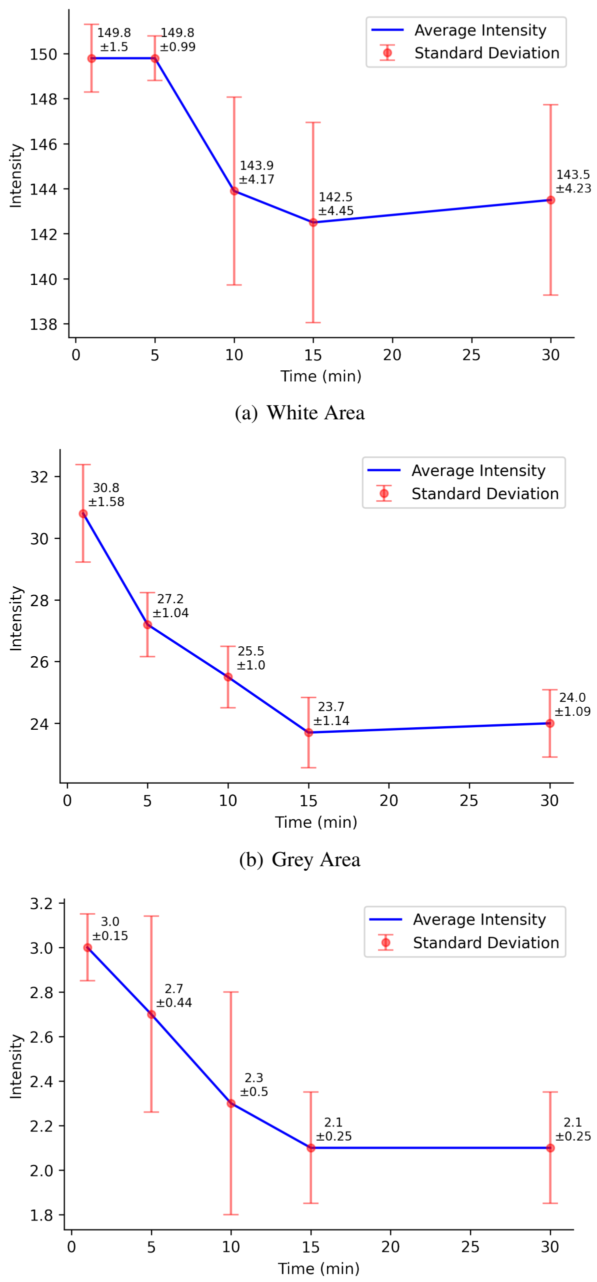
3.1 Results for changes over time

In the following charts and tables, the intensity is given as the raw values recorded by the instrument. The values are integers in the interval from 0 (black) to 150 (white). Figure 3 displays the temporal variation in intensity across three regions: white, gray, and black. The intensities shown in the graphs represent the averages of the point cloud intensities over the areas, with error bars representing the standard deviations.

The results indicate a consistent trend of decreasing intensity over time in all three regions with different reflectivity. However, at the 15-minute mark, the intensity levels stabilize and remain relatively consistent with the measurements at the 30-minute mark, suggesting that the intensity measurements reach a state of stability after 15 minutes. When considering the absolute change in intensity values, the white and gray areas exhibit more pronounced changes, with a decrease of 6.3 and 6.8, respectively, over the 30-minute duration. In contrast, the change in the black area is approximately 0.9. However, when examining the relative change, the white area shows the most significant decrease, with a 30% drop compared to the 1-minute value. The gray and black areas experience decreases of 20% and 4%, respectively. It is worth noting that the intensity of the white area remains relatively constant between 1 and 5 minutes, with a smaller standard deviation observed during this period compared to the 10 to 30-minute interval.

3.2 Results for varying reflectance

The data obtained from the intensity measurements is presented in Table 1. Intensity data is the average intensity of the point cloud over the area. The manufacturer's statement refers to the colour of the grey area as 18% grey. The data for the intensity of the point cloud is in relatively close agreement with this value, both when comparing it to the nominal maximum value of 150 for intensity (fourth column) and when comparing it to the observed average intensity of the white area (last column).



(a) White Area

(b) Grey Area

(c) Black Area

Figure 3. The variation of average intensity over time.

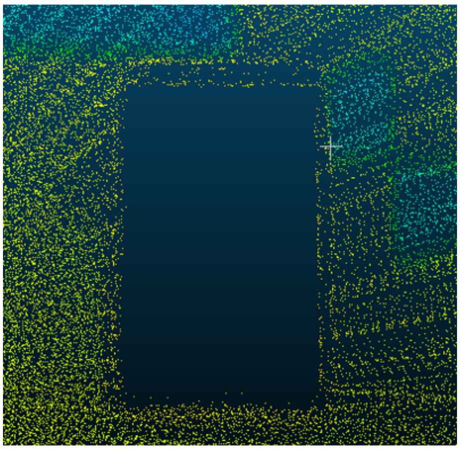
Problems arise when considering the retro-reflective targets. The black retro-reflective target demonstrates a highly uniform intensity value of 153. this is consistent with the manufacturer's specification, that retro-reflective targets are represented as values above 150.

In contrast, the white retro-reflective target initially proved difficult for the laser scanner to measure. The corresponding location became a void area, as depicted in Figure 4(a). This phe-

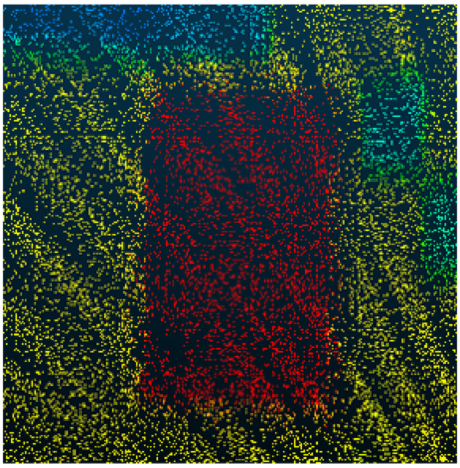
Area	Intensity	STD	Percentage of Max.	Percentage of White
			%	%
White	143.9	7.7	96	100
Grey	25.7	1.7	17	18
Black	2.0	0.6	1	1

Table 1. The intensity data of different areas and the relative percentage.

nomenon persisted in multiple tests before the formal experiment. However, at a certain point in time, the laser scanner was able to accurately detect the presence of the white target, as shown in Figure 4(b), and the measured intensity value was 255, the maximum value. Notably, the position of the target and the scanner remained unchanged during this period. Subsequent repeated experiments consistently detected the target, failing to replicate the initial failure in detecting the target.



(a) Void on the White Retro-Reflective Target

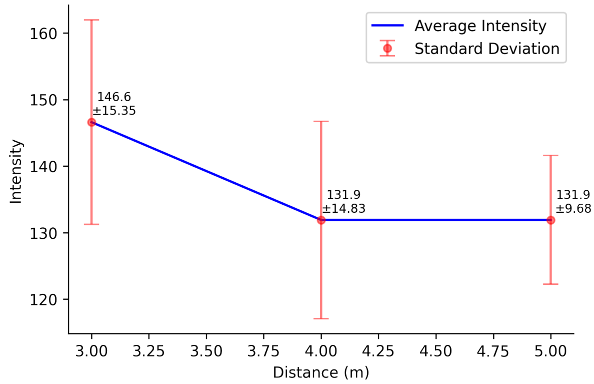


(b) White Retro-Reflective Target with measured points

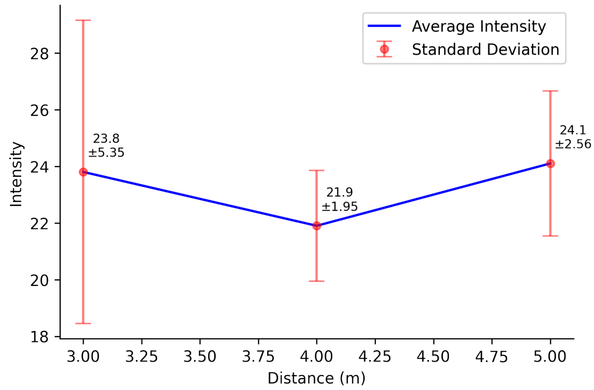
Figure 4. The point cloud data on a white retro-reflective target.

3.3 Results for varying distance

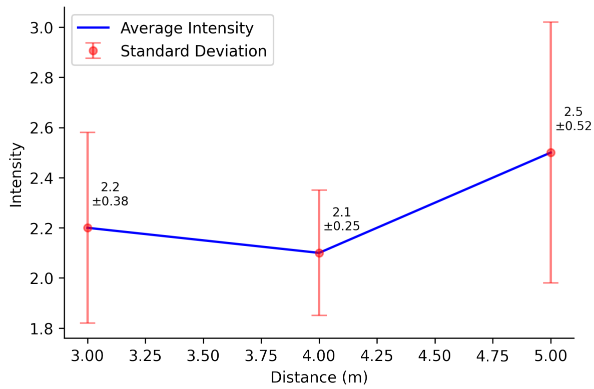
Figure 5 illustrates the variation in intensity across different distances in the white, gray, and black areas, respectively. The graph suggests a decreasing trend in the intensity of reflections in the white area as the distance increases from 3 m to 5 m. However, there is no clear trend observed in the intensity of



(a) White Area



(b) Grey Area



(c) Black Area

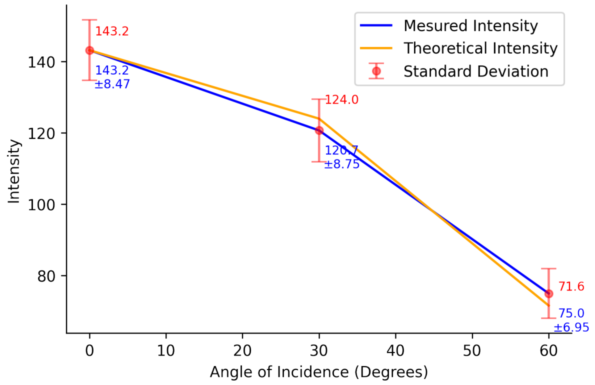
Figure 5. The variation of average intensity over distances from 3 to 5 meters.

reflections in the gray and black areas. Notably, at a distance of 3 m, both the white and gray areas exhibit a large standard deviation in intensity.

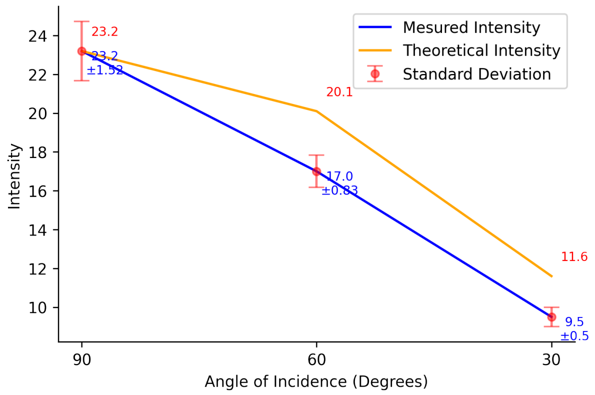
Furthermore, attempts were made to measure the intensity of the scanned target at distances of 1 m and 2 m. However, reliable data could not be obtained. When the target was positioned at a distance of 1 m, the laser scanner malfunctioned, prompting an error warning from the software. After multiple attempts, it was confirmed that, under the conditions of this experiment, the target needed to be approximately 1.8 m away from the Livox Mid-40 to avoid the error message.

Similarly, when the target and the scanner were positioned 2 m apart, the scanner did not display an error message and successfully captured the point cloud data of the target. However, it was unable to obtain accurate measurements of the intensity. In all areas, the recorded intensity was consistently 0. Therefore, the intensity data for the 2 m distance was not considered in the analysis.

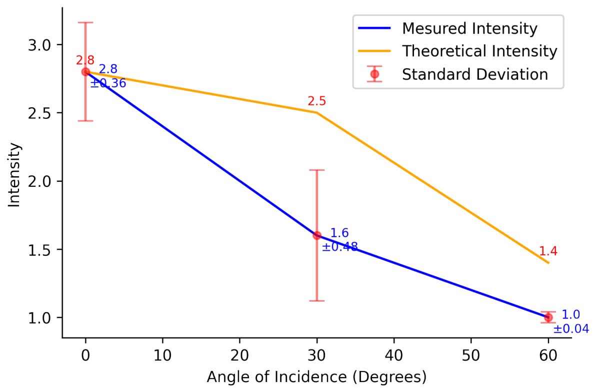
3.4 Results for varying angle of incidence



(a) White Area



(b) Grey Area



(c) Black Area

Figure 6. Measured and theoretical average intensity over angles of incidence.

Figure 6 presents the variation in intensity for different angles of incidence in the white, gray, and black areas, respectively. The theoretical values are calculated using a simplified formula based on the intensity value at zero angle of incidence.

Examining Figure 6(a), it is evident that the intensity values in the white areas closely align with the predicted values. However, the intensity values in the gray and black areas deviate from the predicted values. Notably, the intensity in the black area, while showing a decreasing trend with increasing angle of incidence, significantly differs from the predicted values.

3.5 The effect of intensity on distance measurement

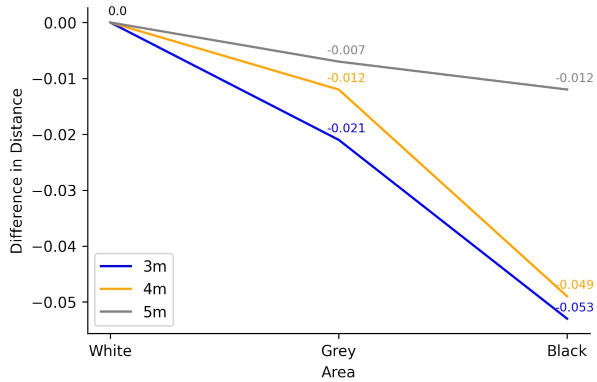


Figure 7. Difference in measured distances over the three areas normalized to the white area at different distances.

In the distance experiment, the measured distance represents the average of the x-values of the point cloud over the selected area. The scanner's coordinate system is aligned so that the x axis is facing the target. Figure 7 illustrates the impact of different intensities on distance measurements at various distances. Deviations up to 5cm are observed.

4. DISCUSSION

4.1 Evaluation of experiment result

In the time experiment, we observe that the intensity of the white area remains relatively unchanged from 1 to 5 minutes, accompanied by a very small standard deviation in the intensity data for these time points. Further analysis reveals that a significant portion of the intensity data corresponds to the value 150. According to the literature review, intensity values ranging from 0 to 150 correspond to reflectivity values within the range of 0-100% for Lambertian reflection, while values greater than 150 correspond to retro-reflective surfaces (Livox, 2019). Therefore, this result suggests that there might be a substantial gap between intensity values of 150 and 151, and any observed intensity falling within that range would be classified as an intensity value of 150. This would introduce a bias to the statistics and explain the low standard deviation.

Regarding the observed trend of intensity decreasing with time, it is likely attributed to the rise in temperature as the instrument warms-up. Temperature can influence various components within the laser scanner, including the detector. This effect is well-known and often compensated for in survey-grade scanners (Errington and Daku, 2017).

In the experiments on varying reflectance, determining the reference reflectance of the different areas was not possible, which made it challenging to establish a direct comparison between the intensity obtained by the scanner and the actual reflectance values. However, considering the consistency between the data provided by the manufacturer of the colour checker and the measured intensity data, it can be assumed that there is a linear relationship between the intensity data obtained by the scanner and the reflectance of the target.

The discrepancy between the minimum distance observed in the experiment (around 1.8 m) and the manufacturer's specification of 1 m suggests more experimentation is needed on the conditions under which the minimum detection distance can be achieved.

In the angular experiment, it is noted that the intensity of the reflection in the black area did not perfectly match the theoretical value, while the white area performed well in this regard. The available data indicates that the measured intensity values are integers, and the average intensity in the black area ranges only between 1 and 3. This suggests that the accuracy of the measurements for low reflectance areas may be compromised. However, the experiment indicates it is possible to determine the actual reflectance of a high reflectance surface using the angle of incidence and the intensity values obtained with the Livox Mid-40 scanner.

The results obtained in the experiment on the influence of intensity on measured distances raise concerns. Differences of up to 5cm were observed between areas of different intensity. This difference is much larger than the manufacturer's stated uncertainty of 20 mm at 20 m. The previous assumption was that this phenomenon was caused by the simple range measuring principle of time-of-flight, which had been eliminated from most survey-grade instruments. The results of this experiment suggest that the cause of this phenomenon might not be as straightforward as initially thought. The effect observed in this experiment gradually diminishes as the distance between the target and scanner increases. These findings highlight the need for careful consideration of potential errors due to intensity variations, especially when applying the Mid-40 scanner to targets with large intensity differences at closer distances.

4.2 Limitation and further work

This study has some limitations that could be addressed in future research. Firstly, the experiments involve manual steps such as the manual selection of target areas in the point cloud. It is challenging due to the lack of clear boundaries (Figure 8). This can introduce a bias or unwanted variation. Using larger targets or exploring alternative methods for accurate area selection could mitigate this issue.

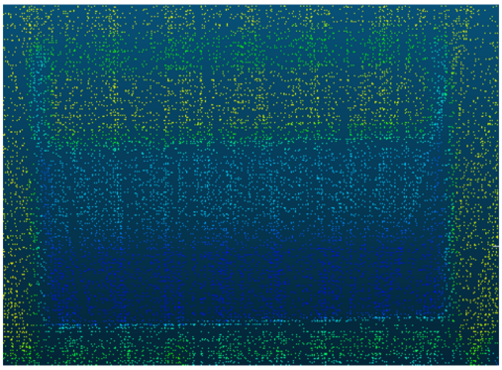


Figure 8. Blurred boundaries of the target.

When varying the distance, the maximum distance is limited by the laboratory environment. It is worth investigating how intensity affects the measured distance at more than 5 metres as we see a diminishing effect at larger distances.

5. CONCLUSION

This study is to investigate the radiometric behaviour of low-cost LiDARs, with a specific focus on the Livox Mid-40 as a representative model. The study aims to analyse the intensity data obtained from the LiDAR point cloud, as it directly reflects the radiometric behaviour. The study has explored the basic principles of intensity data generation in LiDAR systems and examined its applications. Various parameters that can impact intensity, such as time, reflectance, distance, and angle, are chosen as the focus of the experiments. Additionally, the study investigates the influence of intensity on distance measurements.

The results of the study have provided valuable insights into the fundamental radiometric behaviour of the Livox Mid-40. However, there are still limitations in the research that need to be addressed in further studies. Despite its potential for intensity measurement and its ability to accurately reflect different surface reflectance, the Livox Mid-40 may not be suitable for applications requiring precise reflective intensity measurements, particularly under indoor conditions. The study highlights issues related to the influence of distance on the consistency of results, emphasizing the need for careful consideration of reflective intensity in distance measurements, especially at short distances.

Future research can expand the investigation to include other low-cost LiDAR systems similar to the Livox Mid-40. By comparing the performance of different models, researchers can gain a deeper understanding of their capabilities and limitations. Overall, this study serves as an initial exploration of the radiometric behaviour of the Livox Mid-40.

6. ACKNOWLEDGEMENT

Z. Zeng is supported by the Engineering and Physical Sciences Research Council through an industrial CASE studentship with Ordnance Survey (Grant number EP/W522077/1).

REFERENCES

Backes, D., Thomson, C., Malki-Epshtein, L. and Boehm, J., 2014. Chadwick GreenBIM: Advancing operational understanding of historical buildings with bim to support sustainable use. In: Building Simulation & Optimization Conference (BSO14), UCL (University College London).

Boehler, W., Vicent, M. B., Marbs, A. et al., 2003. Investigating laser scanner accuracy. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 34(Part 5), pp. 696–701.

Böhm, J. and Becker, S., 2007. Automatic marker-free registration of terrestrial laser scans using reflectance. In: Proceedings of the 8th conference on optical 3D measurement techniques, Zurich, Switzerland, pp. 9–12.

Brazeal, R. G., Wilkinson, B. E. and Hochmair, H. H., 2021. A Rigorous Observation Model for the Risley Prism-Based Livox Mid-40 Lidar Sensor. Sensors 21(14), pp. 4722. Number: 14 Publisher: Multidisciplinary Digital Publishing Institute.

Crowther, J. M., 2018. Calibrating UVA reflectance photographs – standardisation using a low-cost method. Journal of Visual Communication in Medicine 41(3), pp. 109–117. Number: 3 Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/17453054.2018.1476819.

Errington, A. F. C. and Daku, B. L. F., 2017. Temperature Compensation for Radiometric Correction of Terrestrial LiDAR Intensity Data. Remote Sensing 9(4), pp. 356. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

Glennie, C. L. and Hartzell, P. J., 2020. Accuracy Assessment and Calibration of Low-Cost Autonomous Lidar Sensors. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XLIII-B1-2020, pp. 371–376. Num Pages: 371-376 Publisher: Copernicus GmbH.

Godin, G., Rioux, M., Beraldin, J. A., Levoy, M., Cournoyer, L. and Blais, F., 2001. An assessment of laser range measurement of marble surfaces. In: Conference on Optical 3D Measurement Techniques, Vol. 2985.

Hartmann, J., Heiken, M., Alkhatib, H. and Neumann, I., 2023. Automatic quality assessment of terrestrial laser scans. Journal of Applied Geodesy. Publisher: De Gruyter.

Höfle, B. and Pfeifer, N., 2007. Correction of laser scanning intensity data: Data and model-driven approaches. ISPRS Journal of Photogrammetry and Remote Sensing 62(6), pp. 415–433. Number: 6.

Kaasalainen, S., Hyyppa, H., Kukko, A., Litkey, P., Ahokas, E., Hyyppa, J., Lehner, H., Jaakkola, A., Suomalainen, J., Akujarvi, A., Kaasalainen, M. and Pyysalo, U., 2009. Radiometric Calibration of LIDAR Intensity With Commercially Available Reference Targets. IEEE Transactions on Geoscience and Remote Sensing 47(2), pp. 588–598. Number: 2 Conference Name: IEEE Transactions on Geoscience and Remote Sensing.

Kaasalainen, S., Jaakkola, A., Kaasalainen, M., Krooks, A. and Kukko, A., 2011. Analysis of Incidence Angle and Distance Effects on Terrestrial Laser Scanner Intensity: Search for Correction Methods. Remote Sensing 3(10), pp. 2207–2221. Number: 10 Publisher: Molecular Diversity Preservation International.

Kashani, A. G., Olsen, M. J., Parrish, C. E. and Wilson, N., 2015. A Review of LIDAR Radiometric Processing: From Ad Hoc Intensity Correction to Rigorous Radiometric Calibration. Sensors 15(11), pp. 28099–28128. Number: 11 Publisher: Multidisciplinary Digital Publishing Institute.

Livox, 2019. Livox Mid Series User Manual V1.2.

Ortiz Arteaga, A., Scott, D. and Boehm, J., 2019. Initial investigation of a low-cost automotive lidar system. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 42, pp. 233–240.

Pfeifer, N., Dorninger, P., Haring, A. and Fan, H., 2007. Investigating terrestrial laser scanning intensity data: quality and functional relations. 8th Conference on Optical 3-D Measurement Techniques.

Sanchiz-Viel, N., Bretagne, E., Mouaddib, E. M. and Dassonvalle, P., 2021. Radiometric correction of laser scanning intensity data applied for terrestrial laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing 172, pp. 1–16.

Scaioni, M., Höfle, B., Baungarten Kersting, A. P., Barazzetti, L., Previtali, M. and Wujanz, D., 2018. METHODS FROM INFORMATION EXTRACTION FROM LIDAR INTENSITY DATA AND MULTISPECTRAL LIDAR TECHNOLOGY. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII-3, pp. 1503–1510.

Varghese, D., Wanat, R. and Mantiuk, R., 2014. Colorimetric calibration of high dynamic range images with a colorchecker chart. In: International Conference and SME Workshop on HDR Imaging 2014, International University of Sarajevo.

Voegtle, T., Schwab, I. and Landes, T., 2008. Influences of different materials on the measurements of a terrestrial laser scanner (tls). In: Proc. of the XXI Congress, The International Society for Photogrammetry and Remote Sensing, ISPRS2008, Vol. 37, Citeseer, pp. 1061–1066.

Vosselman, G. and Maas, H.-G., 2010. 1. Laser Scanning Technology. In: Airborne and Terrestrial Laser Scanning, Whittles Publishing.

Wehr, A., Hemmleb, M. and Maierhofer, C., 2006. Multi-Spectral Laser Scanning for Inspection of Building Surfaces: State of the Art and Future Concepts. In: Proceedings of the 7th International Conference on Virtual Reality, Archaeology and Intelligent Cultural Heritage, VAST'06, Eurographics Association, Aire-la-Ville, Switzerland, Switzerland, pp. 147–154.

Wujanz, D., Burger, M., Tschirschwitz, F., Nietzschmann, T., Neitzel, F. and Kersten, T., 2018. Determination of Intensity-Based Stochastic Models for Terrestrial Laser Scanners Utilising 3D-Point Clouds. Sensors 18(7), pp. 2187.