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Characterization of a 2-D Laser Scanner for outdoor wide range measurement

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Characterization of a 2-D Laser Scanner for outdoor wide range measurement

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Abstract. This paper presents a metrological characterization study of SICK LMS 511 laser scanner, with an extended analysis of its main acquisition issues. Various parameters that could affect the sensor performances, such as warm-up time, target properties (color and material), and target position (distance and orientation) are investigated. Moreover, the mixed pixel problem is introduced and, finally, since the sensor is designed to work in a wide outdoor environment, the effect of direct sun light is taken into account. Some cases of faulty data are identified and explanations discussed.

1. Introduction

LIDAR (Light Detection And Ranging) sensing is a popularly used technology to make range maps, with applications in different fields such as geomorphology, archeology and autonomous vehicle driving and robotics [1]. Sometimes, and especially in the last two mentioned areas, objects lying into the scene have to be detected accurately to allow truthful geometrical measurements of their dimensions and spatial positions. In our work, we decided to use a Time Of Flight (TOF) laser scanner by Sick to detect the sail shapes of a small yacht during navigation. The aim was to perform some geometrical measurements on the flying sails in order to evaluate their performances in terms of driving force transmitted to the boat under specific wind condition and sail trimming. The need to characterize the used sensor came out. Many works regarding the characterization of different laser scanner have been published in the last decades. C. Ye et al. [2] tested a Sick laser scanner LMS 200 and other research groups exploited their characterization procedure to estimate the measurement uncertainty for their own devices and applications. A. Diosi et al. [3], for example, extensively characterized another laser scanner from Sick (a PLS101-112 model) and they proposed a systematic error model that might be applied to devices based on similar principle of operation. M. Alwan et al. [4] tested a Infrared Range-Finder PBS-03JN, while L. Kneip et al. [5] characterized a compact Hokuyo considering the dependencies of the measures on operational time, target properties and position. They also performed the tests at night to remove the effect of the ambient light. K. Lee et al. [6] performed the same tests onto two different devices to compare their behavior in detail. For our application, we selected a laser scanner by Sick as the one used by C. Ye. They considered a LMS 200 model for short-range (maximum 10 m) indoor measurements. We decided to characterize a newer product, a Sick LMS 511 PRO, for wide range (up to 80 m) outdoor uses. Taking into consideration our application, we also performed tests onto specific material used in the nautical field for sail production. This paper is organized as follows: in

Section 2 a short functional overview and some technical specifications for the LMS 511 are presented. In Section 3 the experimental setups for the considered tests are described, while Section 4 presents the obtained results.

2. The Sick LMS 511 Laser Scanner

The Sick LMS 511 is a laser scanner based on time-of-flight (TOF) technology. The operating principle is widely described in [7] and [8], while a schematic representation is reported in Figure 1: a pulsed infrared laser beam at 905 nm is emitted and reflected on the target surface back to the sensor.

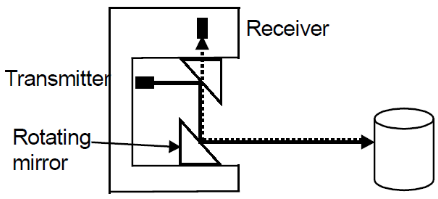
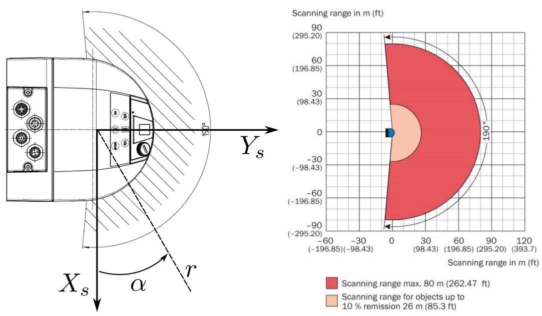


Figure 1. SICK Operating Principle Scheme

The time between the transmission and the reception of the laser beam is used to measure the distance between the scanner and the object. The sensor scans the surrounding perimeter on a plane, thanks to a rotating mirror that deflects the laser beam, so the position of the object is given in the form of distance and angle, as in Figure 2.



(a) Sick1 (b) Sick2

Figure 2. SICK Scanning Principle Scheme and Range of Measurement

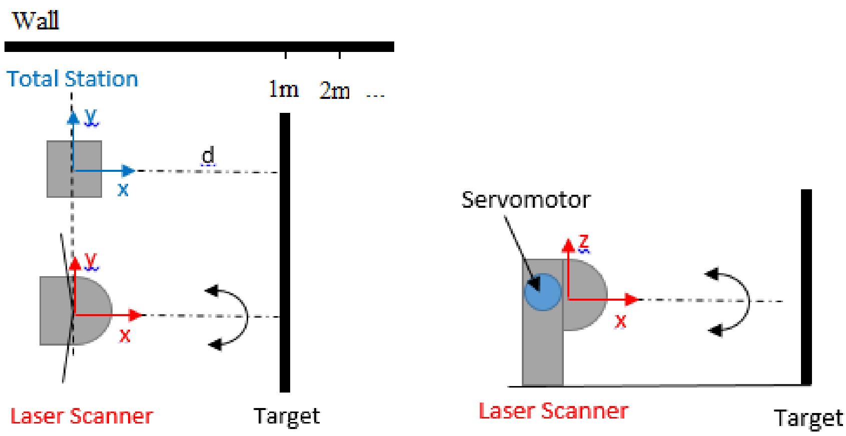
The LMS 511 operates with many possible scanning frequencies (25 Hz - 35 Hz - 50 Hz - 75 Hz - 100 Hz), therefore achieving different angular steps for every configuration. Since the field of view is 190 °, with a starting angle of -5 °and a stop angle of 185 °(see Figure 2), the angular selectable resolutions are 0.167 °, 0.25 °, 0.333 °, 0.5 °, 0.667 °and 1 °. We selected a value of 0.5 °and fixed it for all the tests. Thus, each scan is composed of 381 measured points. According to the manufacturer's specifications [9], the scanner can measure ranges up to 80 m for 100% of object remission with accuracy of ±12 mm at a distance of 6 m. For a 10% target remission, the device presents for distances of 1 to 10 m a nominal systematic error ±25 mm and a statistical error ±7 mm; for distances 10 m to 20 m the nominal systematic error is ±35 mm and the statistical error is±9 mm.

3. Experimental Setups

Acquisition and saving of the data were performed through a dedicated software developed in LabVIEW environment, while the data processing was mostly computed through Matlab scripts. 1000 measurements were performed for each tested configuration, at a room temperature 20±2 °C. A setup using a linear guide, as commonly exploited in [2], [5] and [4], could not be easily realized due to the extended measurement range of interest. In fact, as mention above, the sensor is conceived to be used for scanning small yacht sails that generally present mast high up to 12 m. Two different setups were utilized depending on the type of test to be carried out.

3.1. Setup A

The experimental setup for tests regarding the influence of target distance and material properties is shown in Figure 3.



(a) SetupA1 (b) SetupA2

Figure 3. Setup A. Schematization of the setup components viewed from the top (a) and from a side (b).

The adopted reference was a wall of the wind tunnel of the Politecnico di Milano, which is planar and smooth to avoid any turbulence; and using a Leica Total Station we marked the ground at different distances. We placed the laser scanner parallel to the wall and the planar target perpendicular to it (see Figure 3 - left). In order to properly measure the distance to the target, a whole scan in the XY plane was registered and the beam presenting the minimum distance value was detected. Then, we adjusted the tilt angle of the scanner moving the servomotor 0.5 °each step up or down since a minimum value for the beam selected before was found (see Figure 3 - right). This procedure guaranteed that the scanner measured always the true distance, and that the target plane was always perpendicular to the wall while moving away from the scanner. The distances measured by the LMS 511 were compared to those obtained through the Total Station aligned to the scanner and whose accuracy (0.25 mm at 35 m) is by far smaller than the one of the laser scanner.

3.2. Setup B

A second setup was built up for the tests on the dependency of the angle of incidence between target surface and laser ray direction. Figure 4 shows it.

This setup is composed of a planar base over which a second element can rotate, ensuring that no translation is implied. This movement is obtained inserting a small shaft in the rotating

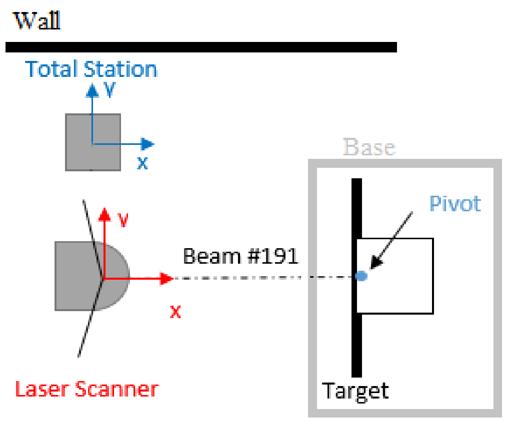


Figure 4. Setup B. Schematization of the setup viewed from the top.

element, that will be inserted in a corresponding hole in the base. Using well-shaped elements and high precision tools we can assure that the faces of the structure are parallel or perpendicular each others. A metal plate is also added to tighten the grip of the shaft on the rotating element, as visible in Figure 4. A goniometer is used only to achieve a coarse measurement of the rotation, while the exact value is given by the computation of the orientation of the plane that fits nine sample points on the target acquired by means of the Total Station. During the orientation test the rotating element was changed to a board supporting the SICK LMS511, while the target was held in the same place, allowing to check the response of different beams ensuring a target at the same distance.

4. Characterization of the LMS 511

This section presents the results of all the tests carried out. First, the effect of drift is analyzed; then the influence of the distance between target and sensor, the target properties (in terms of color and material), the ray orientation and the incidence angle are investigated. Considering the outdoor application, also the influence of lighting conditions is examined, and finally a test showing the mixed pixel problem is reported.

4.1. Drift Effect

Since the warm-up time is expected to increase by increasing the measured distance –as suggested by [6] — , the drift effect was analyzed placing the target at the maximum distance of interest (12 m). The LMS511 sampled 13500 full scans, over a stretch of time of about 2 hours. The results are visualized in Figure 5.

Note that there is not an evident drift effect, neither on the average value nor on the standard deviation of the measurements. This means that the LMS511 is a prompt sensor and does not need a warm-up time. This result is in contrast with the majority of the previously mentioned papers in which the authors highlighted an hour-minimum warm-up time. The test was then repeated at a different distance to verify the results, confirming the above. Moreover, to reject the hypothesis of a warm-up time longer than two hours, an experimental campaign of 9 hours was conducted. Once again, the results were confirmed. Table 1 below presents the trend of the average distance for each hour and the correspondent standard deviation. No significant trend is evinced.

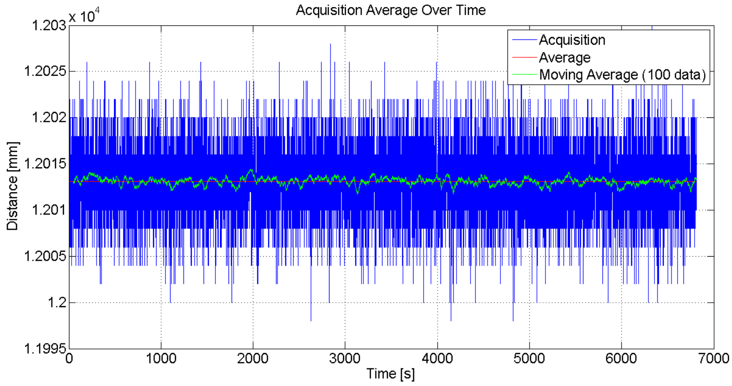


Figure 5. Drift Effect over 2 hours, there is no evident trend in the mean of the measurements.

Hour #	Mean [mm]	Standard Deviation [mm]
1	2971.8	4.2
2	2971.2	4.0
3	2971.1	3.9
4	2971.0	3.9
5	2971.1	4.0
6	2971.2	4.0
7	2971.2	4.0
8	2971.2	3.9
9	2971.1	3.9

Table 1. Drift Effect over 9 hours

4.2. Distance Effect

A planar target was placed in front of the scanner at different distances: from 2 m to 12 m with steps of 2 m each, following the procedure described in Section 3.1. Tests beyond 12 m were not performed as they would overcome the purpose of this paper. Figure 6, 7 and 8 show the absolute and percent errors and the standard deviations respectively.

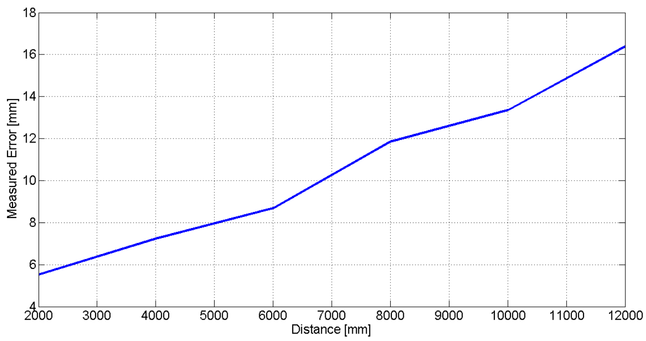


Figure 6. Distance Absolute Error, it increases almost linearly.

The standard deviation varies approximately from 3,5 mm to 4 mm. These absolute values, that meet the manufacturer's specification, can be considered not relevant if compared to the distance measured and the purpose of getting the sail shape.

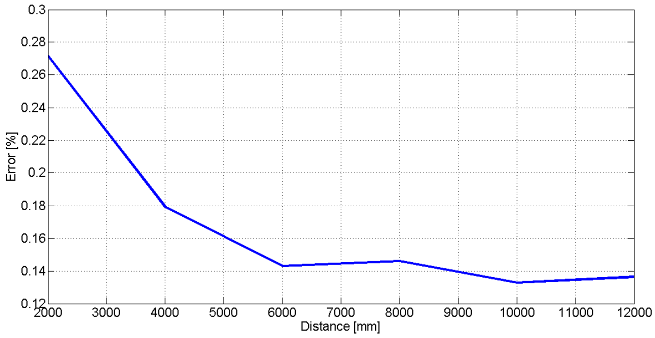


Figure 7. Distance % Error, in the range analyzed has an inverted proportionality relation with the distance.

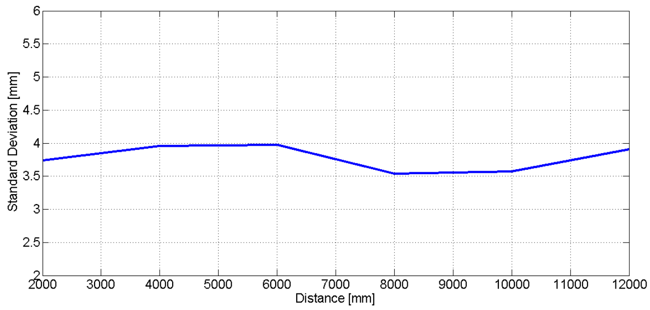


Figure 8. Distance Standard Variation, its trend does not vary significantly with the distance.

4.3. Material Effect

Dependency on the target material properties is discussed in this Section. The experimental setup is depicted in Section 3.1.

To allow the comparison of our results with those obtained by other researchers, we carried out experiments onto some common target materials:

- Wood
- Cardboard
- Aluminum
- Plastic

In addition, considering our specific application, other two targets were built up:

- Reflective tissue
- Sail tissue

Basically, for each material, the planar target was placed in front of the scanner at a distance of around 2 m. The beam perpendicular to the target was identified by searching for the minimum measured distance among those corresponding to the target. 1000 whole scans were acquired for each material. Only distances registered by the perpendicular beam were considered. Figure 9 shows the distribution of the 1000 scans.

Note that the material presenting the lowest standard deviation (3,3 mm) is the reflective one (red line). This could be due to the higher signal intensity that reaches the receiver. The worst material came out to be the sail tissue: standard deviation (4,1 mm, black line). This

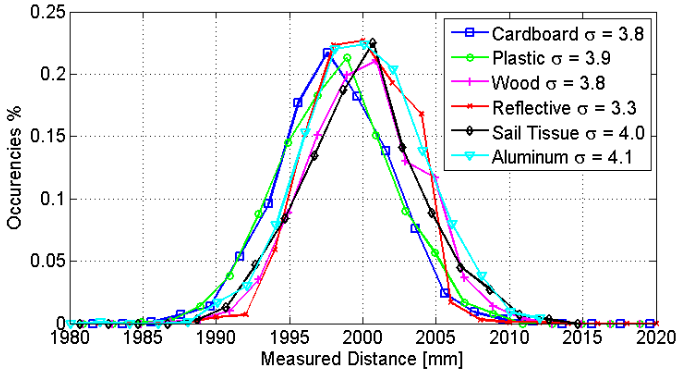


Figure 9. Distributions of ranges sampled for target covered in different materials.

is probably due to the transparency of the mold that did not reflect properly the laser signal. Figure 10 reports a picture of the sail highlighting the transparency of the surface (note the cloud beyond the sail).

Figure 10. Transparency of the sail tissue

4.4. Color Effect

In this section, the effect of the target color is discussed. Different colored adhesive films were pasted, one after the other, onto a glass planar surface placed at a fixed distance of 2000 mm far from the sensor. 1000 scans were acquired for each film. Once more, the data could be approximate by a normal distribution and mean values and standard deviations were computed. Various colored films were available, but we limited the analysis to the most interesting cases suggested by [2], [4] and [3]. In particular these cases are: green, yellow, black, and two different gray level films. Figure 11 shows the results for these tests.

From these tests, we can state that the effect of the color does not influence significantly the measurements. However, looking into detail, we can notice that:

- dark gray and the black target present the highest values of spread (standard deviation respectively 4,0 and 3,9 mm)
- dark gray target presents the worst performance (maximum displacement to the nominal distance: 14,7 mm)
- light grey test presents the best performance (minimum displacement to the nominal distance: 2,3 mm)

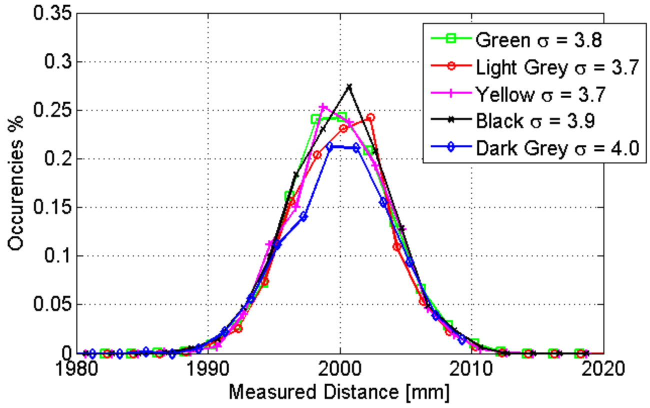


Figure 11. Distributions of ranges sampled for target placed at 2000 mm and covered with the adhesive film of different colors.

Color	Mean [mm]	Standard Deviation [mm]	Nominal-Measured Distance [mm]
Green	1997.8	3.8	2.2
Yellow	2005.3	3.8	5.3
Black	2005.3	3.9	5.3
Light Grey	1997.7	3.7	2.3
Dark Grey	2014.7	4.0	14.7

Table 2. Values of the colors test comparison, the light gray film was the one with the narrowest response.

Thus, we can conclude that brighter targets lead to slightly better performances, probably because of a better reflection of the laser signal. The results obtained are in agreement with the ones reported in the previously mentioned works. Comparing the spread of the measures obtained testing the sail tissue (4,1 mm) to the one obtained in the light gray test (3,7 mm), we thought of coating the sail with this bright film to increase the quality of the field measurements.

4.5. Angle Effect

Considering Setup B (see Section 3.2), the wooden target placed at a distance of 1000 mm is rotated from 0 °(target facing frontally the sensor) to 80 °, with step of 10 °each. The aim is to investigate the influence of the angle of incidence between the laser beam and the target surface. 1000 scans for each angle were acquired, and only the distances retrieved by the central ray were considered. Afterward, the target was moved away from the scanner to reach the distances of 2000 mm and 3000 mm, and the procedure was repeated to support the first test. Figure 12 presents the standard deviation trends for the three distances as a function of the angle of incidence between the laser beam and the target surface.

Standard deviation trends look similar for the three tested distances and the values are comparable with those shown in the Sections above up to an incidence angle of approximately 70 °. A more oblique beam leads to a considerable increase in the data spread. This test was of particular interest to understand some faulty measurements in the data acquired on the boat. In fact, the sensor placed astern and scanning the mainsail was not able to estimate a distance for some point on top of the sail since the laser beams reached the surface with an angle wider than 70 °.

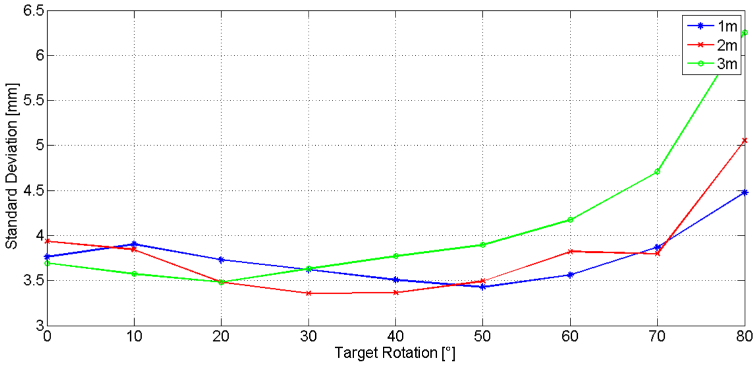


Figure 12. Angle Effect: influence of the rotation of the target on the standard deviation of the measures. Trends for tests at different distance are compared, in all tests over 70 °the standard deviation values rise considerably.

4.6. Angulation Effect

Different from the previous test, this test aims to clear the possible differences in data returning from different angles (i.e. different beams) to the scanner. Recalling the operating principle, these could be caused by imperfection in the rotating prism inside the scanner. For this test the scanner was placed onto the rotating base and the target was fixed at a distance of 2000 mm. The scanner was rotated and 1000 measurements were acquired for the beam perpendicular to the target. The setup is schematized in Figure 13.

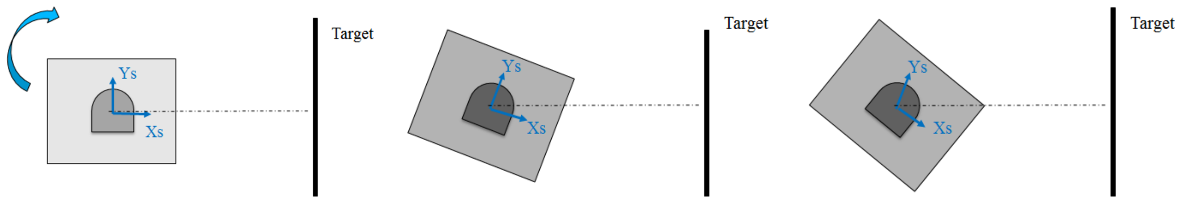


Figure 13. Setup Angulation Test: the scanner is progressively rotated.

Results for the experiments are shown in Figure 14.

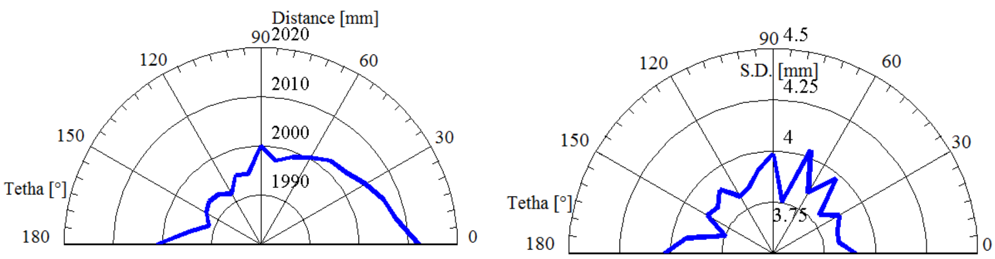


Figure 14. Effect of angulation on measurement: standard deviation is not influenced while distance measurement presents a bigger error for the beams related positive Xs values.

Note that the resulting standard deviation values are all included between 3.7 mm and 4.0 mm, consistent with the previous considerations. On the other hand it seem that the sensor slightly overestimates the distance in the first section of the acquisition, from 0 °to 60 °, and it underestimates it on the opposite side, from 90 °to 180 °. Note that this effect could be due to a misalignment of the center of rotation used from the position of the reference axis of the SICK scanner. The manufacturer assured that they are placed exactly in the middle of the geometrical size of the unit, but the impossibility to open it prevented to verify this information.

4.7. Light Effect

Other faulty cases came out during on field acquisitions because of the sun light that directly hit the scanner. Thus, the effect of an intense light source onto the sensor performances was investigated. To reproduce this situation a lamp was placed beyond the sail target, so that the source of light was completely covered by the sail tissue and then progressively moved close to an edge until it came out completely. The relative distance between sensor and sail tissue did not change. A similar test was carried out outdoor, placing the laser scanner and the sail target in the sun light direction. As one can see from Figure 15, the light source impaired the measures. Moreover, as soon as the light entered the sensor, the standard deviation increased almost three times.

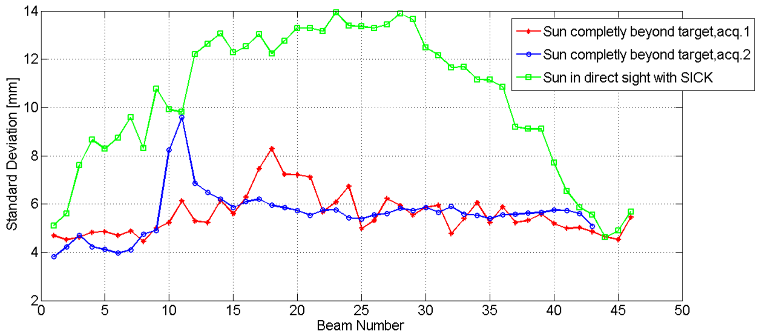


Figure 15. Light Effect: the peak in the blue and red curves corresponds to the position of the sun beyond the target. For each case the measurement standard deviation worsen with respect to a standard lighting case, but the worst situation occurs when the sun hits directly the scanner (+ 350% Standard Deviation).

4.8. Mixed Pixel

The mixed pixel problem occurs when the spot mark of the laser beam, that hits the tested surface, falls on the edge of the target. For that point, the sensor averages the contribute of the signal reflected by the target and the one reflected by the background leading to an averaged estimated distance. Two tests were reported to verify that the mixed pixel problem occurs independently from the gap distance between target and background: test 1 considered a target placed at 1000 mm far from the sensor and a background at 2000 mm; test 2 considered a target placed closer to the background (at 1750 mm far from the sensor). Figure 16 shows these tests.

Both scans present non physical points in the gap between the planar target and the background due to the averaged distance performed by the scanner. Concerning our application, we can correlate the sail surface to the target and the sky to a background placed at an infinite distance from the sensor. Thus, we performed a test with a planar target oriented towards the sky. No mixed pixel error was evident. This is probably due to the fact that the only contribute that can be measured is the one coming from the spot mark onto the sail surface. This might be too low to let the sensor evaluate a distance and thus the point is lost.

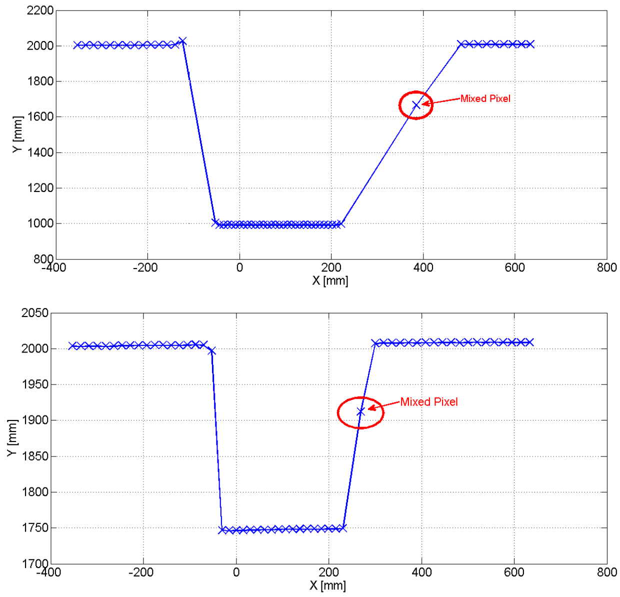


Figure 16. Mixed Pixel: two cases of occurrences. The target profile distortion is more prominent with the higher target-background distance.

5. Conclusions

This work aimed at characterizing a laser scanner, the LMS 511 Pro manufactured by Sick: different tests to investigate several aspects that could affect its measures were performed. From the drift test it is concluded that the instrument does not suffer from a notable warm-up time, unlike others analyzed in previous literature. In the considered range (1m - 12m) the distance error is within the expected tolerance (max 0.27% of measure), while the standard deviation is bounded from 3.5 to 4 mm without an evident correlation with the distance. A comparison of the measurement distribution coming from different materials showed that the sail tissue does not have a good response with respect to others. As expected, a reflective tissue has the lowest measure spread, and could be used to improve the acquisition field, wrapping the target with it. Another possibility is to use an adhesive film, as its color affects the quality of measurement. From the different available colors, the best are light gray and yellow, generally leading to the conclusion that a brighter color leads to a better result. We showed that the effect of the incident angle rises increasing the distance and that a limit angle, around 70 °, is present, over which the accuracy of the laser scanner sensibly drops. The measure is more deeply influenced by the angulation from which the target has been recorded, as the distance is underestimated or overestimated in function of the acquisition angle. Moreover, we proved that the lighting condition affects greatly the measures, as their standard deviation could increase by 50% where the sun is beyond a transparent target and up to 350% when the sun light hits directly the sensor. Finally some cases where the laser scanner fails to correctly detect the target are displayed; these are due to the mixed pixel problem, which occurs when both the target and the background are within the scanner's range, while for outdoor tests, without a fixed background this does not happen, but could lead to a loss of some data points. At the end of the characterization not only we have concluded that the considered scanner has met the manufacturer's specification but also found a quick and inexpensive way to improve the quality of the acquisitions. Moreover, we turned this device originally designed as safety barrier into an effective measurement instrument. Future work could be addressed to find a suitable calibration and/or range measurement model, and adding more tests performed under different ambient conditions, to further explore the scanner behavior.

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