Detection of Range Errors due to Occlusion in Separated Transceiver LADARs

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Abstract— **Laser detection and ranging sensors or LADARs are widely used in mobile robotics as sensing mechanism. When processing LADAR data for the purposes of feature extraction and/or data association, most previous work models such devices as processing range data which follows a Normal distribution. In this paper, it will be demonstrated that commonly used LADARs with separated transmitter and receiver configuration suffer from incorrect range readings at range discontinuities due to occlusion, a much more detrimental effect on feature extraction or data association algorithms than random noise. The occurrence of these errors can be reliably predicted by monitoring the received signal strength. A useful design criterion for the optical separation of the transmitter and receiver is derived for non-coaxial LADARs and the exact environmental conditions which can cause range errors is quantified so that such errors can be reliably predicted.**

I. Introduction

In mobile robotics, range sensing is often a crucial component of navigational and localization tasks. Laser detection and ranging sensors, or LADARs, with range and bearing information, have become an integral component of many autonomous systems due to their accuracy and relatively low cost [4], [5].

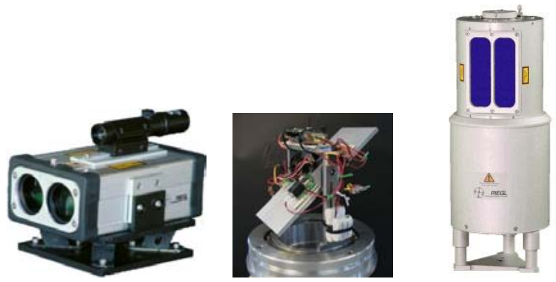
The work here is inspired by processing LADAR range data for the detection of features for mobile robot navigation [1], [5], [8]. Such algorithms are often based on probabilistic methods which attempt to extract information from the range data in an optimal manner, on the assumption that the range data is corrupted with Gaussian noise.

In the authors' experience, such feature extraction algorithms often fail due to systematic, unmodelled errors from LADARs. For example, Kalman Filter based detection algorithms [8] can fail catastrophically when range errors due to *cross talk* [6], *disparity* [7] or *multi-path effects* [1] occur. Removing such "outliers" from range data can be achieved with limited success with standard techniques such as median filters. This paper will demonstrate that significant range errors can occur due to occlusion caused by transmitter and receiver (transceiver) separation. To the authors' knowledge, this is an effect previously not examined for LADARs in the literature.

Firstly, the 3D scanning LADAR systems used in this work will be presented in section II. In section III an overview of range errors of LADARs due to different causes, namely occlusion, cross-talk and random noise will be presented. The occlusion effect will be demonstrated with range/intensity data recorded from a scanning LADAR. The physical cause of this effect will be studied in section IV and a theoretical model will be derived which allows such errors to be predicted and detected from range scans. In particular it will be shown that the received signal amplitude will follow well defined profiles as the scanning mirror rotates. The theoretical analysis applies to all detection methods, since the range errors occur due to a significant drop in received signal amplitude. Then in section V, the theoretical model derived in section IV is analyzed to determine the parameters which cause the range errors. Experimental results are shown in section VI which demonstrate that such spurious range points can be reliably detected, provided that the signal amplitude and orientation of the scanning optics and some environmental factors are monitored with each range data value.

II. 3D Scanning LADAR Systems

Two LADAR systems are used in this work. The main LADAR system is based on a 1D Riegl LD90-3300EHS-FLP model, as shown in figure 1(a). For robot navigation, a desirable feature of any ranging system is to provide full 360^o coverage around the robot in bearing, so that all objects within the field of view of the sensor can be "seen" from any vehicle orientation. Figure 1(b) shows a 3D scanning system developed at NTU which achieves this together with limited control of the scanning elevation angle. The 1D LADAR in figure 1(a) is mounted inside this system to perform as a 3D LADAR scanner.



(a) (b) (c)

Fig. 1. LADARs used in this work.

The 3D LADAR shown in figure 1(c) is a LMS-Z210i model from Riegl. Its rather slow rotating rate (At the fastest rotating rate, it takes around 20 seconds for the LADAR to fulfil a single 2D scan) limits its use in mobile robotic applications. However, in this work, this kind of 3D LADAR is still used for comparison.

III. RANGE ERRORS IN LADARS

Reported range errors in LADARs are due to cross-talk and random noise [6], [1], [3]. A third type of error which has received attention in triangulation systems, but has not been analyzed in LADAR systems, is occlusion.

Figure 2 shows an intensity image from the 3D scanning Riegl LADAR (figure 1(c)) in a laboratory environment. Intensity is also known as received signal amplitude. In the paper, the two words "intensity" and "amplitude" or "signal amplitude" will be used interchangeably. The intensity is a ratio, which is a dimensionless quantity that ranges from 0 (least reflective) to 255 (most reflective) which is based on the strength of the return signal.

Fig. 2. A received signal amplitude image.

In figure 2 the blue circle (labelled with "A") denotes zero, or extremely low received signal amplitude values. These low amplitude values cause erroneous range values. These could easily be detected as being false if the range values were always zero. In reality, LADARs commonly used in mobile robotics research such as those from Riegl, Acuity Research and Sick respond in different ways to such range discontinuities. Actually *all* scanning LADARs with separated transmitter and receiver configurations will suffer a minimum in received signal amplitude due to the disparity between the transceiver aperture *irrespective of the technique used to estimate range*. This paper will present a method to reliably predict such range failures.

Few articles address the causes and effects of range errors in LADARs. Notable exceptions are papers by Hebert and Krotkov [6], Reina and Gonzalez [2] and recently by Cang and Borenstein [3]. These articles address the issues of range errors caused by *random receiver/reflection noise*, *cross talk* and *multiple path reflections*.

In general, the receiver electronics of a LADAR functions optimally only within a small dynamic range of received signal intensities in comparison with the large dynamic range of intensities which can be observed by the sensor. Therefore, materials which produce signals beyond the functioning dynamic range can produce erroneous range estimates. When the laser beam is projected at edges, this cross-talk effect becomes more noticeable [6].

In order to demonstrate the cross-talk effect, figure 3 shows the amplitude and range information recorded in an experiment. In the experiment, a black canvas target and a white one behind it were put together. The 1D LADAR in figure 1(a) was slid precisely in a direction parallel to the target surfaces so that it translated to scan the edges formed by targets. Seen from the figure 3, at

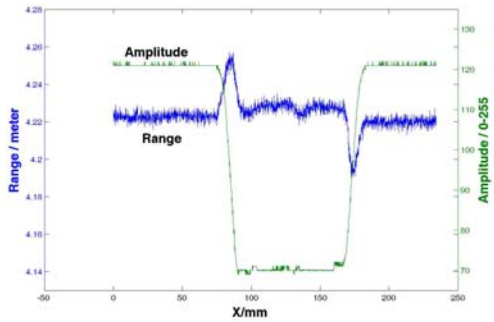


Fig. 3. Range and amplitude profiles to quantify the cross-talk effect.

the edges formed by the two targets, range measurements are erroneous. The range errors (two 'peaks') are of the order of several centimeters, much smaller compared to the range errors caused by the occlusion effect, which is several meters. However, the range errors caused by this cross-talk effect are "unpredictable" [6], but can be related to electronic interference within the LADARs or optical leakage directly between the transmitter and receiver [1].

Most researchers model range data from LADAR sensors as an estimated value with Gaussian noise [1], [4]. In figure 4, the histograms show the range data from the LADAR in figure 1(a) at a constant target distance while the target reflectivity and illumination condition vary. The range data in each case follows Gaussian distribution well. The range of the standard deviation is from $1.5mm$ to $3.5mm$. Hence, the random range errors are much smaller than the range errors caused by the occlusion effect and the cross-talk effect, which is true in many tested commercially available LADARs such as Sick ones and IBEO ones etc.

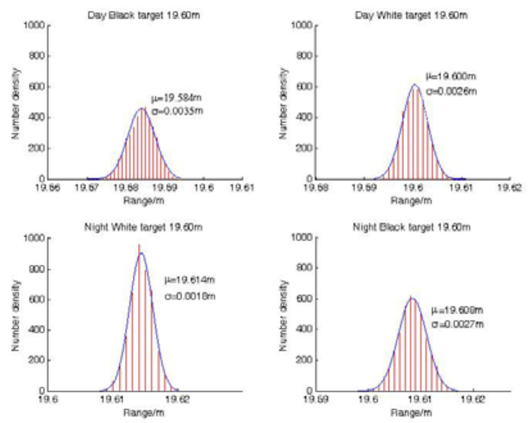


Fig. 4. Range distributions showing the resulting range variance for varying target reflectivities and day/night conditions. In each case 4,000 independent range readings were recorded from a fixed target.

IV. Occlusion due to Transceiver separation

To study the occlusion effect, an experimental setup was made as shown in figure 5. The 1D LADAR in

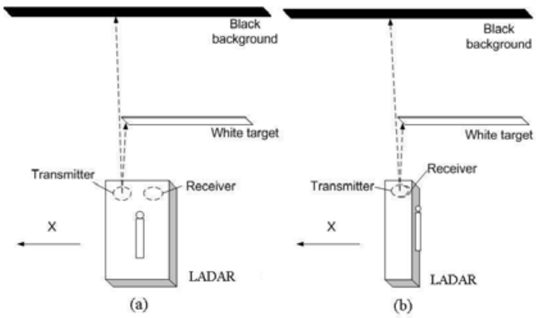


Fig. 5. (a) The LADAR is displaced past on a vertical edge formed by a target and a background. (b) The sensor is rotated 90° right so that the transmitter and the receiver are displaced "coaxial" to the vertical edge .

figure 1(a) was mounted on the stacker of a milling machine and was translated to scan the vertical edge of two targets in a direction parallel to the target surfaces, as shown in 5(a). The range and amplitude information were recorded and for one particular experiment, are shown in figure 6. A minimum in the amplitude profile occurs because of the separated transceiver configuration of the sensor. There is a loss in received energy due to the non-coaxiality of the sensor. When the amplitude drops below the minimum working threshold of the LADAR, the range reading cannot be trusted (it reads zero for these LADARs in figure 1 but in general it may read any arbitrary value and hence cannot be compensated by a simple low-pass filter). This is occlusion. Most LADAR sensors fall into two categories: coaxial (such as the often used Sick LADARs on mobile robots) or separated (such as most Riegl LADARs) transceiver configurations with respect to vertical edges. These configurations determine if occlusion occurs or not.

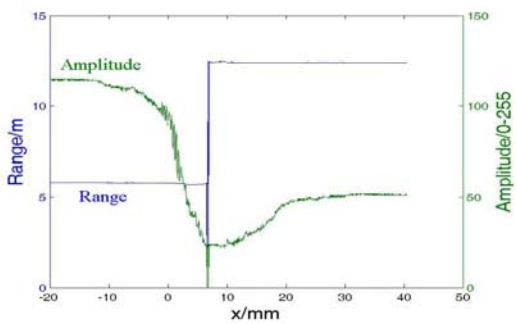


Fig. 6. Range and amplitude when scanning a vertical edge.

The following analysis will mathematically derive the profile of the received signal power from these two LADARs, as their scanning mirrors rotate so that the transmitted laser is scanned past a range discontinuity. It will then be shown how this profile can be used to predict when range errors will occur and how to detect them. In the analysis, the following assumptions are made:

1) The power in the transmitted and reflected light beams is uniformly distributed over the circular, cross-sectional area of the LADAR.[1]
2) Assumptions 1 allows us to model the scanning procedure with targets 1 and 2 parallel to the motion of the LADAR, irrespective of their true orientation.
3) Due to assumption 2, the rotational, scanning motion of the LADAR's mirror can be modelled as a linear displacement of the LADAR's optical footprint.

Initially, before the transmitted optical footprint intersects the edge, it will fully illuminate target 1 at range d_1, as shown in figure 7(a). In this case, the received

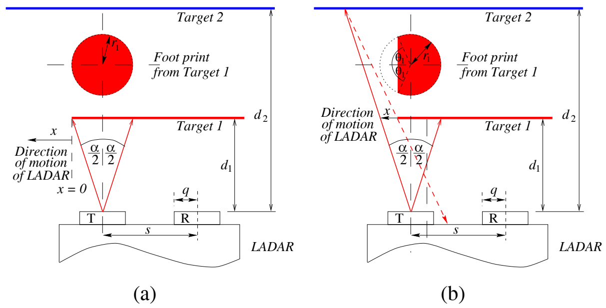


Fig. 7. (a) Only target 1 is illuminated. (b) Target 2 is completely occluded due to the transmitter – receiver separation s. The footprint's area on target 1 is reduced.

signal strength is P_1 watts, which can be measured if the amplitude of the received signal is available (as in the case of the Riegl and some Sick devices). As the mirror scans, the projected optical footprint will eventually completely traverse the edge, so that it fully illuminates target 2 at range d_2. In this case the received signal strength is assumed P_2 watts (figure 8(d)).

In figures 7(a) and 8(d) the *end condition* received power *densities* are defined as:

$$\mathcal{P}_{(x\le 0)} = P_1/\pi r_1^2 \qquad \mathcal{P}_{(x\ge X_2)} = P_2/\pi r_2^2 \tag{1}$$

where x is the motion of the LADAR measured from the edge of target 1 and r_1 and r_2 are the radii of the normal components of the optical footprints on targets 1 and 2 respectively. The point $x = 0$ is defined when the transmitted light beam just reaches the edge of target 1, as shown in figure 7(a). The scanning of the LADAR's mirror is then considered to be equivalent to displacing the LADAR in the direction shown in figures 7(a) to (b) and figures 8 (a) to (d).

1) **LADAR displacement** $x \le 0$ **(figure 7a).** The received signal power is given by:

$$P_{(x\le 0)} = \mathcal{P}_{(x\le 0)}\pi r_1^2 = P_1 = \text{constant} \tag{2}$$

[1]Note that the following analysis could be easily extended to other non-uniform optical power distributions.

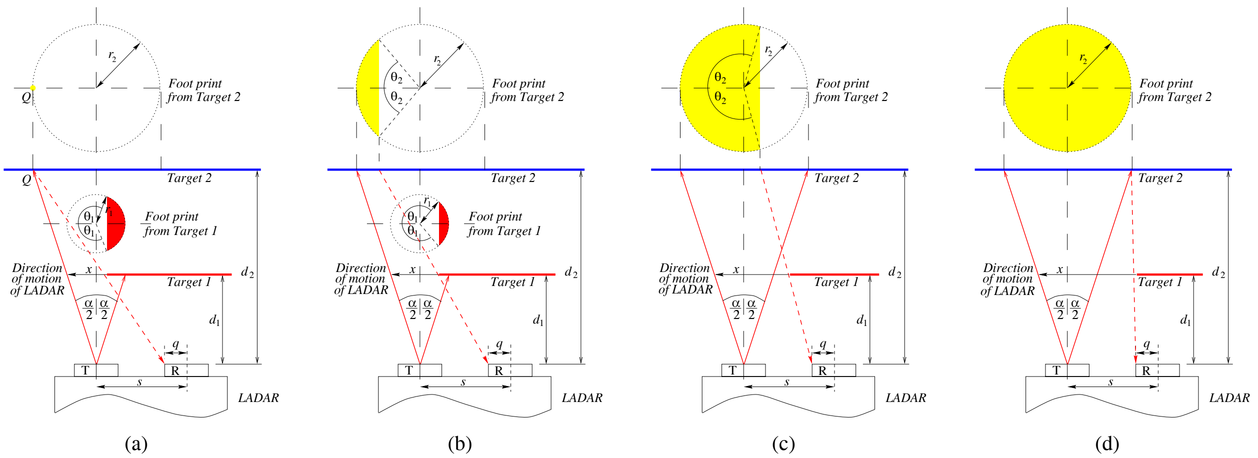


Fig. 8. (a) Point Q on target 2 just enters the field of view of the receiver aperture. (b) Light is now received from both targets 1 and 2. (c) Target 1 is no longer illuminated. (d) Light is now received from target 2 only, with no occlusion from target 1.

Define X_1 as being the value of x at which target 2 just becomes visible to the receiver aperture. This scenario is depicted in figure 8(a):

$$X_1 = (s - q)(d_2 - d_1)/d_2 \tag{3}$$

where s is the transmitter – receiver aperture separation and q is the effective radius of the receiver lens.

2) **LADAR displacement** $0 \le x < X_1$ **(figure 7(b))**.The received power in this interval is:

$$\begin{aligned} P_{(0\le x<X_1)} &= P_1\left(1 - \frac{\theta_1}{\pi} + \frac{\sin 2\theta_1}{2\pi}\right) \\ \theta_1 &= \cos^{-1}\left(1 - \frac{2x}{d_1\alpha}\right) \end{aligned} \tag{4}$$

3) **LADAR displacement** $X_1 \le x < 2r_1$ **(figure 8(b)).**
The power results from the *two* footprint sections shown in figure 8(b),

$$\begin{aligned} P_{(X_1\le x<2r_1)} &= P_1\left[1 - \frac{\theta_1}{\pi} + \frac{\sin 2\theta_1}{2\pi}\right] \\ &\quad + P_2\left[\frac{\theta_2}{\pi} - \frac{\sin 2\theta_2}{2\pi}\right] \end{aligned} \tag{5}$$

with

$$\theta_1 = \cos^{-1}\left(1 - \frac{2x}{d_1\alpha}\right) \quad \theta_2 = \cos^{-1}\left[1 - \frac{2(x - X_1)}{d_2\alpha}\right] \tag{6}$$

Let $x = X_2$ be the displacement at which target 1 just fails to occlude target 2. From geometrical considerations,

$$X_2 = \frac{(s-q)(d_2 - d_1)}{d_2} + d_1\alpha \tag{7}$$

4) **LADAR displacement** $2r_1 \le x < X_2$ **(figure 8(c)).**
The power received in this displacement interval results from the single footprint in figure 8(c):

$$\begin{aligned} P_{(2r_1\le x<X_2)} &= P_2\left(\frac{\theta_2}{\pi} - \frac{\sin 2\theta_2}{2\pi}\right) \\ \theta_2 &= \cos^{-1}\left[1 - \frac{2(x - X_1)}{d_2\alpha}\right] \end{aligned} \tag{8}$$

5) **LADAR displacement** $x \ge X_2$ **(figure 8(d)).**
Finally target 2 is fully illuminated , so that no part of the footprint is occluded from the LADAR's receiver aperture. Then:

$$P_{(x\ge X_2)} = p_{(x\ge X_2)}\pi r_2^2 = P_2 = \text{constant} \tag{9}$$

$$r_1 \approx d_1\alpha/2 \qquad r_2 \approx d_2\alpha/2 \tag{10}$$

where α is the beam width of the transmitted laser.

Equations 2, 4, 5, 8, 9 and between them, when θ_1 and θ_2 are replaced by their respective functions of x, describe the complete expected received amplitude profile as the LADAR's transmitted laser is scanned past a range discontinuity. In figure 9, the amplitude profile is plotted versus the illuminated footprint displacement. Compared

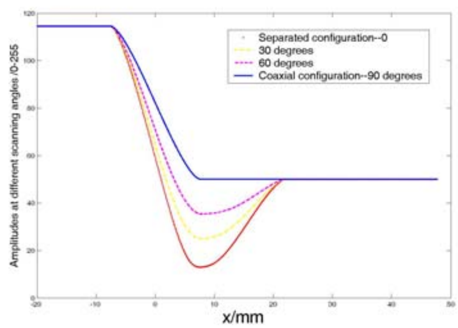


Fig. 9. Estimated amplitude profiles of separated transceiver configuration and "coaxial" configuration LADARs. In this case, the values of involving parameters are: $d1 = 5.8$m, $d2 = 12.6$m, $P1 = 115$, $P2 = 50$ and $s - q = 2.9$cm.

with the measured amplitude in figure 6, the estimated profile in figure 9 (the red dotted profile) is similar and the minimum value in the amplitude is almost the same. However the width of the change in the amplitude curve in the actual case is smaller than that in the simulated case. The possible reason is due to the assumption that the laser energy is uniformly distributed over the beam cross section, which is probably not true. In reality, the laser energy concentrates around the center of the beam cross section, rather than being normally distributed, which causes the actual beam width of the transmitted laser, α, to be smaller than its theoretical value and then causes the actual r_1 and r_2 to be smaller than the theoretical values (Eqn 10). Hence the real LADAR displacement regions $X_1 \leq x < 2r_1$ and $2r_1 \leq x < X_2$ are smaller.

In Figure 9, individual estimated amplitude profiles corresponding to a certain transceiver separation angle of the LADAR relative to the sensed target are shown for particular values of $d1$, $d2$, $P1$, $P2$, α and $s - q$. In this paper, the transceiver separation angle θ is defined as the angle between the direction of the transmitted laser beam and the center line of the transceiver of the LADAR when the LADAR's scanning mirror rotates. When the LADAR scans, each θ corresponds to a bearing angle (the angle the LADAR's mirror rotates about the vertical axis). The relationship between the transceiver separation angle and transceiver configuration is that, the transceiver separation angle 0^o corresponds to the separated transceiver configuration, equivalent to the experimental set up of figure 5(a) and the transceiver separation angle being 90^o, corresponding to the "coaxial" configuration equivalent to the set up in figure 5(b). As the transceiver separation angle increases, the minimum value of the amplitude profiles increases which means potential elimination of the measurement error at a certain angle. If the transceiver separation angle reaches 90^o, which corresponds to the case in figure 5(b), the transceiver configuration effectively becomes "coaxial" with respect to any vertical edge and the minimum in the amplitude profile disappears (as shown in figure 9, the blue solid profile).

The above analysis applies to the 3D LADAR scanner in figure 1(b). For the 3D LADAR in figure 1(c), the rotating mirror rotates in unison with the transceiver and their relative position is constant. That means, for this kind of LADAR scanner, the transceiver is always "separated" no matter what the LADAR scanning mirror's real bearing angle is. When this LADAR scans past a vertical edge as in figure 5, the estimated profile will always have the form of the red dotted curve in figure 9.

V. Causes of Range Errors

To avoid range errors the minimum amplitude in the profile must be increased to a value above the minimum detectable amplitude value of the LADAR. In this section, the theoretical model will be analyzed to determine the effect of different LADAR design parameters and environmental parameters which can cause the received amplitude to fall below a predefined minimum value.

For the 3D LADAR in figure 1(b), the fundamental parameter is the transceiver separation angle θ. For the 3D LADAR in figure 1(c), it is not affected by this parameter since the transceiver is always "separated" with respect to a vertical edge. In figure 10, the estimated signal amplitude is shown versus the sliding distance (x in mm) and the transceiver separation angle (in degrees). This

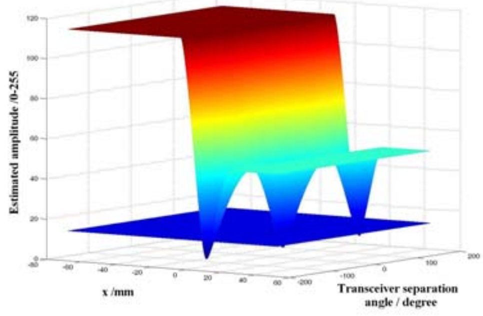


Fig. 10. Estimated amplitude versus the sliding distance x and the transceiver separation angle θ. The other parameters: $d1 = 5.8$m, $d2 = 12.6$m, $P1 = 115$, $P2 = 50$, $s - q = 2.9$cm and $\alpha = 3mrad$.

angle corresponds to different transceiver configurations (This procedure is similar to setting the 1D sensor at a transceiver separation angle θ and allowing it to repeat the scan in figure 5). The minimum detectable amplitude of this Riegl LADAR is assumed to be 18 (found by experiment), and as the transceiver separation angle θ reaches $(n + 1/2)\pi\ rads$ (n integer), there will be no minimum in the amplitude and then no range error will occur. Since the minimum detectable amplitude of each LADAR is different, the particular angular bearing range in which the range error will disappear depends on this value for the given device. For LADARs which maintain a constant separation between the transmitter and receiver (figure 1(c)), the range errors may always occur.

The second parameter to be analyzed is a sensor parameter, the transceiver separation, $s - q$ (the transceiver separation) in equation 3. Both LADARs are affected by this parameter. By decreasing $s - q$, the minimum amplitude value can also be increased, thus decreasing the chances of false range values. During LADAR design, this parameter should be kept as small as possible while keeping the transmitter and receiver still separated to guarantee that all of the transmitted light leaves the LADAR.

Further parameters which affect the minimum value of the received amplitude are environmental, namely the distances and the reflectivity of the targets which form the scanned vertical edge. If the distance of the background target is decreased, the minimum amplitude value is also increased. This makes sense since if the two targets are put at the same distance, the front target cannot occlude the reflected laser from the background target. When the received power from either target is increased (corresponding to a higher reflectivity of that target), the minimum amplitude value is then also increased. It is interesting to note that for almost all combinations of edge separation $d_2 - d_1$, increasing the reflectivity of either of the surfaces *does not significantly increase the minimum in amplitude*, as shown in figure 11.

VI. Experimental Results

Finally, some experimental results are presented. Figure 12 shows a received amplitude image recorded from the

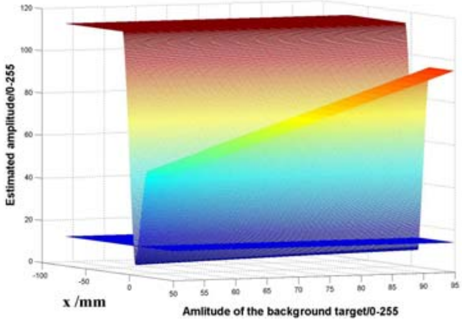


Fig. 11. Estimated signal amplitude versus the sliding distance x and the amplitude of signal received from the background target.

3D LADAR scanner in figure 1(b) in a semi-structured, outdoor environment (a car park area within the NTU campus). In figure 12, a black container (position ‘A’) and

Fig. 12. An intensity image of an semi-outdoor environment from the 3D LADAR scanner in figure 1(b). ‘A’ in the figure denotes a container.

the behind white wall form an edge where the occlusion effect could possibly occur in a LADAR scan. The ranges of the container and the wall were recorded and so were the received signal amplitudes. As shown in figure 13, an amplitude profile (the red amplitude profile denoted as ”Estimated amplitude” in the legend) similar to those in figure 9 from the theoretical model was produced. It can be seen that the minimum expected amplitude value in this case is lower than the LADAR’s minimum detectable amplitude. Hence, in this case, range errors are expected at the edge and they do occur. Compared with the actual amplitude data (the blue dotted profile) in figure 13, the shape and minimum of the amplitude in both actual and estimated profiles are almost the same except that the width of the change in the estimated amplitude is larger than that in the actual one, for the probable reason that the actual laser power distribution is different from the theoretical one used in the estimation as analyzed above.

From the above analysis and results, it can be seen that the theoretical model is effective in predicting range errors caused by occlusion. After the range errors are detected, it is necessary to replace these erroneous points with predictions when the LADAR is used in feature detection applications [5], [8].

VII. Conclusion

This paper evaluates false range values caused by occlusion effects when using LADARs with non-coaxial transceiver configurations and the range errors caused by this effect is much larger than those caused by cross-talk effect and random noises. For applications such as feature detection and data association, this effect will

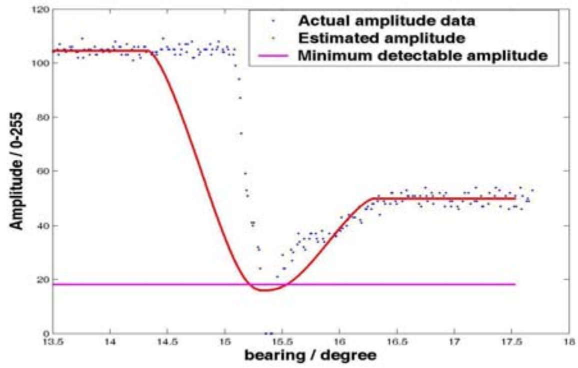


Fig. 13. Estimated amplitude profile from the middle row (elevation angle is 40^o) of the scan in figure 12 compared with the actual one.

introduce unwanted measurement errors and can cause the failure of feature detection algorithms and range noise reduction techniques. However, by using the proposed received signal power model, such erroneous range values can be predicted and detected before further processing.

Also, from this model, it can be seen that the minimum received signal power depends on sensor parameters such as the transceiver aperture separation and the scanning angle, as well as environmental parameters such as the reflectivity and separation of the targets. This dependency information is important for LADAR users as well as LADAR designers and allows them to avoid or, at least predict false range data caused by occlusion. This paper has shown that the chances of occlusion errors can be minimized by minimizing the separation of the LADAR’s transceiver at the design stage. Further, a large separation of the targets being sensed is much more likely to cause false estimation than the reflective qualities of the targets themselves. Hence the derived models can be used to guarantee that all range values at edges will be sensed correctly within certain target separation bounds.

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