Investigation of the Influence of Surface Reflectance on the Measurements with the Terrestrial Laser Scanner Leica HDS 3000

Yuriy Reshetyuk

Summary
The results of some indoor laboratory experiments are presented aimed at the investigation of the relationship between the surface reflectance and the measured range and intensity with terrestrial laser scanner Leica HDS 3000. Depending on the surface material, offsets are introduced into the measured ranges. The recorded intensity allows one to differentiate between different materials and to detect the surface condition (wetness – in the case presented in this paper).

Zusammenfassung
Es werden die Ergebnisse einiger Innenlaborexperimente vorgestellt, die auf die Erforschung der Beziehungen zwischen dem Oberflächenreflexionsvermögen und der gemessenen Strecke und Intensität mit dem terrestrischen Laserscanner Leica HDS 3000 abzielen. In Abhängigkeit vom Oberflächenmaterial wird Versatz in die gemessenen Strecken eingeführt. Die aufgezeichnete Intensität ermöglicht eine Unterscheidung zwischen verschiedenen Materialien und die Bestimmung der Oberflächenbeschaffenheit (Feuchtigkeit – in dem Fall, der hier vorgestellt wird).

1 Introduction

The fundamental property of terrestrial laser scanning (TLS), as a reflectorless survey technique, is the strong dependence of the measured range and intensity on the surface reflectance. Additional factor to be considered is the laser wavelength λ: for different parts of the electromagnetic spectrum the interaction of the laser beam with the surface will be different. The laser scanner discussed in this paper, Leica HDS 3000, operates in the visible region (λ = 532 nm). Knowledge of the relationship between the surface reflectance and laser measurements is very important, because it allows the user to make more sound statements on the accuracy that can be achieved and how the results can be improved when the reflective properties of the surface are taken into account. Thus, a detailed study of this relationship has been conducted. In addition to surface reflectance, the effect of ambient illumination and the relationship between the surface reflectance and surface condition (in our case: surface wetness) has been investigated as well. During these experiments, a number of different materials were scanned three times each:

- with the lights on
- in the darkness
- with the lights on and wet surface of the material.

The investigations were conducted indoors in December 2004.

2 Description of the experiments

The following materials (the samples have different sizes) were scanned with the sampling resolution 5 × 5 mm:

- a metal survey target painted with »warning« colours (red and yellow) (Fig. 1)
- a piece of pressed cardboard painted black
- a piece of synthetic material with porous surface
- a piece of untreated wood
- a piece of wood with a polished surface
- a piece of aluminium
- a stone slab.

Fig. 1: Survey target used in the experiments.

The experimental setup was similar to that used by Lichti and Harvey (Lichti and Harvey 2002). All the samples scanned were placed on the table, about 10 m from the scanner, with two heavy boxes on it to prevent its movements while changing the objects. The samples were aligned with a line drawn on the table, parallel to its edge, and set at a vertical position with a ruler as precisely as possible, in order to ensure that the surface of each object was at the same position with respect to the scanner. Unlike in Lichti and Harvey 2002, the objects were watered in a contact way, with a cloth. The restoring of the objects' position was, however, made as carefully as possible, so it may be assumed that they occupied the same place.

In addition to the »reflectance tests«, the following issues have been investigated:

1. The »mixed pixels« problem, which occurs when a laser footprint falls at the edge of two surfaces separated by a certain distance. Since the range is measured by integrating over the footprint area, the measured range can be anywhere along the line of sight (Hebert and Krotkov 1992). Not only has the magnitude of the error but also its dependence on the type of material been determined.
2. Range/reflectance crosstalk – the difference of the measured range and intensity at the surfaces of different reflectance, but at the same distance from the scanner. For this purpose, a piece of black cardboard with

an A4 sheet of white paper attached to it was scanned at the table.
3. Effect of the beam incidence angle on the recorded intensity. A narrow section of the white concrete wall (from about 3 m distance) was scanned with the lights on and in the darkness, so that the resulting point cloud had the variable angle of incidence (from 0° to about 60°).
4. Reproduction of the object spectral reflectance by the scanner. For this purpose, several photographic calibration targets – reference objects used for exposure evaluation and control of the quality of the photographic process – were scanned:
   - Densitometer calibration black-and-white target – a circular, plastic, two-sided (black and white sides) target;
   - Kodak grey card – a rectangular cardboard grey-colour target;
   - Kodak colour control target – a cardboard target consisting of 10 rectangular colour patches (see Fig. 8).

The first two targets were scanned from the ranges of about 2 m and 10 m, the last one was scanned only from about 2 m. These targets have been taken because they have surfaces with known spectral reflectance, which can be compared with the intensity recorded by the scanner, and the conclusions can be drawn concerning how the object reflectance is reproduced by the laser scanner.

3 The results

For the purpose of the following discussion, a short summary of the results obtained in Lichti and Harvey 2002 is presented in Appendix A. For more details, the reader is referred to this reference.

3.1 »Reflectance tests« with different materials

The results are summarized in Tab. 1 to Tab. 3 below. For each scan taken, the following was performed:

- The scanned surface was segmented from the rest of the point cloud. The surface points were exported to MATLAB® and the mean intensity and range and their standard deviations were computed. The results are shown in Tab. 1 and Tab 2. Similar computations were made in Lichti and Harvey 2002.
- A plane was fitted to the surface and the statistics of the quality of the fit were computed (Tab. 3). The quantities in Tab. 3 refer to the distances between the points belonging to the object surface and the surface fitted.

Scanning the surface of the survey target (Fig. 1) resulted in recording two surfaces separated by a distance

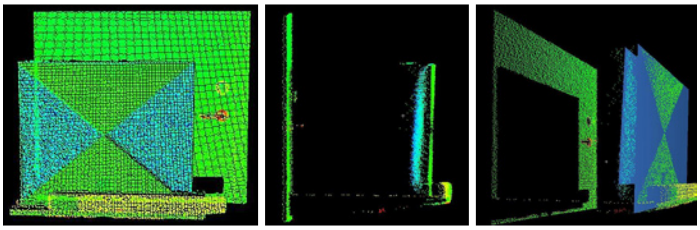

Fig. 2: Scan of the survey target shown in Fig. 1. Left: front view of the scan; the red and yellow parts are coloured in blue and green, respectively. The moiré pattern is due to the insufficient display resolution. Centre: side view of the scan where the range offset is clearly seen. Right: planes fitted to each part of the survey target.

of roughly 5 cm and corresponding to the red and yellow parts (Fig. 2). Such an outcome was, in principle, expected since it has been confirmed in a number of tests (see e. g. Boehler et al. 2004) that very bright colours (like those in which the target was painted) may produce significant range offsets, due to the detector saturation. In this study, the result obtained is rather a very good demonstration of the range-reflectance crosstalk mentioned above. The red colour was much brighter than the yellow one, which produced such a large offset. In this case we can rather speak about the influence of the *colour* of the surface on the range measurements, rather than the surface *material* (since the whole target is made of steel). A study of the influence of different colours on the laser scanner measurements (Cyrax 2500 scanner) was conducted by Clark and Robson 2004. Because of the fact mentioned above, two separate planes were fitted to the two parts of the target and all further computations were made separately for each part.

The analysis of the results shows the following:
1. It is possible to distinguish between different materials used in the experiment based on the recorded intensity. Most of the intensities recorded are in quite a narrow range 0.45–0.59, however.
2. Wetness of the surface leads to the changes in the intensity standard deviation (Tab. 1) of all the materials used in the experiments, to a smaller or larger degree. The change is most significant for the yellow part of the survey target, black cardboard, aluminium and stone slab. This means that the condition of the surface (in this particular case: wetness) can be determined by investigating the intensity distribution in the point cloud of this surface. In fact, the results obtained agree with the results obtained in Lichti and Harvey 2002. The mean recorded intensity in general does not change significantly when the surface is wet. The change is most noticeable for the wood, black cardboard, stone slab (decrease) and yellow part of the survey target (increase). This allows us to assume that the mean intensity decreases with wetness when the surface is composed of the absorbing material (like the first three surfaces).

Tab. 1: Intensity statistics for the surfaces scanned

Material	With the lights on		In the darkness		Wet	
	Intens. mean	Intens. std.	Intens. mean	Intens. std.	Intens. mean	Intens. std.
Wood	0.4704	0.0050	0.4710	0.0064	0.4647	0.0053
Polished wood	0.4791	0.0172	0.4790	0.0173	0.4797	0.0196
Synth. mater.	0.5404	0.0103	0.5405	0.0098	0.5396	0.0100
Survey target						
– Red part	0.5858	0.0190	0.5863	0.0201	0.5865	0.0196
– Yellow part	0.5114	0.0085	0.5117	0.0070	0.5184	0.0121
Black cardb.	0.4415	0.0050	0.4416	0.0051	0.4370	0.0152
Alum.	0.5523	0.0134	0.5519	0.0143	0.5552	0.0081
Stone slab	0.4594	0.0042	0.4593	0.0047	0.4504	0.0078

Tab. 2: Range statistics for the surfaces scanned. Unit: m

Material	With the lights on		In the darkness		Wet	
	Range mean	Range std.	Range mean	Range std.	Range mean	Range std.
Wood	9.033	0.004	9.033	0.004	9.032	0.004
Polished wood	9.028	0.011	9.028	0.011	9.031	0.011
Synth. mater.	9.036	0.007	9.036	0.007	9.036	0.007
Survey target						
– Red part	9.077	0.016	9.079	0.016	9.077	0.018
– Yellow part	9.027	0.009	9.026	0.009	9.030	0.008
Black cardb.	9.028	0.009	9.029	0.009	9.028	0.008
Alum.	9.029	0.004	9.029	0.005	9.031	0.004
Stone slab	9.018	0.009	9.020	0.009	9.021	0.009

Tab. 3: Statistics on the quality of plane fits to the surfaces scanned. Unit: mm

Material	With the lights on			In the darkness			Wet		
	Error Std.	Abs Error Mean	Max Abs Error	Error Std.	Abs Error Mean	Max Abs Error	Error Std.	Abs Error Mean	Max Abs Error
Wood	3	2	9	3	2	10	3	2	9
Polished wood	3	2	10	3	2	11	3	2	12
Synth. mater.	3	2	16	3	2	9	3	2	14
Survey target									
– Red part	7	6	28	8	6	32	9	7	36
– Yellow part	3	2	16	3	2	18	3	2	12
Black cardb.	2	2	9	2	2	11	2	2	9
Alum.	2	1	6	2	1	6	2	2	11
Stone slab	2	1	6	2	2	10	2	2	10

3. An interesting phenomenon was observed for the black cardboard surface. The change in intensity due to wetness can be seen directly from the point cloud (Fig. 3), unlike the rest of the surfaces. One can clearly distinguish the wet parts of the surface identified by lower intensity (red colour). This fact explains the significant increase in the intensity standard deviation in the case of »wetness« (three times!) for this surface (see Tab. 1).
4. No considerable changes in the intensity and range means and standard deviations were observed between the scans taken with the lights on and in the darkness (Tab. 1 and Tab. 2). Based on the results of the experiment, one can state that the regular indoor illumination does not exert any tangible influence on the results of the scanning.
5. The range standard deviation for most of the surfaces is at the level of 1 cm (Tab. 2); it is at 4 mm level – range accuracy declared by the manufacturer – only for the wooden and aluminium surfaces. The largest deviation was observed for the red part of the survey target (about 2 cm). In addition, an offset of roughly 5 cm is present in the range to this surface, probably because of the detector saturation. Please note that in spite of high reflectance, the measured range is larger than it should be (based on the results obtained for the rest of the surfaces), while the opposite was expected. The measured range to the synthetic material also somewhat deviates from the ranges to the other surfaces, possibly due to the laser beam penetration. A bit surprising were range measurements to the stone slab – a constant offset from the rest of the surfaces of about 1 cm is present.

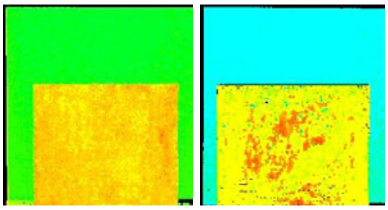

Fig. 3: Results of scanning dry (left) and wet (right) black cardboard surface. The red spots of lower intensity correspond to wet areas. The reason for the change in the intensity of the wall in the background in the right-hand image is so far unknown.

6. For some materials (polished wood, aluminium, stone slab and yellow part of the survey target) a systematic increase in the measured range by 2–3 mm has been observed for the wet surface. In Lichti and Harvey 2002 such changes were considered as insignificant since they are below the accuracy of the individual measurements (4 mm). For the rest of the materials the changes are even smaller (up to 1 mm) and cannot be attributed to some systematic effects.
7. The modelled precision (absolute error mean in Tab. 4) for most of the surfaces is within the limits specified by the manufacturer (2 mm). The only exception is the red part of the survey target showing quite a large error (6–7 mm) because of high surface reflectance. The maximum absolute errors are at 1 cm level for most of the surfaces, which can be considered as good, taking into account that HDS 3000 data has in general a root mean square error of 6 mm. Slightly larger values are obtained for the synthetic material and yellow part of the survey target. The errors are largest (28–36 mm), once again, for the red part of the survey target.
8. It should be noted that the observed range differences between the different materials used in the tests could be partially attributed to the eventual alignment errors (cf. Lichti and Harvey 2002).

In general, the results of the experiment agree with the results obtained in Lichti and Harvey 2002 for different surface materials with the scanner Cyrax 2400 and similar experimental setup. Additionally, the effect of the ambient illumination on the laser scanning measurements has been investigated in our case.

3.2 Range/reflectance crosstalk

The point cloud obtained in this experiment is shown in Fig. 4. A row of pixels (laser beam responses) was extracted from the point cloud and the range and intensity values are plotted in Fig. 5.

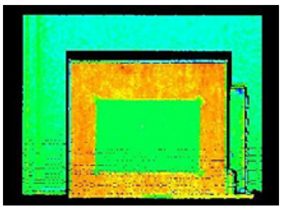

Fig. 4: Point cloud obtained in the range/reflectance crosstalk experiment. A sheet of white paper (green) is markedly contrasted with the black cardboard (brown).

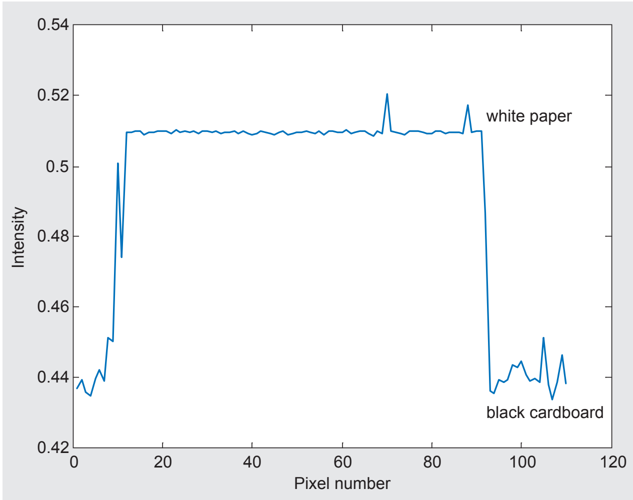

Fig. 5: Intensity jump as the beam crosses the boundary between the white paper sheet and black cardboard surface.

As one might expect, an abrupt change (about 0.07) in the recorded intensity is present between the black and white surfaces. The results agree with those obtained by Hebert and Krotkov 1992 with a phase-based laser rangefinder. The planes were fitted to the white and black parts and the distance between them was 3 mm. This can be regarded as the magnitude of influence of the range/reflectance crosstalk on the range measurements with the laser scanner for this case. In general, this magnitude is a function of the type of the surface material or colour; for example, the error for the survey target was about 5 cm.

3.3 The »mixed pixels« problem

The mixed pixels can be clearly seen in the point cloud (Fig. 6). For the purpose of our tests, the points at the upper edge of each sample (for the case with the lights on) were extracted together with the mixed pixels corresponding to this edge and the means and standard deviations of the ranges to the edge and the intensity values at the edges were computed in MATLAB®. The results are shown in Tab. 4.

The distributions of the range and intensity measurements are shown in the histograms in Fig. 7. In all of these cases the mixed pixels emerged due to the reflec-

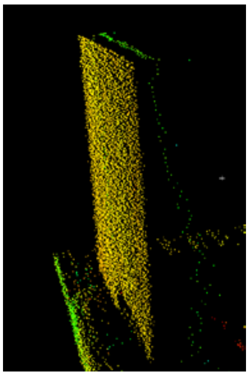

Fig. 6: Fragment of the point cloud of the piece of the black cardboard. The mixed pixels close to the upper edge are clearly visible (green).

Fig. 7: Range and intensity histograms for the »mixed pixels experiment«. Frequency refers to the number of the responses.

Tab. 4: Range and intensity statistics for the »mixed pixels« experiment

Material	Range, m		Intensity	
	Mean	Std.	Mean	Std
Wood	9.073	0.041	0.5129	0.0444
Polished wood	9.027	0.011	0.4921	0.0186
Synth. mater.	9.078	0.037	0.5198	0.0315
Survey target – Yellow part	9.039	0.038	0.5546	0.0246
Black cartb.	9.036	0.018	0.4739	0.0335
Alum.	9.041	0.018	0.5475	0.0221
Stone slab	9.043	0.029	0.4813	0.0249

tion of the part of the laser beam from the wall behind the samples (for large samples) or from the wooden boxes on which the samples were leant (smaller samples). The comparison of these results with those given in Tab. 1 and Tab. 2 shows that considerable biases are introduced into the range measurements. The mixed pixels increase the range standard deviation to the order of several centimetres. The only exception is the piece of polished wood, for which all the statistics remain at approximately the same level, except the change in the mean intensity. The range histogram for this surface gives, however, a more complete picture, showing that the same number of responses is recorded for the distances within the interval 9.01–9.04 m (3 cm!). The obtained value of the range 9.027 is »correct« (cf. Tab. 2) only by coincidence since it is approximately in the middle of this interval. Analysis of the histograms shows that the maximum error of the range measurements caused by the mixed pixels may reach the order of more than 10 cm. The largest error is obtained for the synthetic material. The intensity standard deviation increased in several times for all of the samples (except for the polished wood), and for the piece of untreated wood the increase was about one order of magnitude. In most cases the intensity of the mixed pixels was larger than that of most of the »correct points« in the samples, which is manifested by the increase of the intensity means. As can be seen from the histograms in Fig. 7, the intensity and range distribution for many surfaces is changed compared to the »no mixed pixels case« leading to the appearance of the two peaks corresponding to the »intensity (range) of the surface« and »intensity (range) of the mixed pixels«. This trend is most obvious for the wood, survey target (range) and black cardboard (intensity).

3.4 Photographic calibration targets

The results are presented in Tab. 5. As expected, they indicate a very low intensity variance due to the calibrated target reflectance. The recorded intensity and its standard deviation decrease with the increased range, the result that agrees with the results obtained in Lichti and Harvey 2002 for the natural surfaces at the distances 3 m and 53 m. A remarkable decrease in the intensity variance (six times) with the distance is observed for the white side of the densitometer calibration target. As one can see from Tab. 5, the reflectivity of the calibration targets covers wider range than intensities recorded with the laser scanner. Although, one cannot state that these reflectivity and intensity values are directly comparable. What can be seen from Tab. 5 is how the reflectivity of the calibration targets is reproduced by the laser scanner. This issue needs further investigation. Interesting results have been obtained for the Kodak colour control target (Fig. 8).

Tab. 5: The intensity statistics for the photographic calibration targets

Target	Range 2 m		Range 10 m	
	Intens. mean	Intens. std.	Intens. mean	Intens. std.
Densitometer calibr. targ., black side, refl. 3 %[1]	0.4458	0.0041	0.4395	0.0033
Densitometer calibr. targ., white side, refl. 76 %	0.5106	0.0018	0.5093	0.0003
Kodak Grey Card, refl. 18 %	0.4613	0.0026	0.4572	0.0025

1 Reflectivity of this target has been determined with the reflection densitometer SOS 40.

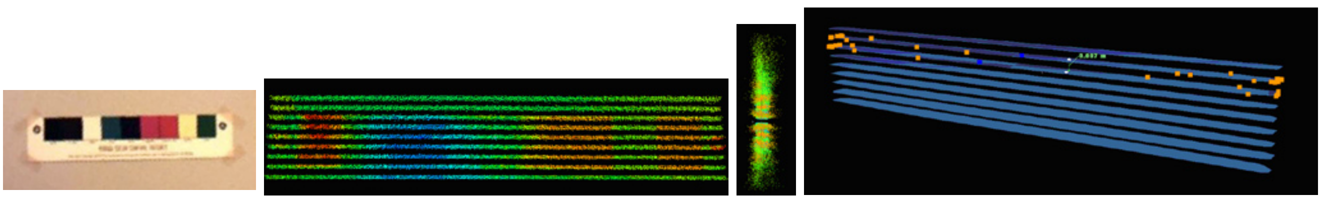

Fig. 8: Results of the experiments with Kodak colour control target. From left to right – image of the target; point cloud, front view; point cloud, side view; planes fitted to the target.

One can see that the recorded intensity differs depending on the colour of the patch: as expected, the highest values (shown in blue) are recorded for the patches with good reflectance at the wavelength of the laser (e. g. white) and the lowest (shown in red) – for those with poor reflectance (black and red). But the most remarkable result is that the point cloud is divided into nine equally separated *horizontal* strips. The planes were fitted to each of them and the distances between the planes were computed at 7 mm for each but the lowest two planes (the distances between them were 8 mm). The maximum error in the range direction was about 5 cm (»thickness« of the point cloud). The exact reason for such a result is so far unknown but it is assumed it could be caused by the range/reflectance crosstalk.

3.5 Relationship between the intensity and the laser beam incidence angle

A row of pixels was extracted from the two point clouds of the section of the wall, and the recorded intensity values were plotted versus the beam incidence angle. A 3rd order polynomial was fitted to the data. The results are shown in Fig. 9.

As one can see, the behaviour of the recorded intensity is basically the same, independent on the ambient illumination. High noise is present in the data but the general trend is obvious: the recorded intensity I is the highest at the incidence angle 0° after which it decreases a bit and remains at the same level from 10° to about 30°. Afterwards, the intensity drops rapidly as the incidence angle increases. This behaviour agrees, by and large, with the Lambertian reflectance model (Hancock 1999):

$$I \infty \frac{\rho \cos\theta}{R^2} \qquad (1)$$

where ρ is the surface albedo, θ is the beam incidence angle and R is the measured range. According to this model, the intensity decreases continuously with the increase in the incidence angle. The fact that the mean intensity between 10° and 30° remains at the same level points out to some deviations from this model. This phenomenon requires further investigation.

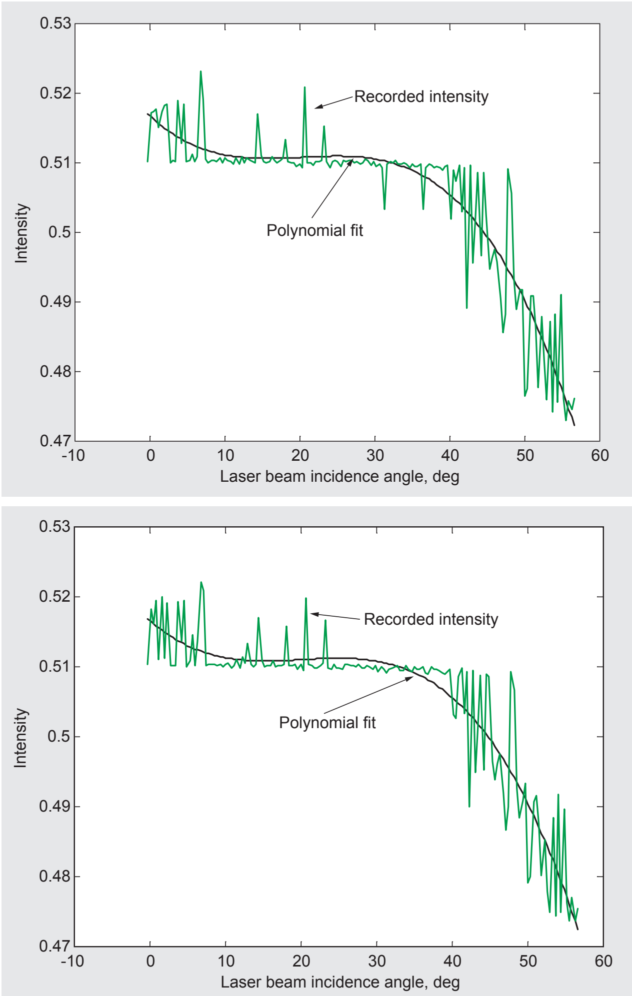

Fig. 9: Relationship between the recorded intensity and the laser beam incidence angle. Top: results for the case with the lights on. Bottom: results for the scan taken in the darkness.

4 Conclusions

The paper discusses the results of the experiments conducted with the laser scanner Leica HDS 3000, aimed at the determination of the relationship between the material surface reflectance and the measured range and intensity with the laser scanner. The setup for the experiments was partly borrowed from Lichti and Harvey 2002 and new investigations have been conducted. The results obtained can be summarized as follows:

- The recorded intensity allows one to distinguish between the different types of materials used in the experiments.
- The range measured to most of the materials did not exhibit significant variations; however, considerable offsets can be observed to the high reflectance materials (about 5 cm) and porous surfaces.
- The wetness of the surface scanned leads to changes in the recorded intensity distribution. The measured ranges are, generally, not affected by this factor.
- The »mixed pixels« phenomenon exerts considerable effect on the range measurements to the edges, depending on the material being scanned. The errors of 2–5 cm may be expected (more than 10 cm in the worst case).
- Indoor illumination does not exert any tangible effect on the recorded range and intensity.
- The results of the tests with the photographic calibration targets have shown that the recorded intensity

with the scanner is not reproduced at the same scale as the object spectral reflectance. In addition, some interesting effects have been observed with the colour calibration target.

- The relationship between the recorded intensity and the laser beam incidence angle follows, principally, the Lambertian reflectance model; some deviations are present however.

The last two issues need further investigation.

Acknowledgements

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Appendix A

A short summary of the results obtained by Lichti and Harvey 2002 is given (Tab. A1). The experiments were conducted at the ranges 3 m (indoors) and 53 m (outdoors). Only the results for the first case are presented as comparable to our results.

Tab. A1: Range and intensity statistics for different materials scanned in Lichti and Harvey 2002 at the range of 3 m (from ibid.)

Material	Condition	Range statistics, m		Intensity statistics	
		Mean	Std.	Mean	Std.
Red brick	Dry	3.063	0.005	0.25	0.02
	Wet	3.063	0.004	0.22	0.03
Limestone	Dry	3.062	0.006	0.39	0.03
	Wet	3.064	0.005	0.46	0.09
White granite	Dry	3.068	0.006	0.35	0.05
	Wet	3.066	0.007	0.42	0.16
Black coal	Dry	3.061	0.005	0.17	0.03
	Wet	3.061	0.005	0.25	0.09
Concrete	Dry	3.063	0.006	0.30	0.02
	Wet	3.062	0.006	0.25	0.05
Basalt	Dry	3.065	0.005	0.30	0.05
	Wet	3.071	0.009	0.59	0.31
Laterite	Dry	3.065	0.007	0.26	0.04
	Wet	3.065	0.007	0.29	0.11
White quartz	Dry	3.069	0.007	0.32	0.06
	Wet	3.070	0.007	0.35	0.13

Author's address:
Yuriy Reshetyuk, MSc., doctoral student
Department of Transport and Economics
Royal Institute of Technology (KTH)
Drottning Kristinas Väg 30
S-10044 Stockholm, Sweden
Tel.: +46 8 790 7333 | Fax: +46 8 790 7343
yuriy.reshetyuk@infra.kth.se